Plant Diseases and Pests 2025, 16 (2-4): 13-18, 23 DOI: 10.19579/j.cnki.plant-d.p.2025.02-04.003

Comparison of Efficacy of Various Control Agents for Citrus Psyllid and Advances in Related Research

Zhihao YE[1], Xiaoshan LI[1], Haowen ZHANG[1], Yupai ZENG[1], Weifeng HOU[1], Chenglang LIANG[1], Ranran NIE[1,2], Qianhua JI[1,2*]

1. College of Life Sciences, Zhaoqing University, Zhaoqing 526061, China; 2. Institute of Pomology, Zhaoqing University, Zhaoqing 526061, China

Abstract Given that the citrus psyllid is the primary vector of citrus Huanglongbing (HLB), there is an urgent need to control this pest to mitigate the spread of the disease. This paper reviews the current research on two predominant control strategies: chemical control and biological control agents, in managing the citrus psyllid. It emphasizes the mechanisms of action, efficacy, and application advancements of these control methods. Finally, the paper analyzes the principal challenges associated with the sustainable management of citrus psyllids and offers perspectives for future research.

Key words Citrus psyllid, Chemical control agent, Biological control agent, Efficacy, Comparison

1 Introduction

Citrus is one of the fruit trees with the largest cultivation area and holds significant economic importance in southern China. Citrus psyllid is the principal pest threatening citrus production and serves as the primary vector of citrus Huanglongbing (HLB)[1]. HLB is a devastating disease affecting global citrus production and is recognized as a key quarantine disease in China[2]. HLB manifests in citrus plants through symptoms including withered and shrunken leaves, irregular flowering, reduced quantity and quality of fruit production, yellowing, and potentially plant death. If not promptly and effectively controlled, the disease can spread rapidly, resulting in widespread tree mortality, substantial yield reductions, and significant economic losses to the citrus industry[3]. Currently, there is no cure for HLB. The primary strategy to delay the spread of this disease involves the prevention and control of citrus psyllids. Among the various control methods available, chemical control is the predominant approach due to its ease of application and rapid efficacy. However, the extensive use of chemical agents not only progressively increases the drug resistance of citrus psyllids but also diminishes the effectiveness of their control. Furthermore, such usage may cause ecological damage, including soil and water pollution, and potentially raise food safety concerns that are of growing public interest[4]. In addition to chemical control methods, biological control has garnered significant attention owing to its environmentally friendly characteristics, specificity, and safety. It is a crucial approach for managing plant diseases and holds considerable potential for the prevention and control of citrus psyllid infestations. This article reviews the current research status of various agents used for the control of citrus psyllids, compares their efficacy, and discusses recent advancements in agent development. The objective is to provide a scientific basis for the environmentally sustainable management of citrus psyllids and the prevention and control of HLB.

Received: May 10, 2025 Accepted: July 12, 2025

Supported by National Undergraduate Training Programs for Innovation and Entrepreneurship (202510580009); Special Project for Promoting the Coordinated Development of Urban and Rural Areas and Regions by Introducing Scientific and Technological Achievements of Guangdong Province into Counties and Towns (2025B0202010051); Project of High-quality Development in Hundred Counties, Thousands Towns and Ten Thousand Villages of Guangdong Provincial Department of Science and Technology: Key Dispatch Project for Rural Science and Technology Commissioners (KTP20240704).

* Corresponding author. Qianhua JI, doctoral degree, professor, research fields: pomology.

2 Primary agents used for controlling citrus psyllids

2.1 Chemical control agents In recent years, chemical agents have been widely employed to control citrus psyllid populations. Commonly used chemical agents include chlorpyrifos, cypermethrin, imidacloprid, and thiamethoxam. These chemical agents can be classified into two primary categories: broad-spectrum pesticides, such as organophosphates, pyrethroids, neonicotinoids, and abamectin; and selective pesticides, including amides and insect growth regulators. The mechanisms of action of various chemical agents differ. For example, neonicotinoid pesticides function as agonists of nicotinic acetylcholine receptors (nAChRs), disrupting normal signal transmission in the central nervous system and ultimately causing insect paralysis or death[5]. Pyrethroid pesticides are classified as neurotoxic agents, primarily functioning by disrupting voltage-gated sodium ion channels in insects[6].

Among the two aforementioned categories of chemical agents, broad-spectrum pesticides have been extensively utilized owing to their notable efficacy in pest control[4]. Numerous researchers have conducted efficacy assessments and determined that various chemical agents exhibited excellent control effects against citrus psyllids. For example, Song Xiaobing *et al.*[7] demonstrated that 22% lambda-cyhalothrin · thiamethoxam CS, 10% imidacloprid WP, and 4.5% beta-cypermethrin EC effectively controlled citrus psyllids and exhibited a relatively prolonged duration of efficacy. Lai Jiasheng *et al.*[8] reported that 21% thiamethoxam SC, 2.5%

beta-cyfluthrin EC, 25% bifenthrin EW, and 50% pymetrozine WP demonstrated effective control of citrus psyllids and were both safe and non-toxic to citrus plants. Deng Mingxue *et al.* [9] reported that 18% spirotetramat · amide SC at a concentration of 60 mg/kg exhibited effective control of citrus psyllids. Similarly, He Ling *et al.* [10] demonstrated that 4.5% bifenthrin EW diluted 800-fold and 10% pyriproxyfen - imidacloprid SC diluted 2 000-fold not only provided rapid insecticidal action but also maintained prolonged efficacy against citrus psyllids.

2.2 Biological control agents The implementation of the national policy on "carbon peak and neutrality goals" alongside the advancement of green agriculture has positioned biological control agents as a prominent focus of contemporary research. Currently, the primary biological control agents employed to manage citrus psyllids include botanical pesticides, microbial pesticides, and mineral-based pesticides.

2.2.1 Botanical pesticides. Botanical pesticides are a novel category of pesticides possessing insecticidal or antibacterial properties, synthesized through direct or indirect processing of bioactive compounds extracted from plants[11]. Currently, the primary botanical pesticides for the management of citrus psyllids include essential oil from *Melaleuca alternifolia*, essential oil from *Coriandrum sativum*, azadirachtin, and volatiles from *Psidium guajava*. Ye Zidong *et al.* [12] reported that the essential oil derived from *M. alternifolia* and its primary constituent, 4-terpineol, exhibited significant repellent effects against adult citrus psyllids. Mann *et al.* [13] employed a T-type olfactometer to investigate the effects of essential oils, finding that those from *C. sativum* and *Lavandula angustifolia* demonstrated high contact toxicity against citrus psyllids. Lai Duo *et al.* [14] employed both the leaf immersion and spray methods to evaluate the virulence of azadirachtin against the nymphs of citrus psyllids, finding it to be relatively effective. Onagbola *et al.* [15] demonstrated that volatiles emitted from *P. guajava* leaves significantly inhibited the taxis behavior of citrus psyllids toward the volatile compounds of their conventional host plants (citrus). Cen Yijing *et al.* [16] demonstrated that the volatile oils extracted from *Mikania micrantha*, *Lantana camara*, *Sphagneticola calendulacea*, and *Praxelis clematidea* significantly inhibited the taxis behavior of citrus psyllids toward their host plants.

2.2.2 Microbial pesticides. Microbial pesticides are formulations derived from live microorganisms or their metabolic byproducts. These pesticides are noted for their environmental friendliness and high safety concerning non-target organisms. Currently, the primary microbial pesticides investigated for controlling citrus psyllids include *Beauveria bassiana*, *Isaria fumosorosea*, and *Bacillus thuringiensis*, *etc.*, which have demonstrated efficacy in managing citrus psyllid populations. Song Xiaobing *et al.* [17] demonstrated that the entomopathogenic fungus *B. bassiana* exhibited strong pathogenicity against citrus psyllids. Similarly, Lu Lianming *et al.* [18] confirmed, through strain isolation and virulence assays, that the strain MSC-f1 of *Cordyceps javanica* also possessed significant pathogenicity toward citrus psyllids. Xia Shuang[19] identified that the strain F-HY002-ACPHali of *Isaria javanica* exhibited a relatively high mortality rate against citrus psyllids. Yan Jianquan *et al.* [20] reported that the GDIZM-1 strain of *Aspergillus fijiensis* demonstrated effective control of citrus psyllids, thereby offering a novel strain resource for the development of new biological control agents.

2.2.3 Mineral-based pesticides. Mineral-based pesticides are a class of pesticides derived from natural minerals or their processed derivatives, characterized by environmental compatibility and a reduced propensity for inducing resistance. Huang Zhendong *et al.* [21] demonstrated that a 2% HMO emulsion significantly inhibited the feeding behavior of adult citrus psyllids on citrus leaves and consequently decreased the risk of transmitting HLB. Liu Zeyu *et al.* [22] demonstrated that the application of botanical glycerides alone effectively controlled pest populations and achieved a relatively high corrected population decline rate, which can be used for managing both the nymph and adult stages of citrus psyllids.

Based on these findings, it can be concluded that biological control agents demonstrate significant potential for managing citrus psyllid populations. Botanical pesticides act through volatile compounds or natural active ingredients, exhibiting repellent properties and contact toxicity. Microbial pesticides display strong pathogenicity and result in high mortality rates among citrus psyllids. Additionally, mineral-based pesticides inhibit the feeding behavior of citrus psyllids, thereby preventing the transmission of HLB. Overall, biological control agents can effectively manage citrus psyllid populations and reduce dependence on chemical pesticides, thereby serving as a crucial strategy for promoting environmentally sustainable management of citrus psyllids.

3 Comparison of efficacy of various control agents against citrus psyllids

3.1 Comparison of virulence Song Xiaobing *et al.* [23] reported that the LC_{50} values of chemical control agents against citrus psyllids, including 1.8% abamectin EC, 10% beta-cypermethrin EC, 70% imidacloprid WDG, and 25% thiamethoxam WDG, ranged from 0.592 6 to 0.880 2 mg/L. Hu Shuangshuang[24] reported that the LC_{50} values of 10% imidacloprid WP for adult citrus psyllids in Yongxing County and Jiangyong County were 35.986 and 65.967 mg/L, respectively. Xiang Min *et al.* [25] conducted a virulence assay and determined that, after 72 h of chlorantraniliprole treatment, the LC_{50} values for nymph and adult citrus psyllids were 0.782 and 1.984 mg/L, respectively. Song Xiaobing *et al.* [7] reported that the average control efficacies of 22% lambda-cyhalothrin · thiamethoxam CS at 73.3 mg/kg, 10% imidacloprid WP at 66.7 mg/kg, and 4.5% beta-cypermethrin EC at 45 mg/kg against citrus psyllids all exceeded 89%.

Regarding biological control agents, Mann *et al.* [13] reported that the median lethal concentration (LC_{50}) of essential oils derived from *C. sativum*, *L. angustifolia*, and *Allium tuberosum* against Asian citrus psyllids ranged from 0.16 to 0.25 μg per adult insect. In contrast, the LC_{50} values for essential oils from *Rosa rugosa* and *Thymus mongolicus* were comparatively higher, ranging from 2.45 to 17.26 μg per adult insect. Lai Duo *et al.* [14] reported that the LC_{50} values for third instar nymphs of citrus psyllids exposed to azadirachtin were 2.77 mg/L after 1 d, 1.14 mg/L after 3 d, and 0.61 mg/L after 7 d of treatment. Song Xiaobing *et al.* [17] evaluated the virulence of the strain GZMS-28 of *B. bassiana* against adult citrus psyllids. Following treatment with a conidial suspension at a concentration of 1.0×10^8 spores/mL for 7 d, the corrected mortality rate reached 95.7%. Similarly, Lu Lianming *et al.* [18] inoculated citrus psyllids with a conidial suspension of the strain MSC-f1 of *C. javanica* at 1.0×10^8 spores/mL, reporting a median lethal time (LT_{50}) of 4.96 d. Yan Jianquan *et al.* [20] demonstrated that the GDIZM-1 strain of *A. fijiensis* was capable of infecting citrus psyllids across all developmental stages, from first to fifth instar nymphs as well as adults. Following a 7 d exposure to a conidial suspension at a concentration of 1×10^8 spores/mL, the mortality rate of citrus psyllids at all ages exceeded 70% (Table 1).

Table 1 Comparison of virulence of various control agents against citrus psyllids

Category	Name	Target insect state	Virulence index
Chemical control agent	1.8% Abamectin EC	Sensitive population	LC_{50}: 0.592 6 - 0.880 2 mg/L[23]
	10% Beta-cypermethrin EC	Sensitive population	LC_{50}: 0.592 6 - 0.880 2 mg/L[23]
	70% Imidacloprid WDG	Sensitive population	LC_{50}: 0.592 6 - 0.880 2 mg/L[23]
	25% Thiamethoxam WDG	Sensitive population	LC_{50}: 0.592 6 - 0.880 2 mg/L[23]
	10% Imidacloprid WP	Adults (Yongxing County)	LC_{50}: 35.986 mg/L[24]
	10% Imidacloprid WP	Adults (Jiangyong County)	LC_{50}: 65.967 mg/L[24]
	Chlorantraniliprole	Nymphs	LC_{50}: 0.782 mg/L[25]
	Chlorantraniliprole	Adults	LC_{50}: 1.984 mg/L[25]
	22% Lambda-cyhalothrin · thiamethoxam CS	-	Average control effect ≥89%[7]
	10% Imidacloprid WP	-	Average control effect ≥89%[7]
	4.5% Beta-cypermethrin EC	-	Average control effect ≥89%[7]
Biological control agent	Essential oil from *Coriandrum sativum*	Adults	LC_{50}: 0.16 - 0.25 μg/individual[13]
	Essential oil from *Lavandula angustifolia*	Adults	LC_{50}: 0.16 - 0.25 μg/individual[13]
	Essential oil from *Allium tuberosum*	Adults	LC_{50}: 0.16 - 0.25 μg/individual[13]
	Essential oil from *Rosa rugosa*	Adults	LC_{50}: 2.45 - 17.26 μg/individual[13]
	Essential oil from *Thymus mongolicus*	Adults	LC_{50}: 2.45 - 17.26 μg/individual[13]
	Azadirachtin	Third instar nymphs	LC_{50}(1 d): 2.77 mg/L[14] LC_{50}(3 d): 1.14 mg/L[14] LC_{50}(7 d): 0.61 mg/L[14]
	Strain GZMS-28 of *Beauveria bassiana*	Adults	Corrected mortality rate: 95.7%[17]
	Strain MSC-f1 of *Cordyceps javanica*	Adults	LT_{50}: 4.96 d[18]
	Strain GDIZM-1 of *Aspergillus fijiensis*	First to fifth instar nymphs and adults	Mortality rate >70%[20]

3.2 Comparison of rapid efficacy and persistence Rapid efficacy and persistence are critical indicators for assessing the field effectiveness of control agents against citrus psyllids. Research indicates that most chemical agents exhibit both rapid efficacy and persistence, resulting in effective control of citrus psyllid populations. Deng Mingxue *et al.* [9] reported that the control efficacy of 18% spirotetramat · amide SC at a dosage of 60 mg/kg against citrus psyllids increased progressively over time. The total control efficacies were 77.21%, 91.50%, and 84.97% at 1, 4, and 7 d post application, respectively. He Ling *et al.* [10] reported that a 4.5% bifenthrin EW diluted 800-fold and a 10% pyriproxyfen-imidacloprid SC diluted 2 000-fold exhibited control efficacies of 80% against citrus psyllids 1 d post application, which further increased to over 90% 5 d after application. Tang Mingli *et al.* [26] reported that 22% Wente SC exhibited both rapid efficacy and sustained stability against the nymphs of citrus psyllids. The control efficacies of 22% Wente SC at concentrations of 48, 60, and 80 mg/L, measured 3 d post application, ranged from 90.7% to 100.0%. Furthermore, 22% Wente SC effectively controlled citrus psyllids in field conditions for a duration exceeding 14 d. Liang Zailin *et al.* [27] reported that a 20% clothianidin SC exhibited rapid efficacy in controlling citrus psyllid populations. Specifically, the control efficacies of 20% clothianidin SC at dilution ratios of 1 500-, 2 000-, and 2 500-fold against nymphs were 89.93%, 85.07%, and 81.01%, respectively, 1 d post application. Corresponding efficacies against adult psyllids were 91.67%, 85.55%, and 81.65%, respectively. Notably, 10 d after application, the control efficacy against nymphs reached 100%, while efficacies against adults were 100%, 88.89%, and 84.40% for the respective dilution ratios. Chen Hong *et al.* [28] reported that the application of 30% clothianidin and diflubenzuron SC, diluted 1 000 to 1 500 times, achieved a control efficacy of 94.97% to 99.17% against citrus psyllids 15 d post application. Furthermore, this treatment demonstrated notable control effects on the eggs, nymphs, and adults of citrus psyllids. Lu Huanxiang *et al.* [29] conducted a comparative study of multiple chemical agents and found that when 52.25% beta-cypermethrin · chlorpyrifos EC at 1 000-fold, 4.5% bifenthrin SC at 1 500-fold, 5%

lambda-cyhalothrin EW at 1 500-fold, and 25% thiamethoxam WG at 3 500-fold were applied, the overall prevention efficiency measured at 1 and 7 d post application exceeded 90%.

Although the initial efficacy of biological control agents is slower compared to chemical agents, their persistence is more pronounced, and they demonstrate effective control of citrus psyllids. Among botanical pesticides, Lai Duo *et al.* [14] reported that a 0.3% azadirachtin EC diluted 800 times achieved a field control efficacy of 86.4% against citrus psyllid nymphs 7 d after application. Liu Zeyu *et al.* [22] reported that after 14 d of treatment with a 125-fold diluted botanical glyceride, the corrected population reduction rate of both adult and nymph stages of citrus psyllids exceeded 88%. Regarding microbial pesticides, Yan Jianquan *et al.* [20] applied the GDIZM-1 strain of *A. fijiensis* at a conidial suspension concentration of 1×10^8 spores/mL for 14 d, resulting in a survival rate of adult citrus psyllids of only 3.33%. Similarly, treatment with the strain GDIZM-2 of *Purpureocillium lilacinum* at the same concentration (1×10^8 spores/mL) for 14 d yielded a survival rate of adult citrus psyllids of merely 1.67% [30] (Table 2).

Table 2 Comparison of rapid efficacy and persistence of various control agents against citrus psyllids

Category	Name	Rapid efficacy	Persistence
Chemical control agent	18% Spirotetramat · amide SC (60 mg/kg)	Control effect 1 d post application: 77.21% [9]	Control effect 4 d post application: 91.50%; Control effect 7 d post application: 84.97% [9]
	4.5% Bifenthrin WE (800-fold)	Control effect 1 d post application: ≥80% [10]	Control effect 5 d post application: ≥90% [10]
	10% Pyriproxyfen-imidacloprid SC (2 000-fold)	Control effect 1 d post application: ≥80% [10]	Control effect 5 d post application: ≥90% [10]
	22% Wente SC (48, 60, 80 mg/L)	Control effect 3 d post application: 90.7% – 100% [26]	Duration: ≥14 d [26]
	20% Clothianidin SC (1 500-fold)	Nymph: control effect 1 d post application: 89.93% Adult: control effect 1 d post application: 91.67% [27]	Nymph, adult: control effect 10 d post application: 100% [27]
	20% Clothianidin SC (2 000-fold)	Nymph: control effect 1 d post application: 85.07% Adult: control effect 1 d post application: 85.55% [27]	Nymph: control effect 10 d post application: 100% Adult: control effect 10 d post application: 88.89% [27]
	20% Clothianidin SC (2 500-fold)	Nymph: control effect 1 d post application: 81.01% Adult: control effect 1 d post application: 81.65% [27]	Nymph: control effect 10 d post application: 100% Adult: control effect 10 d post application: 84.40% [27]
	30% Clothianidin and diflubenzuron SC (1 000 – 1 500-fold)	–	Control effect 15 d post application: 94.97% – 99.17% [28]
	52.25% Beta-cypermethrin · chlorpyrifos EC (1 000-fold)	Control effect 1 d post application: 90% [29]	Control effect 7 d post application: ≥90% [29]
	4.5% Bifenthrin SC (1 500-fold)	Control effect 1 d post application: ≥90% [29]	Control effect 7 d post application: ≥90% [29]
	5% Lambda-cyhalothrin EW (1 500-fold)	Control effect 1 d post application: ≥90% [29]	Control effect 7 d post application: ≥90% [29]
	25% Thiamethoxam WG (3 500-fold)	Control effect 1 d post application: ≥90% [29]	Control effect 7 d post application: ≥90% [29]
Biological control agent	0.3% Azadirachtin EC (800-fold)	–	Nymph: control effect 7 d post application: 86.4% [14]
	Botanical glyceride (125-fold dilution)	–	Nymph, adult: control effect 14 d post application: >88% [22]
	Strain GDIZM-1 of *Aspergillus fijiensis* (1×10^8 spores/mL)	–	Adult: control effect 14 d post application: 3.33% [20]
	Strain GDIZM-2 of *Purpureocillium lilacinum* (1×10^8 spores/mL)	–	Adult: control effect 14 d post application: 1.67% [30]

4 Research progress of major control agents

4.1 Chemical control agents Currently, chemical agents play a crucial role in the management of citrus psyllids. Owing to their advantages, including rapid efficacy, ease of application, and consistent control outcomes, they have long been the primary method within the integrated management system for citrus psyllids. Currently, commonly used chemical agents include neonicotinoids, pyrethroids, and insect growth regulators. Although these agents have different mechanisms of action, improper application practices, such as the prolonged use of a single compound or repeated use of insecticides from the same class, have led to a continuous increase in resistance among citrus psyllids[31]. For example, Deng Mingxue *et al.* [32] reported that the resistance of citrus psyllids to chlorpyrifos had increased by a factor of 8.8. Additionally, Guo Qizhong *et al*.[33] observed that emamectin benzoate exhibited minimal control efficacy against citrus psyllids, whereas abamectin and pyrethroids were susceptible to resistance development in these pests, resulting in suboptimal control outcomes. The widespread application of chemical pesticides has led to significant issues, including environmental degradation and pesticide residues. Consequently, when employing chemical agents to control citrus psyllids, it is essential to precisely determine the optimal timing for application and to standardize both the spraying methods and dosages to enhance efficacy. In agricultural practice, it is also important to minimize the continuous use of a single chemical agent and to implement a scientifically informed rotation of chemicals with different mechanisms of action to prevent the rapid emergence of pesticide resistance[34].

4.2 Biological control agents The use of biological agents for the control of citrus psyllids is becoming increasingly prevalent and constitutes a significant component of environmentally sustainable pest management. Compared to chemical agents, biological agents possess several distinct characteristics. Primarily, they are environmentally friendly and non-polluting. Many biological agents, including essential oil from *C. sativum*, azadirachtin and other botanical pesticides, microbial pesticides such as *B. bassiana* and *I. fumosorosea*, as well as mineral-based pesticides like 2% HMO emulsion and botanical glycerides, result in minimal environmental pollution following application. These agents are readily biodegradable and exhibit relative safety toward natural enemies of citrus psyllids, thereby effectively preserving the ecological balance within orchards. Secondly, the risk of developing drug resistance is low. The active components of biological control agents are primarily natural substances or microbial metabolites with diverse compositions. Consequently, citrus psyllids are less likely to develop resistance, which helps mitigate the challenges associated with increased resistance to chemical agents. However, the technology of biological control agents remains imperfect, with several existing challenges. First, the rapidity of their efficacy is limited, and the control effects are often unstable. Biological agents primarily function by disrupting the physiological metabolism of pests or through microbial infection processes. Consequently, their effectiveness is slower compared to chemical agents, and their preventive and control outcomes are influenced by the agents' activity levels. Second, these pesticides exhibit a strong dependence on environmental conditions. For example, the efficacy of microbial pesticides is significantly influenced by temperature and humidity, limiting their functionality to specific suitable conditions. Third, technical challenges remain. For instance, the extraction processes for the primary components of botanical pesticides, as well as the optimal application concentration and duration for microbial pesticides, require further optimization. In this context, the use of biological agents to control citrus psyllids can be effectively combined with low-toxicity, fast-acting chemical agents. This approach not only enhances the rapid efficacy but also leverages the specificity of biological agents, thereby mitigating the limitation of their slow onset of contact lethality. For example, Hu *et al*.[35] demonstrated that, in combined treatments, the mixture of mineral oil and thiamethoxam yielded the most effective control outcomes. Gao Jing *et al*.[36] reported that, in their experimental mixed solution, a combination of nC22 mineral oil and imidacloprid at a 7 : 3 ratio demonstrated high toxicity against young nymphs of citrus psyllids and was identified as the optimal ratio in their study. Wang Fangfei *et al*.[37] demonstrated that the combined application of *Verticillium lecanii* and flupyradifurone produced a significant synergistic effect on the mortality rate of citrus psyllids.

5 Existing deficiencies and challenges

5.1 Resistance to chemical control agents Chemical control remains the primary method for managing citrus psyllids, but its sustainable implementation is consistently challenged by the emergence of pesticide resistance. Prolonged reliance on a single class of chemical agents has resulted in a rapid increase of resistance within citrus psyllid populations. Given the high reproductive rate and overlapping generations of citrus psyllids, the absence of scientifically informed pesticide rotation strategies can lead to a swift expansion of resistant populations. This dynamic compels continuous increases in pesticide dosages, ultimately creating a detrimental cycle characterized by escalating resistance, higher application rates, and further intensified resistance. Currently, there is a relative paucity of systematic research on the mechanisms underlying resistance development in citrus psyllids, dynamic monitoring of resistant lineages across different regions, and the implementation of scientifically informed pesticide rotation strategies based on these resistance mechanisms. Consequently, effective and specialized theoretical guidance for managing field resistance is lacking.

5.2 Application bottleneck of biological control agents Although biological agents align with the principles of sustainable agricultural development, their practical application encounters several challenges. Firstly, the stability of their control efficacy is inadequate. Botanical pesticides primarily consist of volatile compounds, resulting in limited persistence. Additionally, the effectiveness of microbial pesticides is influenced by environmental factors. Secondly, the technical research remains imperfect. At present, most studies are limited to indoor virulence assessments and small-scale field trials. Systematic investigations into standardized application timing and dosage of biological agents, large-scale microbial strain fermentation, and formulation processes are comparatively underdeveloped, thereby constraining the application and widespread adoption of biological agents.

6 Future research directions and prospects

6.1 Chemical control agents Firstly, it is essential to improve the monitoring and evaluation of resistance in citrus psyllids, to further investigate the mechanisms underlying their resistance to commonly used chemical agents, and to develop rational and effective resistance management strategies[38]. Secondly, the selection and application of chemical agents should be tailored to the specific context. For example, in regions exhibiting high levels of resistance, alternating the use of agents with different modes of action and lower resistance prevalence is advisable. In areas with moderate resistance, the use of chemical agents should be restricted to prevent the accelerated development of resistance[39].

6.2 Biological control agents The first approach involves combining botanical pesticides with microbial pesticides to enhance their persistence and stabilize their efficacy. For example, the emulsifiable formulation (SAE-EC) containing *Sophora alopecuroides* extract, developed by Hussain *et al.* [40], has been shown to increase the persistence of the extract and improve its control efficacy against citrus psyllids. The second approach focuses on strain improvement. Specifically, genetic engineering techniques can be employed to enhance the pathogenicity and spore production of target strains, thereby enabling the development of efficient, stable, and multifunctional engineered strains[17].

6.3 Intelligent monitoring and precise pesticide application By integrating artificial intelligence, the Internet of Things, and big data technologies, the intelligent monitoring system for citrus psyllids enables real-time surveillance of pest populations. This system facilitates precise pesticide application based on current pest conditions, thereby preventing missed optimal control periods and minimizing the excessive use of chemical pesticides. Consequently, it contributes to delaying the development of resistance in citrus psyllids and reducing the unintended harm to natural enemy pests. The intelligent monitoring device developed by Li Shanjun *et al.* [41] accurately identifies and counts citrus psyllids, thereby fulfilling the monitoring requirements for these pests and aiding in their prevention and control management. Additionally, Miranda *et al.* [42] demonstrated that the application of pesticides via unmanned aerial vehicles effectively controlled citrus psyllid populations.

7 Conclusions

Citrus psyllids are the exclusive vectors responsible for the transmission of HLB. Effective management of citrus psyllid populations is a critical component in mitigating the spread of HLB and promoting the sustainable development of the citrus industry. Conventional chemical agents are widely used due to their ease of application, rapid and persistent efficacy, and reliable control outcomes. However, challenges such as the increasing development of pesticide resistance, environmental contamination, and residual pesticide accumulation have become significant concerns, thereby limiting their extensive application. Biological agents have increasingly become a significant method for controlling citrus psyllids, owing to their environmental friendliness and reduced likelihood of inducing drug resistance. Nevertheless, their practical application is limited by drawbacks such as slow action and inconsistent efficacy. In this context, a sustainable management system for citrus psyllids can be developed in the future to advance the environmentally friendly and high-quality growth of the citrus industry. This can be achieved by enhancing the monitoring and rotation of pesticide resistance in citrus psyllids, promoting the use of compound formulations and improved strains, and integrating intelligent monitoring with precise pesticide application.

References

[1] LIANG ZL, LIANG MW, DENG TJ, *et al.* Outbreak causes and control strategies of the *Diaphorina citri* and its relation with citrus Huanglongbing [J]. Plant Quarantine, 2023, 37(3): 26 – 30. (in Chinese).

[2] WANG XD, HU HQ, LIN XJ, *et al.* Inhibiting effect of three disinfectants against candidatus *Liberibacter asiaticus* [J]. South China Fruits, 2016, 45(6): 6 – 9, 14. (in Chinese).

[3] QIU FJ, LI XZ. Control strategies of citrus Huanglongbing[J]. Seed Science & Technology, 2022, 40(13): 87 – 89. (in Chinese).

[4] LI J, ZHAO MP, WANG XQ, *et al.* Research progress on prevention and control of *Diaphorina citri*[J]. South China Agriculture, 2025, 19(9): 152 – 155, 160. (in Chinese).

[5] MA SZ. Current development and utilization of neonicotinoid insecticides [J]. Southern Horticulture, 2023, 34(4): 69 – 73. (in Chinese).

[6] XU ZH, LUO L, CHEN ZJ, *et al.* Rogress on the development of immunoassays for pyrethroids insecticides and their metabolites[J]. Food and Fermentation Industries, 2022, 48(8): 320 – 328. (in Chinese).

[7] SONG XB, PENG AT, CHEN X, *et al.* Control effects of six pesticides such as beta-cypermethrin · thiamethoxam on citrus psyllid[J]. Agrochemicals, 2015, 54(12): 915 – 917. (in Chinese).

[8] LAI JS, LIU ML, MA DF, *et al.* Field efficacy trials of four insecticides against citrus psyllid[J]. Modern Agriculture, 2022(11): 7 – 8. (in Chinese).

[9] DENG MX, WEI W, TAN YL, *et al.* Field efficacy trials of 18% spirotetramat and amide SC against four pests including citrus aphids and psyllids[J]. Southern Horticulture, 2022, 33(3): 61 – 64. (in Chinese).

[10] HE L, LUO HY, YIN ZY, *et al.* Field efficacy tests of several insecticides against citrus psyllid[J]. Journal of Hunan Ecological Science, 2019, 6(3): 29 – 33. (in Chinese).

[11] LIU XJ. Advances in research and application of botanical pesticides[J]. Guangdong Landscape Architecture, 2006(S1): 60 – 64. (in Chinese).

[12] YE ZD, LIN ZY, YANG CY, *et al.* Effect of *Melaleuca alternifolia* Cheel and its volatile compounds on behavior of *Diaphorina citri* Kuwayama and its application[J]. Plant Medicine, 2024, 3(5): 63 – 73. (in Chinese).

[13] MANN SR, TIWARI S, SMOOT MJ, *et al.* Repellency and toxicity of plant-based essential oils and their constituents against *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae)[J]. Journal of Applied Entomology, 2012, 136(1 – 2): 87 – 96.

[14] LAI D, CAO X, SHAO XH, *et al.* Determination of indoor toxicity of azadirachtin to *Diaphorina citri* and its control effect in field[J]. Guangdong Agricultural Sciences, 2019, 46(12): 89 – 94. (in Chinese).

[15] ONAGBOLA EO, ROUSEFF RL, SMOOT JM, *et al.* Guava leaf volatiles and dimethyl disulphide inhibit response of *Diaphorina citri* Kuwayama to host plant volatiles[J]. Journal of Applied Entomology, 2011, 135(6): 404 – 414.

[16] CEN YJ, YE JM, XU CB, *et al.* The taxis of *Diaphorina citri* to the volatile oils extracted from non-host plants[J]. Journal of South China Agricultural University, 2005(3): 41 – 44. (in Chinese).

[17] SONG XB, PENG AT, CHENG BP, *et al.* Review of biological controls of *Diaphorina citri* using entomopathogenic fungi[J]. Journal of Biosafety, 2016, 25(4): 255 – 260. (in Chinese).

[18] LU LM, DU DC, HU XR, *et al.* Isolation and identification of *Cordyceps javanica* MSC-f1 and its toxicity against multiple citrus pests[J]. Journal of Plant Protection, 2025, 52(2): 468 – 478. (in Chinese).

[19] XIA S. Study on fermentation and insecticial spectrum of high virulent entomopathogenic fungi of *Diaphorina citri*[D]. Wuhan: Huazhong Agricultural University, 2021. (in Chinese).

[20] YAN J, LIU H, IDREES A, *et al.* First record of *Aspergillus fijiensis* as an entomopathogenic fungus against Asian citrus psyllid, *Diaphorina citri* Kuwayama (Hemiptera: Liviidae)[J]. Journal of Fungi, 2022, 8(11): 1222.

[21] HUANG ZD, PU ZX, HU XR, *et al.* Effect of horticultural mineral oils on the penetration behavior of adult *Diaphorina citri* (Hemiptera: Liviidae)[J]. Acta Entomologica Sinica, 2021, 64(4): 471 – 478. (in Chinese).

(To page 23)

Management, 2023, 44(8): 49 – 54. (in Chinese).

[3] ZHANG S, WANG YP, LI YP, *et al*. Key techniques and suggestions of weed control in soybean and maize strip compound planting field[J]. Modern Agrochemicals, 2023, 22(5): 46 – 48. (in Chinese).

[4] ZHANG Y, GU LL, CAO L, *et al*. Herbicides and their application for corn-soybean strip compound planting[J]. China Plant Protection, 2022, 42(5): 71 – 75. (in Chinese).

[5] FAN XP, WANG QW, ZHANG K, *et al*. Field efficacy evaluation of four kinds of herbicides on weeds in soybean-corn strip compound planting area [J]. Shaanxi Journal of Agricultural Sciences, 2023, 69(9): 64 – 70. (in Chinese).

[6] GAO XX, FENG K, ZHANG GF, *et al*. Effect of combination of pyroxasulfone and metribuzin in maize and soybean intercropping patterns[J]. Journal of Plant Protection, 2024, 51(2): 361 – 368. (in Chinese).

[7] ZHAO FY, CHENG DQ, WANG XC, *et al*. Efficacy and safety evaluation of 52% flumioxazin · S-metolachlor EC against annual weeds in maize-soybean strip intercropping fields[J]. Contemporary Horticulture, 2024, 47(13): 96 – 98. (in Chinese).

[8] ZHAO YQ, WANG JS, ZHOU RW, *et al*. The control effects of different herbicides combinations on weed in corn-soybean strip compound planting field[J]. Modern Agrochemicals, 2023, 22(5): 49 – 52. (in Chinese).

[9] GENG YL, WANG H, WANG LH, *et al*. Effects of 10 pre-emergence herbicides applied in soybean-maizestrip intercropping field[J]. Acta Agrestia Sinica, 2023, 31(9): 2890 – 2895. (in Chinese).

[10] XU P, JU YW, WANG HC, *et al*. Selectivity of several herbicides to different varieties of soybean and maize and their biological activity of weed in soybean-maize strip compound planting fields[J]. Journal of Weed Science, 2023, 41(4): 67 – 73. (in Chinese).

[11] ZHU DH, YU T, CHEN Y, *et al*. Preliminary study on the optimization experiment of herbicides on weeds in soybean-corn strip compound planting field in the Northern Anhui Province[J]. Modern Agrochemicals, 2023, 22(5): 53 – 58. (in Chinese).

(From page 18)

[22] LIU ZY, GONG BY, HUANG CY, *et al*. Decrement and synergism effect of plant-derived glyceride combined with several pesticides to control citrus psyllid[J]. Hunan Agricultural Sciences, 2024(11): 51 – 54. (in Chinese).

[23] SONG XB, CUI YP, PENG AT, *et al*. Resistance to commonly used insecticides of *Diaphorina citri* field populations in Zhaoqing City, Guangdong Province[J]. Journal of Environmental Entomology, 2021, 43(5): 1321 – 1324. (in Chinese).

[24] HU SS. Monitoring of occurrence dynamics and evaluation and screening of control agents for citrus psyllid in southern Hunan[D]. Changsha: Hunan Agricultural University, 2021. (in Chinese).

[25] XIANG M, LIU H, GONG BY, *et al*. Toxic effects of four kinds of insecticides on nymphs and adults of *Diaphorina citri* Kuwayama[J]. Hunan Agricultural Sciences, 2022(12): 63 – 65. (in Chinese).

[26] TANG ML, ZHANG SY, MEN YJ, *et al*. Field efficacy trials of 22% wente SC against citrus psyllid[J]. Southern Horticulture, 2019, 30 (5): 29 – 31. (in Chinese).

[27] LIANG ZL, CAO XY, YANG YN, *et al*. Efficacy of 20% clothianidin SC against *Diaphorina citri* in the field[J]. Guangxi Plant Protection, 2018, 31(1): 22 – 24. (in Chinese).

[28] CHEN H, WEI SL, CHEN W, *et al*. Field efficacy trials of 30% clothianidin and diflubenzuron SC against citrus psyllid[J]. Agriculture and Technology, 2017, 37(10): 48,148. (in Chinese).

[29] LU HX, HUANG YD, ZHANG JH, *et al*. Field efficacy trials of several insecticides against citrus psyllid [J]. Guangxi Plant Protection, 2016, 29(4): 21 – 22. (in Chinese).

[30] YAN JQ, LIU H, CHEN FH, *et al*. Isolation and identification of a *Purpureocillium lilacinum* GDIZM-2 isolate and its toxicity evaluation against *Diaphorina citri* [J]. Journal of Environmental Entomology, 2023, 45(6): 1718 – 1729. (in Chinese).

[31] SUN Y, XIE XT, QIN WJ, *et al*. Screening and field control experiments of different complex formulations of amitraz and cyantraniliprole to control *Diaphorina citri* Kuwayama[J]. Journal of Anhui Agricultural Sciences, 2019, 47(6): 132 – 135. (in Chinese).

[32] DENG MX, PAN ZX, TAN YL, *et al*. Monitoring of resistance of citrus psyllid in Guangxi orchards to six pesticides including chlorpyrifos[J]. China Plant Protection, 2012, 32(4): 48 – 49. (in Chinese).

[33] GUO QZ, WU HY, ZHU TY. *Diaphorina citri* and its control techniques[J]. Modern Horticulture, 2023, 46(7): 94 – 96. (in Chinese).

[34] ZHAO QY, YUAN H, ZHANG WM, *et al*. Field control effect of 25% chlorfenapyr and tolfenpyrad SC against *Diaphorina citri* [J]. Hubei Plant Protection, 2022(6): 44 – 46. (in Chinese).

[35] HU W, WANG K, ZHONG X, *et al*. Enhanced control efficacy of different insecticides mixed with mineral oil against Asian citrus psyllid, *Diaphorina citri* Kuwayama, under varying climates[J]. Insects, 2024, 16(1): 28.

[36] GAO J, YANG QY, FENG YH, *et al*. Evaluation of laboratory toxicities of nC22 agricultural mineral oil and its mixture with imidacloprid against the Asian citrus psyllid, *Diaphorina citri* (Hemiptera: Liviidae) [J]. Acta Entomologica Sinica, 2020, 63(2): 191 – 198. (in Chinese).

[37] WANG FF. Study on the pathogenicity of *Verticillium lecanii* against *Diaphorina citri* and its joint toxicity with flupyradifurone[D]. Fuzhou: Fujian Agriculture and Forestry University, 2019. (in Chinese).

[38] TIAN FJ, LIU JL, ZENG XN. Progress in research on insecticide resistance in the Asian citrus psyllid, *Diaphorina citri*[J]. Chinese Journal of Applied Entomology, 2018, 55(4): 565 – 573. (in Chinese).

[39] HU YY, SUN Y, ZOU ZW, *et al*. Resistance of *Diaphorina citri* Kuwayama to five conventional insecticides in Jiangxi Province[J]. Chinese Journal of Applied Entomology, 2022, 59(2): 419 – 425. (in Chinese).

[40] HUSSAIN ASR, FENG X, SIQUAN L, *et al*. Development and evaluation of emulsifiable concentrate formulation containing *Sophora alopecuroides* L. extract for the novel management of Asian citrus psyllid[J]. Environmental Science and Pollution Research, 2019, 26(21): 21871 – 21881.

[41] LI SJ, LIANG QY, YU YH, *et al*. Research on asian citrus psyllid YOLO v8-MC recognition algorithm and insect remote monitoring system [J]. Transactions of the Chinese Society for Agricultural Machinery, 2024, 55(6): 210 – 218. (in Chinese).

[42] MIRANDA PM, EDUARDO IW, SCAPIN SDM, *et al*. Insecticide application using an unmanned aerial vehicle for *Diaphorina citri* control in citrus orchards[J]. Journal of Applied Entomology, 2023, 147(9): 716 – 727.