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Review

# Peach–Potato Aphid *Myzus persicae*: Current Management Strategies, Challenges, and Proposed Solutions

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**Abstract:** The peach–potato aphid, *Myzus persicae* (Sulzer), is one of the most important pests of economic crops. It damages the plant directly by consuming nutrients and water and indirectly by transmitting plant viruses. This pest has the unenviable title of having resistance to more insecticides than any other herbivorous insect pest. Due to the development of its resistance to chemical pesticides, it is necessary to find other control options. Consequently, increased efforts worldwide have been undertaken to develop new management approaches for *M. persicae*. In this review, we highlight the problems associated with the peach–potato aphid, its economic importance, and current management approaches. This review also describes the challenges with current management approaches and their potential solutions, with special focus given to the evolution of insecticidal resistance and sustainable pest management strategies, such as biocontrol agents, entomopathogens, the use of natural plant-derived compounds, and cultural methods. Furthermore, this review provides some successful approaches from the above eco-friendly pest management strategies that show high efficacy against *M. persicae*.

**Keywords:** *Myzus persicae*; biocontrol agents; integrated pest management; parasitoid; insecticide resistance; crop protection

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## 1. Introduction

Aphids are one of the most economically important hemipteran pests, with about 100 aphid species being reported to cause significant agricultural losses worldwide [1,2]. Aphids are silent feeders that cause less tissue damage than chewing insects and, during feeding, release effector proteins in their saliva that suppress host plant defence responses [3]. Damage caused by aphids reduces plant fitness due to their feeding on phloem sap, which makes the plant nutritionally weaker compared to uninfested ones [4,5]. They also serve as important vectors for the transmission of plant viruses and produce honeydew that serves as a breeding medium for pathogens, which affect plant photosynthetic activities [2,3]. The peach–potato aphid, *M. persicae*, also known as the green peach aphid, is a highly polyphagous and cosmopolitan pest that has a global distribution, predominantly in North America, Europe, and Asia [3,6]. Winged adults measure up to 2.1 mm and reproduce parthenogenetically by a single sexual generation with a life cycle of 15 days [7]. In terms of damage, *M. persicae* causes direct and indirect damage to a wide range of crop plants [6,8–10].

The peach–potato aphid is considered one of the most destructive agricultural pests that feeds on over 40 plant families including Apiaceae (carrot, *Daucus carota* (Hoffmann)); Asteraceae (lettuce, *Lactuca sativa* (Linnaeus); artichoke, *Cynara cardunculus* (L.)); Amaranthaceae (beet, *Beta vulgaris* (L.); spinach, *Spinacia oleracea* (L.)); Brassicaceae (broccoli, *Brassica oleracea* var. *italica* (L.); brussels sprouts, *Brassica oleracea* var. *gemmifera*; cabbage, *Brassica oleracea* var. *capitata* (L.); cauliflower, *Brassica oleracea* var. *botrytis* (L.); kale, *Brassica oleracea* var. *acephala* (L.); mustard, *Brassica juncea* (L.); radish, *Raphanus raphanistrum* (L.); and turnip, *Brassica rapa* (L.)); Cucurbitaceae (cucumber, *Cucmis sativus* (L.); squash, *Cucurbita pepo* L.)); Fabaceae (bean, *Phaseolus vulgaris* (L.); pea, *Pisum sativum* (L.)); Poaceae (maize, *Zea mays* (L.); wheat, *Triticum aestivum* (L.); barley, *Hordeum vulgare* (L.); and rice, *Oryza sativa* (L.)); and Solanaceae (potato, *Solanum tuberosum* (L.); pepper, *Capsicum annuum* (L.); and tomato, *Solanum lycopersicum* (L.) [9–14]. Additionally, the peach–potato aphid acts as an important vector and transmits over hundreds of plant viruses, including potato leafroll virus (PLV), potato virus Y (PVY), beet western yellows viruses, beet yellows viruses, lettuce mosaic virus, cauliflower mosaic virus, turnip mosaic virus, cucumber mosaic, and watermelon mosaic viruses, which indirectly affect the growth and development of the host plant [3,9,15–18].

This review provides a summary of the ecological traits associated with *M. persicae* that affect the effectiveness of control strategies adopted against *M. persicae*. This review presents the economic importance of *M. persicae*, including current management practices and problems associated with these practices. This review also examines the potential of biological control agents, entomopathogens, natural plant-derived compounds (plant defence elicitors), and cultural methods as alternatives to the use of synthetic chemical insecticides for controlling *M. persicae*. Hence, this review will discuss both current and potential future approaches that may be helpful in the sustainable management of *M. persicae*, including presenting success stories of a few management strategies, suggesting an integrated pest management (IPM) program for the control of *M. persicae*, and recommending areas in which future research should be directed.

## 2. Pest Traits Influence Control Strategies

The ecological success of *M. persicae* as a polyphagous pest could be attributed to its short generation time, high fecundity, the presence of sexual and asexual populations, polyphenism (biotype), the ability to shift to new host plants, the transmission of viruses, and the development of resistance [6,11]. The transmission of plant viruses (persistent and non-persistent) by *M. persicae* is mostly facilitated by the winged forms due to their ability to fly, enabling the spreading of viruses between hosts [18,19]. This allows for both short-distance and long-distance transmission, with the latter playing a significant role in the spread of viral diseases across extensive geographic areas. The ability of aphids to transmit viruses over long distances is of great concern in an agricultural context, as it contributes to the rapid dissemination and establishment of viral infections in susceptible plant populations.

*M. persicae* also excretes honeydew (a sugary liquid), which affects the physiology of host plants and their interaction with other herbivores [20]. A list of challenges associated with *M. persicae* is presented in the chart given below in Figure 1. Increasing restrictions in the registration of new pesticides and the evolution of resistance to available insecticides are narrowing down the control strategies for *M. persicae* [21]. Therefore, before taking any further steps in this direction, it is necessary to review the existing methods and the advantage and disadvantages associated with them. To address the significant economic and agricultural impacts of the peach–potato aphid and the limitations of current control options, it is imperative to explore novel and sustainable approaches for its management.

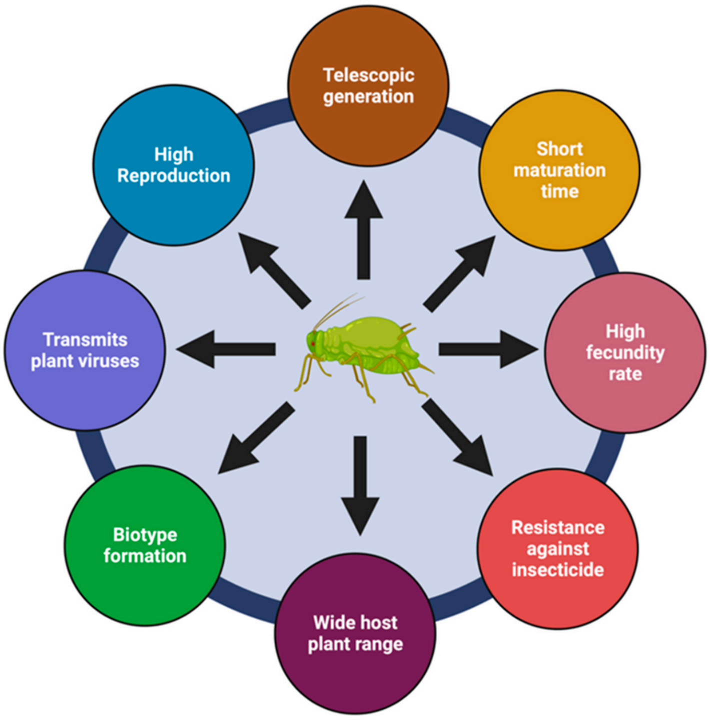

**Figure 1.** Factors that ensure the ecological success of *Myzus persicae* as a polyphagous and cosmopolitan pest of economic importance.

## 3. Suppression of Plant Defence

*M. persicae* is known for its ability to subvert plant defences and disrupt defence-related pathways [22]. Unlike herbivores with chewing-type mouth parts, *M. persicae* is a silent feeder that causes less physical damage [23,24]. Previous studies have shown that plants can recognize the salivary proteins of *M. persicae* and modulate their defence strategies by producing deterrent compounds, including indole glucosinolates that covert indol-3-ylmethoxyglucosinolates (I3M) to 4-methoxyindol-3-ylmethoxygluosinolates (4MI3M)), callose formation, the plugging of sieve tubes, and the accumulation of reactive oxygen species (particularly hydrogen peroxide) [25–28]. However, *M. persicae* releases specific effector proteins, including Mp1, Mp55, MpC002, Mp59, Mp60, Mp61, Mp62, and Mp63, to counteract or reduce plant-induced defence responses, such as the synthesis of antifeedants and antibiotic compounds [29,30]. Additionally, *M. persicae* produces a sticky secretion, honeydew, containing effector proteins that negatively affect the activation of host-plant-defence-related pathways [31].

The expression of *M. persicae* salivary proteins in the host plant makes the plant more susceptible to it by increasing fecundity and reducing the synthesis of defensive compounds [28]. For example, the overexpression of the salivary proteins Mp55 and MpC003 is responsible for high aphid fecundity, reduced production of deterrent compounds, and making host plants more susceptible to *M. persicae* [32,33]. When *Arabidopsis thaliana* (L.) overexpressed Mp55 proteins, it resulted in high aphid fecundity; reduced levels of deterrent compounds, such as indole glucosinolates and 4MI3M; decreased callose deposition; and a lower abundance of defence signalling molecules, like hydrogen peroxide [28]. The expression of *M. persicae*-induced salivary proteins (Mp55) presumably avoids the activation of plant defence systems and promotes aphid feeding [34]. Furthermore, the salivary effector proteins Mp1, Mp59, Mp60, Mp61, Mp62, and Mp63 did not show any effect on aphid performance [28]. The expression of these effector proteins is host-specific, and *M. persicae* modulates them according to the host plant [35]. Previous studies have reported a positive correlation between the expression of Mp55 proteins and the performance of *M. persicae* in *B. oleracea*, *Nicotiana tabacum*, and *A. thaliana* [28,36]. Conclusively, effector proteins perform a broad range of anti-defensive functions in host plants, such as a reduced accumulation of toxic compounds, the inhibition of callose formation, and the lowering of defence signalling molecules [28].

## 4. Economic Importance of Peach–Potato Aphid

*Myzus persicae* is responsible for both qualitative and quantitative losses in agricultural production by causing chlorosis, necrosis, wilting, defoliation, and fruit abortion. It directly affects plant nutritional status via feeding on plant sap [37]. According to previous studies, *M. persicae* is responsible for a considerable loss in crop yield, causing billions of dollars of losses globally [11,38]. Specifically, in the UK, aphid infestation causes up to a GBP 70 million loss per year [39]. *M. persicae* is considered one of the most common and devastating brassica (*B. oleracea*) pests in the UK, causing direct and indirect damage by spreading one of the most deleterious plant viruses, turnip yellow virus (TuYV), which can reduce final yield up to 26% [39]. Controlling this virus could result in an increase in total yield profit equivalent to GBP 60–90 million per year for oilseed rape growers in the UK [40]. In India, the peach–potato aphid is a key pest of sweet pepper that causes a 38 to 42% yield loss under a controlled environment [41]. In Brazil, the peach–potato aphid primarily serves as a vector for PYV and tomato yellow top virus (ToYTV), which causes a 20–70% loss of tomato (*S. lycopersicum*) yield and reduces fruit production by up to 85% [42]. In Australia, this pest is responsible for the transmission of TuYV in pea (*P. sativum*), faba bean (*Vicia faba* (L.)), lupin (*Lupinus albus* (L.)), chickpea (*Cicer arietinum* (L.)), and lentil (*Lens orientalis* (L.)) crop fields, and a loss of 46% in canola (*Brassica napus* (L.)) yield has been reported [43]. In New Zealand, *M. persicae* transmits potato virus Y (PVY) and leaflet curl virus (LCV), which are among the most damaging potato viruses and cause significant yield loss [44]. In China, *M. persicae* is also considered a primary pest for *N. tabacum* [45]. Interestingly, in the absence of a suitable host plant, *M. persicae* can easily switch to non-crop plants including weeds, such as *Convolvulus arvensis* (L.), *Chenopodium album* (L.), and *Amaranthus retroflexus* (L.), which act as aphid reservoirs and threaten subsequent crops [46,47]. For instance, in Washington, weeds grown on the floor of peach orchards had 3 to 16 million aphids, and one-third of the aphids were infected with the beet western yellows virus (BWYV) [48,49]. However, the loss caused by *M. persicae* depends on the plant cultivar, the time of infestation, and the environmental conditions [50].

## 5. Current Management Practices

New pest management and control strategies are being developed in order to meet current and future challenges [51]. These pest management practices fall under the following categories “chemical, biological, and cultural” [52]. However, the use of chemical pesticides is one that is common due to their availability, efficacy, and ease of use [53]. Therefore, the majority of current management practices for *M. persicae* are based on chemical pesticides [54]. Synthetic pesticides containing active ingredients, such as pyrethroids, carbamate, organophosphates, and neonicotinoids, have a strong negative effect on a number of herbivores, including *M. persicae* [55–57]. Even though *M. persicae* shows a certain level of resistance to most of these chemical compounds, some of them still have a high potential to be used as synergists with other control measures against *M. persicae* [58,59]. However, growing concerns about their adverse effect on the environment and non-target organisms are leading to restrictions on their use [60].

Besides chemical methods, there are several other management approaches that show high potential in managing this pest, such as the use of natural defence elicitors and biocontrol agents, the application of entomopathogens, and cultural methods [3,61]. An accumulating body of evidence shows that the use of biocontrol agents, i.e., parasitoids and predators, can be an excellent managing tool to protect crop plants from direct damage caused by this pest [62,63]. Similarly, the use of entomopathogens against *M. persicae* have revealed a hidden potential for its management [64,65]. Cultural methods, such as intercropping companion plants [60], the application of neem leaf extract [66], and winter pruning, have also been found to be effective against the peach–potato aphid [67]. Altering plant defence mechanisms using natural compounds is another preventive measure, which presents some potential as a future pest management tool [3,68]. Several crops, when treated with these natural compounds, e.g., benzothiadiazole (BTH), *cis*-Jasmone (CJ), and methyl jasmonate (MeJA), have shown high levels of induced resistance against *M. persicae* [3,69]. Despite being safe and eco-friendly in nature, these control strategies are not being used considerably and do not receive the attention they need [11].

## 6. Challenges with Current Management Practices

Despite extensive research on the development of management strategies against *M. persicae*, this pest continues to significantly impact agricultural production. This could be attributed to the unintended non-target effects and/or side effects of management strategies, as well as a lack of awareness, side effects, and the underutilisation of non-chemical control approaches. After reviewing the published literature on control strategies, several major obstacles to current management practices have been identified.

### *6.1. Development of Insecticidal Resistance*

The majority of current pest management approaches rely on the use of chemical insecticides, either solely or in combination [70]. However, the excessive use of these synthetic chemicals has led to an increased burden on insects to develop resistance against insecticides [54]; similarly, the control of *M. persicae* through chemical means remains difficult, owing to its ability to develop resistance [71]. The peach–potato aphid has developed resistance to various insecticides, with a total of 483 cases of insecticide resistance documented for this species on the APRD (Arthropod Pesticide Resistance Database) involving 84 active ingredients [72], making *M. persicae* the single most resistant aphid pest species and placing it in the overall top ten of the most resistant arthropod pests [73]. The exceptional ability of *M. persicae* to evolve a remarkable diversity of distinct mechanisms of resistance has made this species an emerging model of molecular evolution in insects. The latest reviews on insecticide resistance in this species by Bass and Nauen [74] and Kaleem Ullah et al. [75] have described at least seven independent mechanisms of resistance. These mechanisms include the overproduction of carboxylesterases (E4 and FE4) conferring resistance to organophosphate and carbamate insecticides [76,77], the mutation (S431F) of the acetylcholinesterase (AChE) enzyme conferring insensitivity to dimethyl carbamate insecticides [78,79], the knockdown resistance (kdr) mutation (L1014F), and super-knockdown resistance (skdr) mutation (M918T and M918L) of the voltage-gated sodium channel (VGSC) conferring resistance to pyrethroid insecticides [80–83], the duplication and mutation (A302G) of the GABA receptor subunit gene conferring resistance to cyclodiene insecticides [84], the overexpression of the cytochrome P450 CYP6CY3 conferring resistance to nicotine and neonicotinoid insecticides [12,85], reduced penetration of insecticides through the cuticle conferring resistance to neonicotinoid insecticides [86], and the mutation (R81T) of the nicotinic acetylcholine receptor (nAChR) β1 subunit conferring resistance to nAChR modulators such as neonicotinoid insecticides [12,71,87,88].

The resistance mechanisms described above highlight the remarkable adaptability of *M. persicae* to various insecticides. Recent studies have further expanded our understanding of resistance evolution in *M. persicae* such that Singh et al. [85] conducted a genomic interrogation of global aphid populations and identified a mutation (A2226V) in the acetyl-CoA carboxylase (ACC) enzyme that confers resistance to spirotetramat, a member of the tetronic/tetramic acid insecticide family. In addition to this, Singh et al. [85] discovered a novel VGSC variant (M918L) in a pyrethroid-resistant clone of *M. persicae*. This variant was associated with super-knockdown resistance and pyrethroid resistance. Interestingly, the pyrethroid resistance in *M. persicae* does not follow the typical recessive inheritance pattern observed in most insect species. Heterozygotes with the kdr/skdr mutations have been reported to display a resistant phenotype [12]. In addition, Panini et al. [89] identified the presence of a mutator-like element (MULE) transposon insertion in the VGSC gene that can modify the pyrethroid resistance phenotype in *M. persicae*. Furthermore, exposure to pyrethroid insecticides induces oxidative stress in *M. persicae*, leading to increased expression of the MpHsp70 gene, encoding a heat shock protein [74]. This protein helps protect the aphids against oxidative stress caused by insecticides. According to Bass et al. [12], the mutation and increased expression of detoxifying enzymes are two key factors that regulate insecticidal resistance in *M. persicae* (Figure 2) [12,87]. In conclusion, *M. persicae* has developed multiple mechanisms of resistance to insecticides, making it a challenging pest to control. The study of resistance mechanisms in this species provides insights into molecular evolution in insects and highlights the difficulties in implementing resistance management strategies.

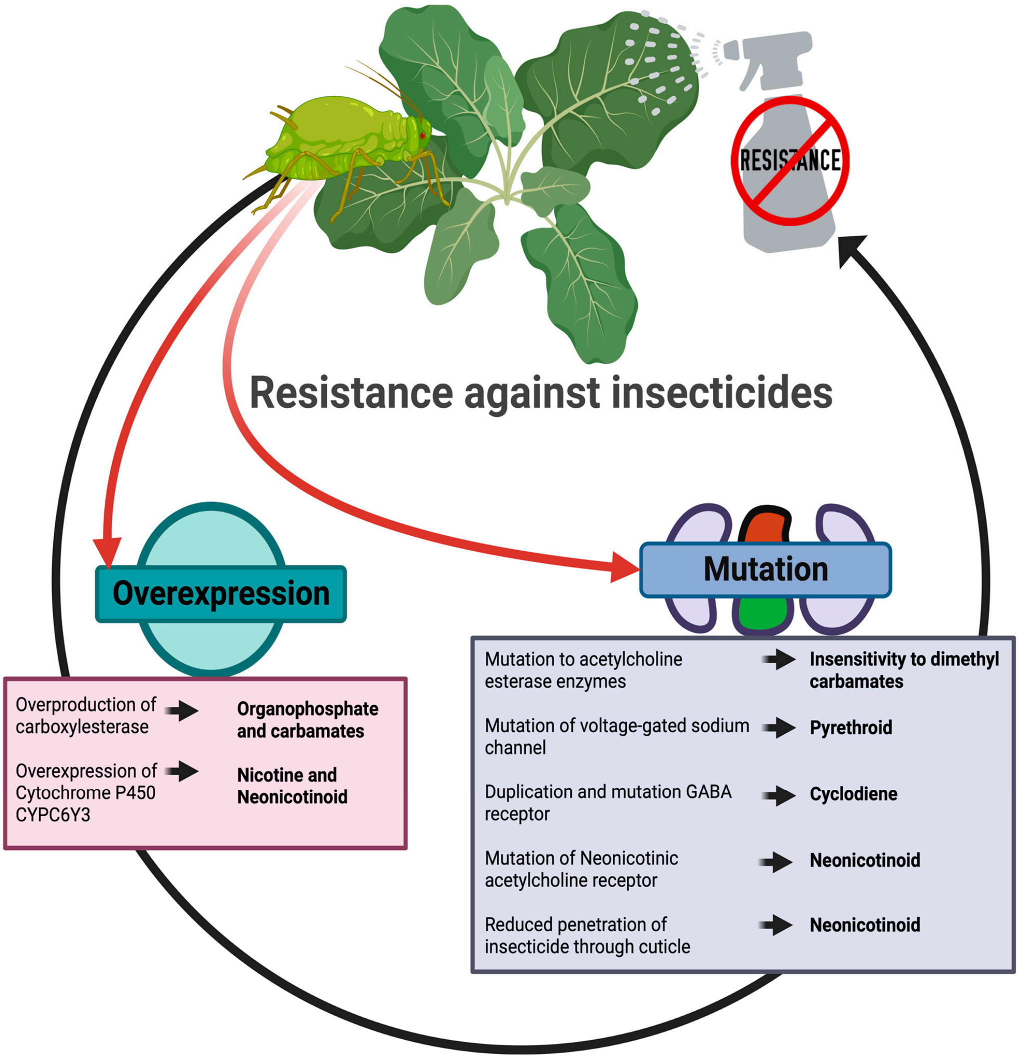

**Figure 2.** Ilustration showing the causes responsible for the development of resistance to particular insecticides. According to Bass et al. [12], there are two main causes that play a significant role in the evolution of resistance in insects against synthetic insecticides: overexpression of genes responsible for the synthesis of detoxifying enzymes and mutation in target sites. The ability to develop and spread resistance against insecticide is also facilitated by high fecundity, short generation times, and the ability to disperse over long distances.

### 6.2. Adverse Effect on Non-Target Organisms

The literature on the insecticidal side effects on arthropods reports that more than 400 agricultural chemicals have adverse effects on natural enemies, ranging from sublethal to lethal [90]. The excessive use of synthetic pesticides is responsible for deleterious effects on non-target organisms, such as pollinators (fields treated with spinosad residues showed the low survival of *Apis mellifera* (L.)), predators (spinosad derivatives caused the mortality of *Hibana futilis* (Banks) and *Araneus prantensis* (Emerton) upon treatment), and parasitoids (severe adverse effects of the dried residue of spinosad have been found on several parasitoids, including *A. colemani*, *Aphytis melinus* (DeBach), *Leptomastix dactylopii* (Howard), and *Encarsia formosa* (Gahan)) [91–93]. Parasitoids, which are of great economic significance in pest management and play a vital role in controlling pest populations, are badly affected by the excessive use of these synthetic chemicals [94]. Studies have shown that the inappropriate use and application timing of insecticides affect parasitoid populations, emergence rates, longevity, reproductive rates, and parasitic behaviour [95–98]. Chemical compounds, such as fenitrothion and spinosad, can affect the longevity and reproductive capacity of the egg parasitoids *Trissolcus grandis* (Thomson) and *Trichogramma* species [96,99]. Similarly, the treatment of crops with deltamethrin negatively affects the emergence and parasitic behaviour of *T. grandis* and *Diaeretiella rapae* (M'Intosh), respectively [100].

### 6.3. Elicitation of Plant Defence: An Underutilized Tool

Despite excellent results, the use of natural defence compounds as plant defence elicitors under field conditions is still in its early stage [3,101]. The majority of these studies are limited to the laboratory and are still waiting for application in the field. For instance, CJ is a natural plant-derived compound that has been tested on several economically important crops (*S. tuberosum*, *B. oleracea*, *T. aestivum*, and *S. lycopersicum*) against various sucking pests, including *M. persicae* [3,102–104]. Many laboratory studies have investigated the role of CJ in inducing resistance in plants against pests, and almost all have validated that CJ induces resistance to pests [3,102–105]. A recent study on CJ treatment of five brassica genotypes showed a high level of induced resistance against *M. persicae* [3]. Similarly, previous studies have reported the high potential of plant extracts in managing pests. For example, olive leaf extract caused 100% *M. persicae* mortality at a 10% concentration. Extracts of *Xanthium strumarium* (L.), *Tanacetum parthenium* (L.), and *Hypericum calycinum* (L.) showed 89%, 88%, and 57% nymphal mortality, respectively, when *M. persicae* was exposed to treated leaf disks [106–108]. Similarly, extracts of *Ricinus communis* (L.), *Solanum nigrum* (L.), and *Nerium oleander* (L.) were found to be highly toxic and showed a high level of *M. persicae* mortality in toxicity bioassays [109].

### 6.4. Underutilisation of Cultural Practices

Cultural methods are commonly used to create unfavourable conditions for pests, which is one of the main goals of pest management approaches [110]. Cultural practices, such as crop rotation and sanitation, intercropping, the destruction of plant debris, and the avoidance of adjacent planting of crops, and trap crops, play a critical role in pest management [111,112]. For instance, winter peach pruning is practised, particularly in fruit orchards, to adjust plant load, which indirectly affects the performance of pests, i.e., *M. persicae* [113]. Reportedly, *M. persicae* is primarily found on mature leaves; therefore, winter pruning has been found to be an effective way to reduce pest infestations [67,113]. By removing some buds, a potential habitat for egg-laying is reduced, leading to a decrease in the overall population of *M. persicae*. Similarly, intercropping companion plants with horticultural crops can be an effective method for pest management. For instance, *Tagetes patula* as a companion plant with *C. annuum* significantly affects the population of *M. persicae* by releasing a blend of deterrent volatile compounds [61,114]. However, due to the wide range of host plants, cultural practices may be a complicated and daunting task to control *M. persicae* [16].

Additionally, insect-proof nets have been found to be an effective method for controlling *M. persicae* infestations in crops [115,116]. A study conducted by Martin et al. [116]

showed that covering plants with insect-proof nets (treated with repellent compounds) significantly reduced the population of *M. persicae* in *B. oleracea*. Similarly, insect-free seedlings are also effective in preventing *M. persicae* infestations [115,116]. A study conducted by Mpumi et al. [117] showed that using insect-free seedlings reduced the severity of aphid infestations (including *M. persicae*) in *B. oleracea*.

### *6.5. Lack of Resistant Cultivars*

The use of aphid-resistant cultivars in combination with integrated pest management approaches represents an excellent option for managing *M. persicae* [118]. One of the significant differences between aphid-resistant and aphid-susceptible lines of the same crop is the length of time required by the aphid to reach the phloem during probing [119]. Aphids take a longer time to reach the phloem on resistant lines (*Medicago truncatula* (Gaertn.) cv. Jester) and cannot feed successively on it [120,121]. However, it has been observed that plant resistance is often overcome after a few years due to the emergence of new biotypes [122,123]. *M. persicae* has the ability to form biotypes, which differ in behaviour or physiology and allow this pest to expand its host range and rapidly occupy a new ecological niche [124].

## **7. Potential Biological Control Agents**

Biological control has the potential to be an excellent alternative to chemical control approaches [125], which involves a number of living organisms belonging to different Phyla and Kingdoms, including microbes (fungi, bacteria, and viruses), nematodes, and insects (parasitoids and predators).

### *7.1. Predators and Parasitoids*

Extensive research has been conducted to evaluate the efficacy of certain biological control agents against *M. persicae* in laboratory and field settings [62]; a diverse range of 200 biocontrol agents from various families, including Coccinellidae, Cantharidae, Syrphidae, Anthocoridae, Pentatomidae, Aphelinidae, Braconidae, and Phytoseiidae, have been identified as potential insect agents for managing *M. persicae* populations [126,127]. The host plant plays a crucial role in implementing the biocontrol approach of naturally occurring biological control agents, and the effectiveness of these agents depends on the species and physiological status of the host plants. Plants release volatile compounds that serve as a cue for pollinators and other natural enemies of pests to locate the host plants [128,129]. Infestation with *M. persicae* has been observed to increase the release of volatile compounds known as herbivore-induced plant volatiles (HIPVs), which recruit parasitoids and predators [130]. A wide variety of natural enemies have been identified from *M. persicae*-infested crop fields, including *Aphidius ervi* (Haliday), *D. rapae*, *Aphidius colemani* (Dalman), and *Coccinella septempunctata* (L.), providing a long list of potential biocontrol agents for *M. persicae*. Earlier studies have reported an approximate number of 150 predators, 50 parasitoids, and 40 entomopathogens that can be used in biocontrol efforts [6].

### *7.2. Entomopathogenic Bacteria*

Previous studies have shown that environmental microbes have the potential to kill herbivorous pests, including aphids, when applied in pest management programmes [131–133]. Several bacterial species (*Pseudomonas fluorescens* (Flügge) PpR24; *Bacillus amyloliquefaciens* [134] strains, CBMDDrag3, PGPBacCA2, and CBMDLO3; *Saccharopolyspora spinosa* [135]; and *Bacillus thuringiensis* (Berliner) [136]) and bacterial-derived insecticides (Bosal 10EC and Spinosad 240SC) have been tested on several important crops, including *B. oleracea*, *A. thaliana*, *B. vulgaris*, and *C. annuum*. On application of bacterial insecticides, a high reduction in the population of *M. persicae* has been recorded; for instance, a diet containing bacterial suspension showed 100% mortality of adults and nymphs [131] and a 57% population reduction in *M. persicae* on cauliflower [133]. *C. annum*, *A. thaliana*, and *B. vulgaris* showed a population reduction of 68%, 57%, and 69%, respectively, after application of *P. fluorescens* PpR24 [132]. Taken together, the use of bacteria and bacterial-derived insecticides as a part of IPM programmes would be an excellent alternative to minimize the use of toxic chemical insecticides.

### *7.3. Entomopathogenic Fungi*

More than 750 species of entomopathogenic fungi (EPF) belonging to 85 genera are functionally known for their ability to infect arthropods [64,65,137–139]. However, most of them have not been used commercially to manage plant pests yet. These fungi are naturally present in agricultural soil, but their efficacy in nature is not high because of the low spore numbers. Their effectiveness can be improved through the inundative release of EPF. The most studied species of EPF belong to the genera *Metarhizium, Beauveria, Hirsutella, Isaria*, *and Lecancillium* [65]. The genus *Metarhizium* has negative effects on arthropods belonging to more than 150 families, while *Beauveria* has been found effective against 200 species of insects and mites [140]. Both species, i.e., *Beauveria bassiana* (Vuillemin) and *Metarhizium anisopliae* (Metchnikoff), have been reported as a potential control method for more than 300 species of arthropods, including *M. persicae* [140,141].

Extensive research has been conducted to evaluate the insecticidal properties of EPF against herbivorous pests belonging to different orders, such as Hemiptera, Hymenoptera, Lepidoptera, and Coleoptera [131,136,138]. In particular, EPFs reduce insect pest populations by reducing their performance, penetrating their body, and feeding on them [142]. Accumulating evidence shows that EPFs have the potential to control *M. persicae* populations by affecting its prefeeding behaviour [142] and reducing its development and fecundity rate [143], as well as causing high mortality in bioassays using cultural filtrates of EPF (*B. bassiana* and *M. anisopliae*) [141,144]. The negative influence of EPF (*B. bassiana*, *Isaria fumosorosea* (Vassiljevsky), and *M. anisopliae*) applications can also extend to the foraging activity of aphids [142]. Furthermore, entomopathogenic fungal strains have been observed to adversely affect various detrimental insect pests, such as the wheat aphid (*Sitobion avenae* (Fabricius)) [145], soybean aphid (*Aphis glycines* (Matsumura)) [146], and cowpea aphid (*Aphis craccivora* (Koch)) [147]. These pests exhibit reduced fitness following infection with such strains, thereby highlighting the potential utility of entomopathogenic fungi as biocontrol agents in agricultural settings.

### *7.4. Entomopathogenic Viruses (EPVs)*

Plants come in contact with numerous viruses due to their interactions with herbivores. This plant–virus interaction serves as a reservoir for viruses and affects the performance of the associated herbivorous community. Plants take advantage of entomopathogenic viruses and utilise them as a defence tool against a number of plant pests [148]. For example, *M. persicae* spread Parvovirus (*M. persicae* densovirus MpDNV) during feeding on plants. The infected host plants use this EPV as a part of their defence strategies by spreading the infection to non-infected subsequent future visiting aphids [149]. Other EPVs also have negative effects on the peach–potato aphid, such as a reduction in *M. persicae* growth recorded on tobacco plants infested with potato virus Y (PVY) [150] and increasing susceptibility to parasitoids [151]. However, a positive effect of EPV (turnip mosaic virus) on *M. persicae* has also been reported, where *M. persicae* showed a high preference for and improved growth, feeding, and fecundity rates on virus-infested plants [152].

### *7.5. Entomopathogenic Nematodes*

Below-ground plant and root–herbivore interactions can affect above-ground plant–herbivore interactions [153,154]. Some nematodes are important entomopathogens that can impact the performance of attacking herbivores (below- and above-ground) on host plants by inducing plant defence mechanisms [155]. For example, entomopathogenic nematodes (EPNs) have been shown to activate polyphenol oxidase and guaiacol peroxidase activity in roots and, at the same time, suppress the same activity in above-ground tissues [155,156]. However, limited research has been conducted to test the efficacy of EPNs against aphids, particularly *M. persicae*; *Steinernema carpocapsae* (Weiser) showed low infectivity when tested against *M. persicae* [157].

## 8. Sustainable Strategies

Previous studies have reported several successful control measures tested against the peach–potato aphid using non-toxic chemical strategies, such as the use of biocontrol agents, resistant cultivars, the induction of plant defence via the application of natural compounds, and priming [3,61,104,158].

### *8.1. Augmentative Release of Biocontrol Agents*

The biological control of insect pests is one of the most efficient and eco-friendly ways to manage them. It involves three basic approaches: the conservation, importation, and augmentation of natural enemies [159]. In Yunnan province, China, the augmentative release of the parasitoid, *Aphidius gifuensis* (Ashmead), significantly reduced the pest population in tobacco fields [160]. Similarly, in Himachal Pradesh, India, three species of parasitoids (*Aphelinus asychis* (Walker), *Aphidius matricariae* (Haliday), and *A. ervi*) showed high parasitism rates when tested against *M. persicae* in greenhouse experiments [161].

### *8.2. Resistant Plant Varieties*

Previous studies have shown that breeding programmes with a primary goal of achieving high yield can have a negative impact on host plant resistance, making crops more susceptible to pests due to the manipulation of their genetics to produce high yields [162–165]. This hypothesis was investigated in an earlier study, where the performance of *M. persicae* on three wild potato, *Solanum stoloniferum* (Schltdl.) (23072, 22718 and 18333) and one cultivated potato, *S. tubersoum* (L.) cv., Desiree lines was observed [149]. All wild potato lines were highly resistant against *M. persicae* and caused high adult mortality in cage bioassays (Figure 3). Similarly, olfactometer studies showed that adult *M. persicae* spent less time in the olfactometer arm treated with volatile organic compound (VOC) samples collected from wild potato lines, while volatile blends released by wild potato lines were highly attractive to *D. rapae*, one of the main natural enemies of *M. persicae* (Figure 4).

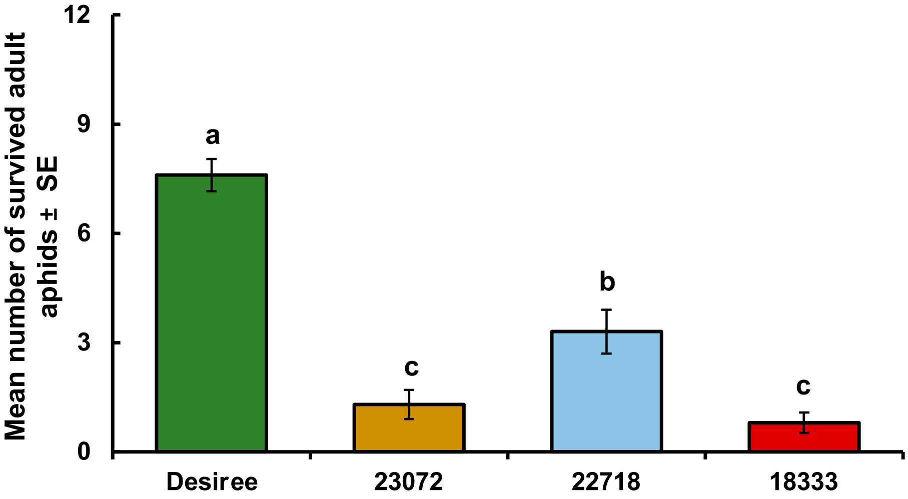

**Figure 3.** The performance of *M. persicae* was compared on cultivated (*Solanum tuberosum* cv. Desiree) and wild (*Solanum stoloniferum* accessions 23072, 22718, and 18333) potato lines. Mean number (±standard error) of surviving adult aphids *M. persicae* after 96 h. Different letters indicate statistically significant differences among plant species (F-test; $p < 0.05$), based on the Holm–Sidak method (one-way ANOVA) [165].

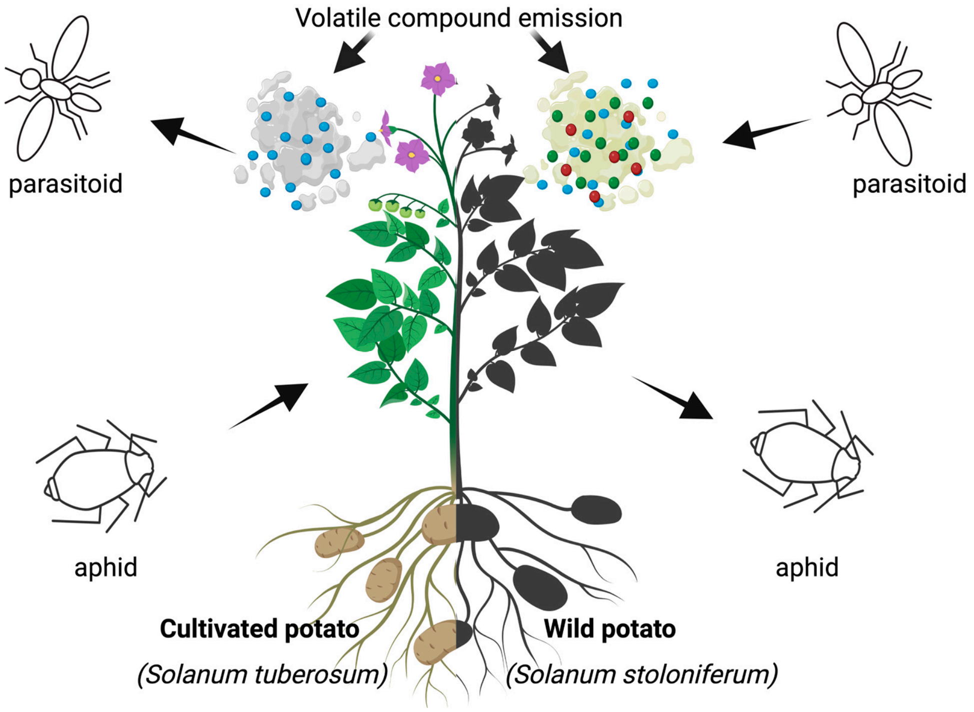

**Figure 4.** A summary of *M. persicae* and parasitoid *D. rapae* performance and behavioural responses on wild potato *S. stoloniferum* accessions [165]. In aphid performance clip-cage bioassay, wild potato lines showed high adult aphid mortality and low larviposition. Similarly, volatile analysis of wild and cultivated potato lines showed high emission of volatile organic compounds (VOCs) in blends released by wild potato lines. These volatile samples were used for olfactometer bioassay, in which the aphid *M. persicae* showed a negative response to volatile samples collected from wild potato lines. In contrast, the parasitoid *D. rapae* showed a positive response to volatile samples released by wild potato lines. Blue and green dots at the top of figures represent the qualitative and quantitative differences in volatile blends released by wild and cultivated potato lines.

### *8.3. Natural Compounds as Plant Defence Elicitor*

Extensive literature is available wherein natural compounds have been found effective in inducing plant defence [166]. Compounds, such as *cis*-Jasmone (CJ), β-ocimene, benzothiadiazole, and methyl jasmonate chitosan, have shown an elevated level of defence in plants, like *B. napus*, *S. tuberosum*, and *L. esculentum*, respectively [3,69]. In particular, the exogenous application of MeJA induces the formation of defence enzymes and reduces pupal/larval weights, performance, population densities, and feeding behaviour [166–170]. CJ is another well-known example of a plant defence elicitor, which has been tested on several important crops, including brassica, tomato, wheat, maize, sweet paper, and cotton, against sucking pests [3,105,106,171–174]. Recently, the effect of CJ treatment of brassica on interactions with *M. persicae* and its natural enemy, *D. rapae*, was investigated [3]; the results showed that CJ-treated plants exhibited high *M. persicae* mortality, low larviposition, and aphid settlement. In contrast, the parasitoid showed a high parasitism rate (Figure 5) and spent more time on CJ-treated plants. In behavioural bioassays, samples collected from CJ-treated plants that were highly repellent to *M. persicae* were found to be attractive to *D. rapae*. A volatile analysis of plant samples revealed high emission of aphid-repellent compounds in CJ-treated plant samples. Overall, the results suggest that CJ treatment of brassica plants makes the plant less favourable to pests while more attractive to its natural enemy, i.e., *D. rapae*. A summary of the results obtained from this CJ-brassica study, including the performance and behavioural bioassays and VOC effects on insect responses, is given in Figure 6.

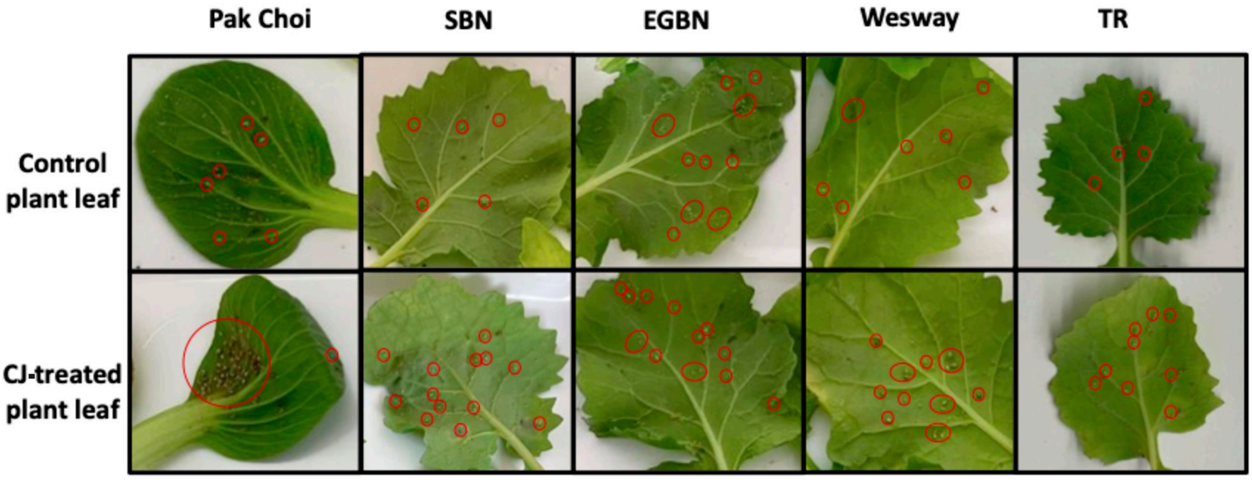

**Figure 5.** *Brassica* leaves (control and *cis*-Jasmone (CJ)) showing a number of mummified aphids (red circle). (Pak choi: *Brassica rapa* cv. Chinensis; SBN: *Brassica napus* cv. Samurai; EGBN: *Brassica napus* cv. Giant British; TR: *Brassica napus* cv. turnip rutabaga) [11]. In parasitism bioassay, four plants (two CJ-treated vs. two control) were placed in a BugDorm diagonally. Each plant was infested with 50 adult aphids, and after two hours, 8 mated female parasitoids were released into the Bugdorm. The plants were exposed to parasitoids for 24 h for aphid parasitisation (oviposition). After 24 h, parasitoids were removed, and the plants were left for the formation of mummies (for 14 days).

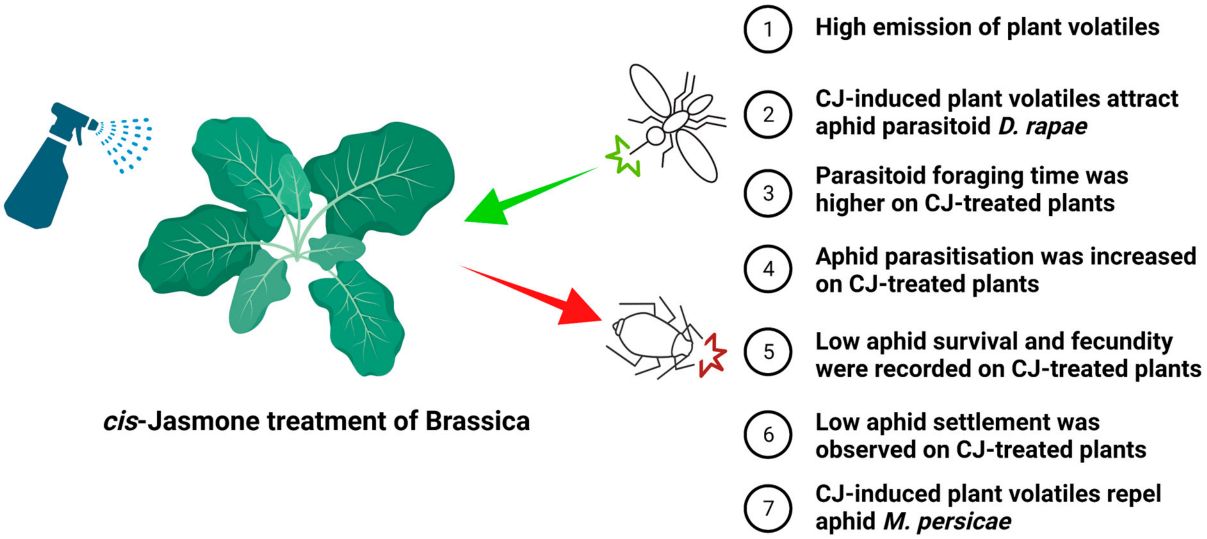

**Figure 6.** A summary of induced resistance and insect (*M. persicae* and *D. rapae*) responses to *cis*-Jasmone (CJ)-treated brassicas [3]. Above study was conducted to investigate the effect of CJ on two *Brassica* species (*Brassica rapa* and *Brassica napus*). A series of performance and behavioural bioassays were performed, i.e., (**1**) in headspace sampling, CJ-treated plants showed significant high qualitative and quantitative differences in volatile emission compared to untreated plants; (**2**) in olfactometer bioassay, parasitoids spent more time in the olfactometer arm treated with the volatiles of CJ-treated plants; (**3**) in foraging bioassay, parasitoids spent more time on CJ-treated plants; (**4**) in parasitism bioassay, a high number of mummies were recorded on CJ-treated plants; (**5**) in aphid performance cage bioassay, high aphid mortality and low fecundity were recorded; (**6**) in aphid settlement bioassay, CJ-treated plants showed low aphid settlement compared to controls; and (**7**) in olfactometer bioassay, *M. persicae* spent less time in the olfactometer arm treated with the volatiles of CJ-treated plants. Green and red arrows represent the behavioural responses, attractant and repellent, respectively.

### *8.4. Intercropping Companion Plants*

Another important aspect of management strategies for *M. persicae* is intercropping. There are various studies against different herbivores (*Thrips tabaci* (Lindeman), *Aphis gossypii* (Glover), and *M. persicae*) that support the idea of planting different crops in the same field [175,176]. A study that was conducted to investigate the effect of companion plants on *M. persicae* showed that *T. patula and Basil* release VOCs that directly and indirectly affect the performance and behaviour of *M. persicae* when used as companion plants with *C. annuum* in the field [61]. Similarly, intercropping garlic with tobacco, and celery, maize, and sunflower with potato reduces *M. persicae* populations significantly [50,177]. A volatile analysis of the blend released by companion plants showed the presence of several compounds, such as (*E*)-β-farnesene, β -linalool, caryophyllene, and pinene, that have a repellent effect on several herbivores, including *M. persicae* [61,114,172]. Preliminary data collected from the study based on combinations of cultivated potato (Desiree) and wild potato, i.e., combination 1 (Desiree plus Desiree) and combination 2 (Desiree plus wild potato), are given in Figure 7. In this study, the cultivated potato plant was exposed to Desiree and wild accession. The current study's findings show that cultivated potato plants that were exposed to wild potato volatiles (combination 2) showed low *M. persicae* survival compared to combination 1 cultivated potato plants, which were exposed to cultivated potato cv. Desiree plant volatiles (Figure 7).

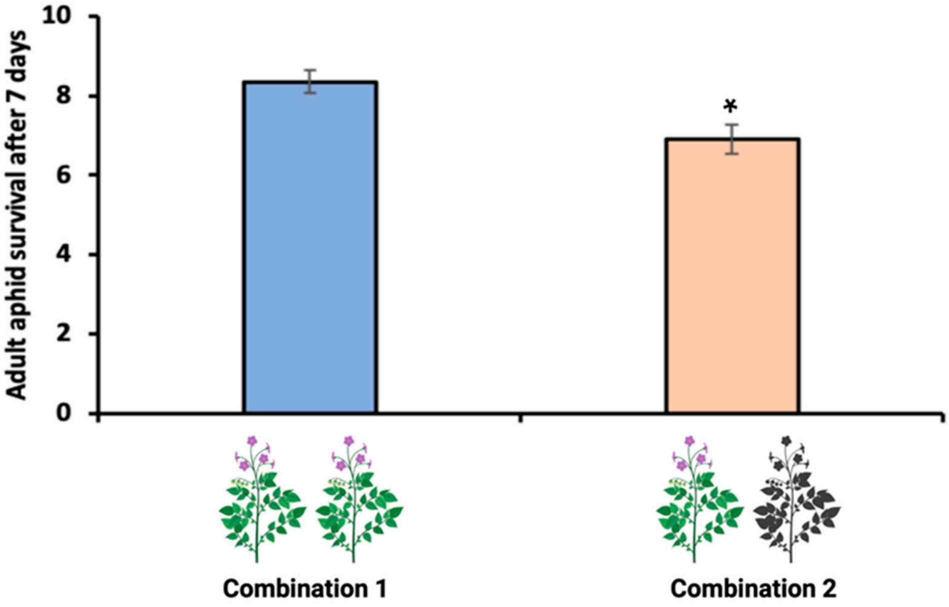

**Figure 7.** Adult *Myzus persicae* survival (mean ± SE) out of the original 10 individuals and after 7 days in clip cages on cultivated and wild potatoes ($n = 10$). Asterisk indicates statistically significant difference among combinations ($p < 0.05$) (one-way ANOVA). Two plants were connected using a sterile glass test tube (75 mm × 12 mm). Combination 1: (Desiree (receiver) plus Desiree (emitter); combination 2: Desiree (receiver) plus wild potato (emitter). Two clip cages were attached to leaves of receiver plants, and after 7 days, the number of live adults was counted [11]. * represents standard error.

## 9. Proposed Integrated Pest Management for *Myzus persicae*

An accumulating body of evidence has reported the economic loss caused by *M. persicae* across a wide range of crop plants, and several studies have been performed to develop control strategies to manage this pest. However, the majority of these studies have focused on a single control measure, either a biological or chemical control, such as the effect of host plants [165,178]; predators [179,180]; EPFs [143,144,181]; EPNs (157); EPVs [150,152]; and push–pull strategies (intercropping and trap crops) [182]. A few pioneering studies used combined biocontrol agents, such as three species of EPF along with

1% azadirachtin [144,181], or biocontrol recruitment via host-plant-induced defence [3]. Moreover, the use of entomopathogens and botanical and chemical pesticides is more likely to enhance control options [52]. The use of natural compounds would also provide additional protection for crops by synthesising defensive compounds and recruiting natural enemies through induced plant VOCs [3]. Previous studies have shown that there is potential to develop an IPM program based on multiple, complementary components [3,182–184].

An IPM pyramid provides detailed information about the actions required to control pests, starting from the bottom (prevention) and progressing towards the top (chemical control), if the prevention and biocontrol strategies fail to suppress the population below the economic threshold [185,186]. Agronomic practices have been extensively reviewed [187], and incorporating these practices would be helpful in reducing the use of chemical pesticides and biological controls [188–190]. To synergise biological controls, the use of conventional aphicides in IPM is also valid while adhering to IPM guidelines regarding chemical pesticides [53]. To boost IPM strategies, the use of biocontrol agents in combination with priming agents benefits overall management strategies [52,185]. Additionally, a wide range of entomopathogens have been employed in crop pest management that have the potential to control pests and diseases considerably [191,192]. It would be better to use these entomopathogens as a preventive treatment, particularly in the earlier stages of plant growth [193]. However, most of these approaches are limited to lab conditions. Given the aforementioned considerations, an IPM pyramid is proposed and illustrated in Figure 8, as a potentially effective tool for managing *M. persicae*.

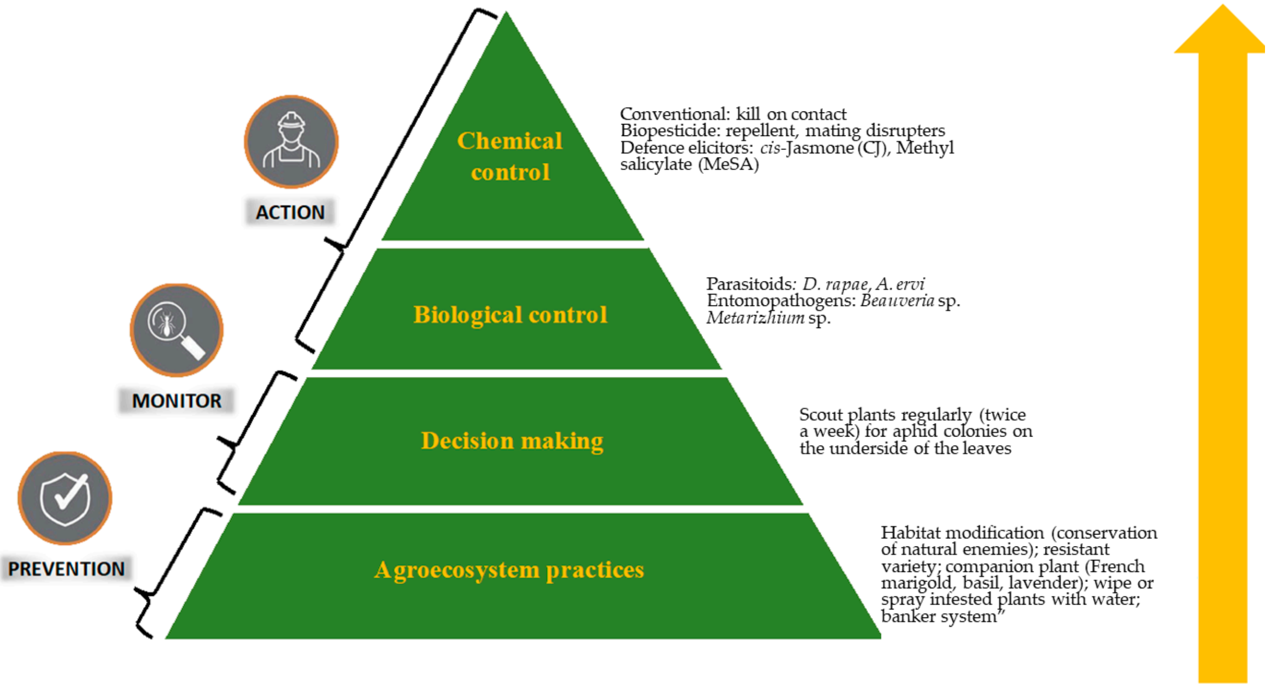

**Figure 8.** A proposed IPM pyramid for the control of peach–potato aphid, *M. persicae*, modified from [3,61,114,165,194]. The pyramid illustrates an IPM approach incorporating cultural practices, biological control, and chemical control for the management of *M. persicae*. The base of the pyramid emphasizes the importance of cultural practices, such as habitat modification, biodiversity, and planting resistant varieties. The second tier emphasizes monitoring and scouting for pests to determine the need for control measures, while the third tier highlights biological control through the use of natural enemies, such as predators and parasitoids. The top tier of the pyramid suggests the use of chemical control as a supplemental means of managing *M. persicae*, emphasizing the importance of choosing pesticides with low toxicity to beneficial insects and following label instructions carefully.

## 10. Conclusions and Future Perspectives

In conclusion, there are several obstacles that hinder the utilization of non-chemical pest control methods, including a lack of awareness, financial instability, a shortage of trained staff, and poor technical advancements [195]. In developing countries, people are either unaware of integrated pest management approaches or there is a lack of trained staff for the successful implementation of control strategies [195]. For example, a survey conducted in Chitwan, Nepal, revealed that only 17% of farmers received one short-term training session on integrated pest management. Financial instability and poor technical advancements are also significant factors that impede the adoption of such potential approaches [196]. In contrast, farmers show a high preference for chemical pesticides due to factors such as falling prices of generic pesticides, their easy availability and readiness for application, and quick response (less time consuming) [197–199]. According to a survey conducted in Chitwan, Nepal, 80% of farmers showed a preference for chemical pesticides, even though 90% of them were aware of their side effects on the environment and non-target organisms [195]. Additionally, the underutilisation of insecticide-compatible entomopathogens [21], regulatory barriers in the registration of new conventional pesticides [200], the lack of availability of potential insecticides [3,38], the lack of supportive policies [38,53,201], the shortage of manpower (labour), and inadequate farmer engagement in IPM-based technology development [53] are several important factors that play a key role in the successful implementation of sustainable pest management strategies.

The formation of biotypes means that developing insect-resistant crop varieties is a more complex and challenging process for this species, as it can easily adapt to new resistant varieties as well [202]. Therefore, resistant-cultivar-based agriculture should be investigated further to make crops more resistant and less palatable to *M. persicae* [11]. The application of natural plant defence elicitors on crops needs to be explored in the field [3,194]. Therefore, there is an urgent need to develop new sustainable methods to protect agricultural production from this pest [3]. There is a need for more studies to elucidate the effect of entomopathogens wherein the target pest is the peach–potato aphid. A combination of control strategies, such as resistant plant varieties, natural plant defence elicitors, entomopathogens, biocontrol agents, and biopesticides, needs to be tested as part of integrated pest management rather than the application of these measures at an individual level. More training and workshops are required to educate and train farmers about IPM-based approaches [203,204].

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