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Review

Whitefly (*Bemisia tabaci*) Management (WFM) Strategies for Sustainable Agriculture: A Review

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Abstract: The whitefly (*Bemisia tabaci* Gennadius) is a notorious devastating sap-sucking insect pest that causes substantial crop damage and yield losses due to direct feeding by both nymphs and adults and also through transmission of viruses and diseases. Although the foliar application of synthetic pesticides is crucial for efficient control of *B. tabaci*, it has adverse effects such as environmental pollution, resistance and resurgence of the pest, toxicity to pollinators, and crop yield penalty. Thus, a suitable, safe, and robust strategy for the control of whiteflies in the agricultural field is needed. The reports on whitefly-resistant transgenic plants are scanty, non-reproducible, and/or need secondary trials and clearance from the Genetic Engineering Appraisal Committee (GEAC), the Ministry of Environment and Forests (MoEF), and the Environmental Protection Agency (EPA). The present review encompasses explicit information compiled from 364 articles on the traditional, mechanical, biological, biotechnological, and chemical strategies for whitefly management (WFM), IPM strategy, and future prospects of WFM for food and agriculture security.

Keywords: whitefly management; sap-sucking; traditional methods; botanical pesticides; biotechnological strategies; IPM

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1. Introduction

The whitefly, *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae), is a worldwide polyphagous insect pest that has wreaked havoc on agricultural productivity, particularly in some plant families such as Solanaceae, Cucurbitaceae, and Fabaceae [1,2]. Whiteflies are tiny sugar-robbers that originated from southern Asia but are now found across all regions of the globe, most notably in tropical regions [3,4], except Antarctica [5]. Their aggressive feeding on plant sap from leaf tissue causes substantial losses to agricultural crops [6]. Each female is capable of producing about 320 eggs within a single life cycle [7,8]. In a controlled environment with warm climatic conditions, whiteflies maintain a high rate of reproduction for the whole year [9,10] and have the capacity to achieve exceptionally high population size within few generations.

Whiteflies cause substantial damage and economic losses to susceptible crops [11]. Both young (nymphs) and the adult stage [12] (Figure 1) suck sap and while feeding, they excrete honeydew (sugary excreta) that promote 'sooty mold' on the foliage and fruits, leading to adverse effects on crop productivity [13,14]. Affected plants show yellowing, folding of the foliage, decreased plant development, and disfigured fruit [15]. The nymphs inject enzymes during feeding which alter the crop physiology and consequently results in decreased internal pigmentation and abnormal fruit ripening [16]. Whiteflies spread viral pathogens that can significantly destroy the crops. *Bemisia tabaci* may disseminate more than 350 species of viruses in plants including Begomovirus, Carlavirus, Crinivirus, Ipomovirus, and Torradovirus [8,17–19]. Tomato, potato, soybean, cassava, okra, and chrysanthemum are among the most susceptible plants to viral infections [20]. Begomovirus infection reduces the crop productivity by 20–100% and brings losses costing millions of dollars [11]. 'Cassava mosaic' and 'cassava brown streak' are two devastating viral diseases throughout Africa disseminated by whiteflies and culminating in 50% loss of cassava production and annual loss of more than a billion USD [21]. In tomato, *B. tabaci*-mediated economic injury level (EIL) was four nymphs/leaf and one adult/each tray [22]. Thus, *B. tabaci* is ranked as a highly disastrous insect pest worldwide [11,23].

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

Due to accumulated impact of direct damage and secondary damages through transmission of viruses, whiteflies pose socioeconomic challenge [6,10]. Many studies across the globe have attempted to reduce its impact on sustainable agricultural productivity [24–26]. Whitefly management (WFM) strategies can be grouped as traditional [27,28], chemical [29,30], herbal [31,32], biological [33,34], biotechnological [35,36], and IPM [37,38]. However, a robust, reliable, and cost-effective WFM strategy is still needed [39,40]. This review focuses on the available WFM strategies, their limitations, and future prospects.

2. Taxonomy of *Bemisia tabaci* Gennadius

All whitefly species are members of the Aleyrodidae family, which is classified into three known subfamilies, Aleurodicinae, Aleyrodinae, and Udamoselinae. The Aleurodicinae subfamily includes 20 genera and 130 identified species, the majority of which are found in Central and South America and the Caribbean. All other species in about 140 genera are members of the Aleyrodinae that are mostly found in pan tropical and warm-temperate regions. The subfamily Udamoselinae consists of only two South American species (*Udamoselis pigmentaria* Enderlein and *Udamoselis estrellamarinae* Martin) in a single genus (Udamoselis) [41–43]. *Bemisia tabaci* (G), *Trialeurodes vaporariorum* (Westwood), and *T. abutilonia* are of great economic importance as they are capable to transmit viruses to several important agricultural crops [4]. *Bemisia tabaci* was reported to transmit about 111 viruses, while *T. vaporariorum* and *T. abutilonia* transmit 3 viruses each [44]. Recently, solanum whitefly, *Aleurothrixus trachoides* (Back). (Hemiptera: Aleyrodidae) was reported to transmit *Duranta leaf curl virus* (DLCV) to tomato, bell pepper, and potato in India [45].

Although *B. tabaci* was previously considered a complex species, current research has disclosed that it is a cryptic species complex composed of morphologically indistinguishable and reproductively isolated species [4,46], previously referred to as biotypes [11,47–49]. *Bemicia tabaci* genotypes and species have been identified based on molecular markers [11,46,49–51]. About 43 genetic groups of *B. tabaci* have been described based on the DNA sequence analysis of mitochondrial cytochrome oxidase subunit I (mtCOI) [5,42,52]. Earlier, it was considered only Middle East-Asia Minor 1 (MEAM1) and the Mediterranean (MED) variants, with a wide range of host species [13,53]. Despite their morphological similarities, *B. tabaci* genotypes show substantial variability in viral transmission efficiency, development of phytotoxic disorders, mechanism of food consumption, and biological control efficiency [54,55].

3. Life Cycle of *Bemicia tabaci*

Females lay pear-shaped eggs (0.2 mm long) on the anterior surface of the leaf, often in a semi-circular form. The egg (Figure 1a) hatches after 5–9 days to first instar, based on the type of host variety, temperature, and moisture [12,14]. The whitish-yellow first instar, or 'crawler,' is flat, oval, and scale-like in form and transform into yellowish dome-shaped nymphs in the 2nd instar (Figure 1b), and then to the bright yellow freshly molted 3rd instar nymphs that gradually darken and appear slightly constricted in structure [20]. The 4th instar nymphs are yellowish-white in color with bulging eyes projecting through the integument; this phase is also known as the "pupal" or "red-eyed nymph" phase [13]. The nymphal phase is flat, with little resemblance to an insect or mature whitefly. The nymph is stationary and generates waxy filamentous fluids periodically [8,56]. The *Bemicia tabaci* adult emerges through the dorsal side of the pupal case via an upturned "T"-shaped incision [20]. The stomach of adult female is big and spherical, while the male's stomach is pointy [13]. The complete life cycle requires about 16–31 days, with considerable variation [57,58].

4. Host Plants

Bemicia tabaci has a broad host range which includes crop plants such as cassava [23] tomato [59,60], eggplant [61], cinnamon, cucurbits [62], muskmelon [63], okra [31], cucumber [33], black pepper [64], sunflower [65], pulses [11], tobacco [66,67], groundnut, cabbage [68], soybeans [69], potatoes [70], cauliflowers [71,72], cotton [35,73], lettuce [74], and numerous other crops of great economic importance. Table 1 summarizes the reports on the effect of whitefly infestations on different agricultural crops.

Table 1. Reports on the impact of whitefly infestation on crop plants.

Crop Name	Study Location	Damages Caused	Reference
Tomato	Florida	Economic loss of >125 million US dollars.	[75]
Tomato	Israel	Leaf curl, flower drop, short internodes, dwarfing, and leathery leaves.	[76]
Tomato	Spain	Multiple necrotic rings on the leaves.	[77]
Tomato	Spain	The average number of holes per leaf were 0.23 ± 0.10 and 0.3 ± 0.12 on the fruits during winter and summer experiments.	[78]

Tomato	Egypt	Reduction in chlorophyll A and B in infected tomato leaves by 8 and 12.8%, respectively.	[79]
Eggplant	China	Reduction in plant height: 12.6%, leaf area: 12.7%, dry matter: 8.2%, absolute growth rate: 26.0%, relative growth rate: 25.0%, and net assimilation rate: 22.2%.	[80]
Eggplant	China	Reduction in leaf area, fresh, and dry weight by 26.6, 21.8, and 19.27%, respectively. Reduction in chlorophyll content and photosynthetic by 9.7 and 65.9%, respectively.	[81]
Tobacco	China	Reduction in plant height: 32.7%, internode length: 4%, and photosynthetic rate: 81.5%.	[82]
Tobacco	China	At 11, 14, and 20 days, infected leaves had 42.36, 56.96, and 81.43% less chlorophyll A than the control plants.	[83]
Sugarcane	Iran	Chlorophyll content reduced to 0.583 mg/g compared to 1.48 mg/g in the control group.	[84]
Cantaloupe, cucumber, and zucchini	Saudi Arabia	Average reduction in cantaloupe pigments: 0.87, cucumber: 1.12, zucchini: 0.54 compared to 1.13, 2.09, and 1.05 in the control.	[85]
Zucchini	Florida	Reduced chlorophyll content by 66% in petioles compared to leaf blades at lower infestation stage.	[86]
Zucchini	Florida	There was a reduction in fruits yield using varied number of whiteflies compared to control (control: 5.1 ± 0.5, 30 pairs: 3.9 ± 0.5, 60 pairs: 0.4 ± 0.1 and 120 pairs: 0).	[87]
Cassava	Fiji Island	Reduced average conductivity rates (M = 11.90 mmol m^2s^{-1}), compared to non-infested foliage (M = 17.80 mmol m^2s^{-1}).	[88]
Soybeans	Brazil	Reduction in grain weight (33 g/1000 grains) and loss in protein contents (440 kg/ha) were recorded.	[89]
Snap bean	Georgia	Up to 45% of snap bean was lost due to whiteflies infestation.	[90]
Squash	Georgia	Up to 35% of the squash was lost due to whiteflies infestation.	[91]
Vegetables	Texas	Economic loss of 29 million US dollars was recorded.	[92]
Vegetables	South Carolina	The infestations resulted in thickened and distorted leaves, which become curled and crumpled.	[93]
Potato	India	The percent incidence (40–75%) of whitefly transmitted viruses was reported.	[94]
Coconut palm	India	In severe cases, the nymphs covered almost 60% of the leaf, which led to yellowing, necrosis, and dehydration.	[95]
Chili	Sri Lanka	Chili leaf curl virus, carried by whitefly, has led to leaf distortion and stunted growth in chili plants.	[96]

5. Whitefly Management (WFM) Strategies

WFM (Figure 2) can be achieved by a combination of physical and mechanical approaches [13,97], indigenous technical knowledge [71,98], biological control [99], plant-based products [100], biotechnological strategies [73,74], spray of synthetic pesticides [101–103], and IPM strategies [104,105].

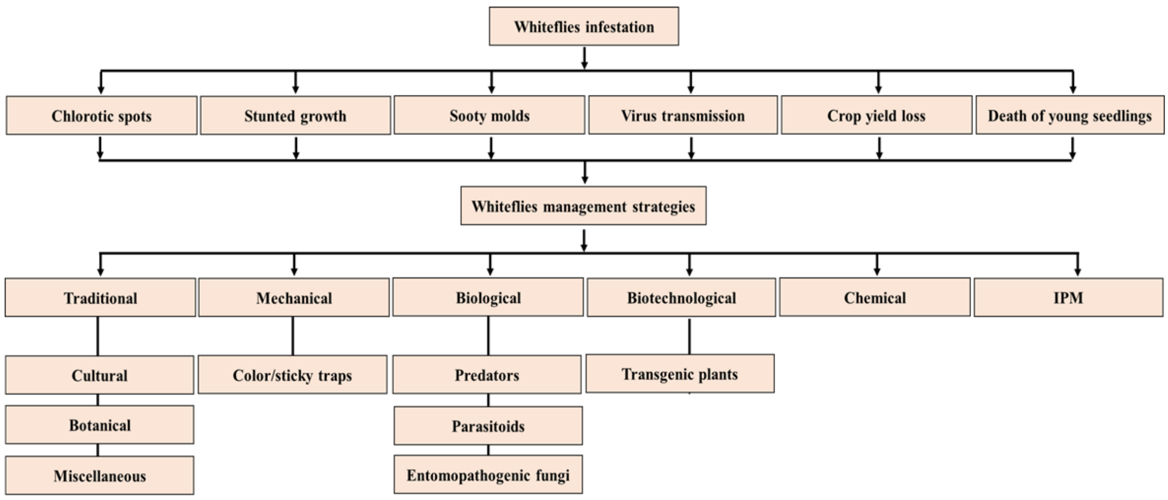

Figure 2. A schematic representation of the available whitefly management (WFM) strategies.

5.1. Traditional Strategies

Indigenous technical knowledge (ITK) has been used to control whiteflies traditionally using locally available materials/techniques and expertise. Some of such methods are briefly discussed below.

5.1.1. Cultural Strategies

Cultural practices such as regulating the irrigation and fertilizer application [106,107] can be modified to make the crop fields unfriendly to insect pests [13,97,108]. Drip irrigation reduces whitefly density and viruses transmitted by them in several crops compared to furrow/sprinkler irrigation [109]. Irrigation using sprinkler technique was also reported to decrease the whitefly population and related viruses in tomatoes intercropped with the coriander plant [110]. Sulfur-containing fertilizers have variable impacts on whitefly population in different crops [111]. By adjusting the crop sowing season, a susceptible host can escape peak population of the pest [112,113]. Maintaining the crop areas free of susceptible species for a period of 60 days during the wet summer season minimizes incidence of whiteflies and associated viruses [114]; however, some studies contradict such strategy [115].

Organic (compost, wheat straw, cocoa hulls, bark and wood chips, etc.) and synthetic (rubber chips and plastic sheeting) mulches are useful to combat *B. tabaci* (G.) infestation on vegetables [106,116]. The organic mulching [11,117,118] and reflective silver or aluminum coated plastic mulches [106,119] lower insect population and viral pathogens in crops such as tomato, squash, melon, and snap bean. Sunlight reflected by silver colorful mulch repels whitefly invasion [120,121]. The trap and barrier crops regulate *B. tabaci* density by interfering with host location. This approach was useful in controlling the viruses associated with different crops [115,122–126]. The use of brinjal and squash has been reported to help in protecting tomato [127,128] and snap bean [119] against whiteflies. The whitefly population on cucumber decreased by 69.7% when intercropped with lettuce [129]. Zucchini intercropped with okra showed lower population of whiteflies and less severity of squash silver leaf disease [118]. Planting okra with coriander or ginger suppressed whitefly numbers in okra [130,131].

A detailed investigation on the cultural measures on WFM revealed that these strategies have received less priority, which may be due to the difficulty involved in execution [114]. Cultural approaches such as sowing dates/rotational systems/crop-free duration require a significant degree of local collaboration among crop growers, which is difficult to accomplish. Strategies such as intercropping or employing trap crops need considerable changes in agricultural systems. Some of the successful accomplishments include physical protection of crops via the row covers, construction of tunnels, screen buildings, field separation, and the use of virus-free seed. Cultural control measures alone are insufficient to manage whiteflies and whitefly-transmitted viruses but play a crucial role in integrated management.

5.1.2. Miscellaneous

This includes the amalgamation of traditional approaches for effective WFM.

Fermented Curd Water

Farmers spray sour buttermilk on their crops for the control of sucking pests [132]. Milk has a good spreading characteristic; it sticks to the wings of whiteflies due to the presence of casein protein and causes their mortality. Spraying fermented cow milk caused a 60% reduction in whitefly population on okra crops [27,133], and when combined with chili extract, it provides systemic tolerance to whiteflies [71,132]. Buttermilk and detergents in combination decreased the whitefly density on black gram [28].

Cow Dung/Urine and Botanical Extracts

Foliar spray of cattle urine has been reported to control diseases and insects and acts as plant growth promoter [134]. Foliar spray of cow urine has been reported to be effective against a number of insect pests, including whiteflies in different crop plants [98,135], and to increase the yields [136]. Foliar sprays of 10% cow urine and 1% starch, alone or in combination with chlorantraniliprole 18.5% SC, control insects on vegetable crops [137]. Herbal aqueous extracts in cow urine have been reported to be effective against whiteflies and safe to their natural antagonists [138–140]. Extracts of *Lantana camara* Linn. and *Vitex trifolia* L. were effective against the aphid *Lipaphis erysimi* when combined with cow urine [134]. A combination of cow dung with urine, ash, slurry, or vermiwash significantly reduced insect pest populations on brinjal [141,142]. The application of chili, garlic, and neen leaf extracts in cow urine on okra reduced the whitefly and other pests' population [143].

Ash

Ash safeguards crops from a wide range of insects including whiteflies [98]. A thick coating of ash on leaves functions as a barrier/toxin, disrupts the molecular signals from the susceptible plants and block insects from locating their host. In brinjal crop, a high benefit to cost ratio of roughly 4.8:1 was achieved by applying 50 kg/ha of ash, 5% kerosene, and spinosad 45SC [137].

Kerosene

The use of a kerosene–soap–water formulation as a contact pesticide for piercing-sucking insects has previously been described [144]. Treatment with kerosene not only lowered whitefly densities on tomato but also caused a yield penalty [145,146]. Table 2 presents the reports on traditional strategies for whitefly management (WFM) in different crop plants.

Table 2. Reports on traditional strategies for whiteflies management (WFM).

Crop	Materials Used	Mode of Preparation	Effects	Reference
Tomato	Yellow sticky traps	The traps were placed at a height of 1.4 m in the middle of the greenhouse.	Up to 67 whiteflies were caught per trap.	[147]
Tomato	Yellow sticky traps	The traps were hung either vertically or parallel to tomato lines.	Vertically hung yellow sticky traps caught more whiteflies (66.57) per row in the fields.	[148]

Tomato	Several colored and shaped adhesive traps	The traps were placed at different rates: 2, 4, and 6 traps per 250 m^2.	The yellow rectangular traps proved more effective with a mean of 5.7 whiteflies/trap.	[149]
Eggplant	Yellow traps	The traps were put at 30 cm above the plants at a rate of 1 trap per 5 m^2 in the field.	Yellow sticky traps caught up to 27 whiteflies in 6 days.	[150]
Eggplant	Sludge/slurry, ashes, cattle urine, and dung	Wood ash sprinkled at 50 g/plants, cow urine, cow dung, slurry and water sprayed at 1:10 ratio for five days.	Lower pest densities, reduced production costs, and less harm to the non-target arthropods were recorded.	[142]
Eggplant	Cow urine and verminwash	They were prepared at 20, 30, 40, and 50% concentrations.	The whiteflies densities were reduced with 50% concentration being the most effective.	[141]
Eggplant	Cow urine, different plant extracts, and vermiwash	Cow urine (CU) alone formulated at 20, 30, 40, and 50%, then mixed with plant extracts and vermiwash.	Lowest whitefly mean number (2.22) was reported in CU 20% + neem leaf extract 10%.	[139]
Cotton	Non-sticky, yellow sticky, and colorless sticky card	The traps with 7.5 × 12.5-cm, 72 cm^2 and 93.75 cm^2 were used.	After 24 h, non-sticky cards trapped 264, sticky cards caught 523, while colorless sticky cards caught 37 whiteflies per card.	[151]
Pepper	Combination of trap crops with yellow traps	Yellow sticky traps and trap crops were evaluated separately and in combination.	Yellow sticky traps were more effective (42 whiteflies/traps).	[152]
Cotton	Yellow sticky traps	The traps were hung vertically at 45 cm above the plant using a wooden pole.	Average densities were 34.07 whiteflies/trap. The whitefly number decreased to 0.83/leaf.	[153]
Okra	Buttermilk	10 L of buttermilk was fermented, 1 L of the fermented material was added to 9 L of water and sprinkled on the crops.	The formulation significantly reduced the whiteflies population by 60%.	[133]
Crop plants	Plants extracts and soap	Mixture of marigold and hot chili pods, filtrates diluted with water at 1:2, 1 teaspoon of soap was added per 1 liter of extracts and sprayed on the crops.	Most agricultural pests are curtailed/managed effectively.	[71]
Cowpea	Cow urine with botanical extracts	The cow urine was prepared at 25, 50, 75, and 100% with 1% extract of neem seed kernel.	Cow urine 100% + neem 1% proved most effective with 13.26/leaf.	[136]
Okra	Cow urine with plant extracts	Pepper, garlic, neem leaf, and cow urine combination at quaternary level were prepared and applied at 10% w/v.	Reduction in whitefly numbers (95.2%) was reported.	[143]
Crop plants	Cow urine, soap, and plant extract	20 g crushed root of turmeric was steeped in 200 mL cattle urine. The mixture was diluted using 2–3 L of tap water (8–12 mL).	Sap-sucking insects including whiteflies, aphids, caterpillars, and red mites were significantly reduced.	[154]

Agricultural crops	Cow urine	Urine diluted in water (1: 20).	The treatment was effective against insects and pathogens and serves as fertilizer to the crops.	[98]
Crop plants	Buttermilk	ITK using fermented curd water (buttermilk).	White fly, jassids, aphids, etc. were managed/suppressed efficiently.	[132]
Agricultural crops	Cow dung and urine with fermented plant extracts	Fermented plant extracts, cow dung/urine in a ratio of 1:20 water.	The insect pests were well managed.	[138,140]
Okra	Colored sticky traps	1500 mL empty Pepsi containers coated with yellow, green, purple, and black were kept in the field, 2 m apart and 0.6 m above the crops.	Yellow traps were found most promising with a mean of 61.13 whiteflies per trap.	[155]
Crop plants	Kerosene–soap–water emulsion	Indigenous technical knowledge (ITK) using kerosene–soap emulsion.	It had a detrimental effect on piercing-sucking insects.	[39,144]
Cotton	Traps/barrier crops and parasitoids	The intercropping and perimeter cropping strategies involving 3 intercrop schemes and 3 peripheral plantings were examined.	About 1.44 and 1.15/100 cm^{-2} of both nymph and adult whiteflies were recorded on the leaf surface.	[24]
Black gram	Soap, indoneem, neem, buttermilk, actara, and lisapol detergents.	The treatments were used separately and in combination	Lower whiteflies number (7.56) was found in treated plants compared to 37.11 whiteflies per leaf in untreated plants. The combined effect led to 26.50–27.35% reduction in whitefly number.	[28]

5.1.3. Botanical Extracts

Several plant-based products have been reported for their efficacy against *B. tabaci* [156–158]. Marigold and chili extract were effective against the majority of insect pests [159] and leaf extracts effective against hemipteran insects [160,161]. The foliar spray of formulation made from crushed roots of turmeric (*Curcuma domestica* Vahl) which is a spice and medicinal plant and cattle urine [162], controls whiteflies, many other insects, and powdery mildew [154]. The formulation made from leaves of *Vitex negundo* L. has been used to control different pests including whiteflies [163]. Moreover, neem-based formulations [164–166], milkweed (*Calotropis* sp.) and garlic extracts [166], *Jatropha curcas* L. extracts [167], and fermented-extracts of neem and wild garlic have also been used against several insect pests [168,169]. Plant-based essential oils have been extensively studied for the control of *B. tabaci*, [60]. Oils of *Piper callosum* Ruiz and Pav, *Adenocalymma alliaceum* Lam, and *Plectranthus neochilus* Schltr. prevent *B. tabaci* adults from settling and ovipositing on tomato plants. Table 3 summarizes the reports on the use of plant-based products for WFM in different crops.

Table 3. Reports on the use of plant-based products for whitefly management (WFM).

Crop Name	Plant Products Used	Results	Reference
Sweet potato	Use of plant extracts (petunia)	Whitefly controlled at 0.5 and 1 mg ml^{-1} concentrations (70% and 82% for adult and eggs mortality).	[170]
Tomato, cucumber, and bean	Aqueous, methanol and acetone fruits and leaf extracts of chinaberry	Methanol extract reduced the whitefly number to 1.44± 0.24 per plant.	[171]
Tomato	Seeds and leaf extracts from eight plant species	The highest lethality (41%) was caused by *Jatropha dhofanica* L. while 30.85% was caused by *Azadirachta indica* A. Juss as the lowest fatality rate.	[172]
Tomato	Ginger oils	The oils were effective in repelling the whitefly on tomatoes	[173]
Melon	Essential oils from thyme and peppermint	The extracts were effective with 62.78% (peppermint) and 100% (thyme) fatality rate.	[174]
Tomato	Seed extracts from *Trichillia havanensis* Jack. and *Passiflora edulis* Sims	*Passiflora edulis* Sims led to 60% lethality while *Trichillia havanensis* Jack. caused 70% whiteflies fatality.	[175]
Winged soapberry	Crude and semi-purified saponin extracts from *Sapindus saponaria* L.D. Benson fruits	Whitefly lethality increased as the quantity of unrefined and semi-purified saponin preparations increased (20 to 80%).	[176]
Soybean, cotton and melon	Oils of sugar apple	Whitefly nymphs shrunk and detached from the surface of the leaf after being exposed to the seed oil.	[177]
Coleus plant	Essential oils from various plant species	After one, two, and three weeks of treatment, none of the essential oil offered sufficient suppression of whitefly.	[100]
Sweet potato	Aqueous plant extracts	The extracts were as lethal as Imidacloprid to the sweet potato whitefly.	[178]
Laboratory	Mint and colothyn foliar extracts (crude or formulated)	At LC_{50}, the extracts were effective (100% toxicity) against whiteflies and aphids.	[179]
Dry bean	Neem oils	On the 6th day after treatment, the fatality rate for first to third instars was above 80% at 1% concentration.	[180]
Laboratory	Essential oils from 4 different plants	Mortality rate of up to 79% was recorded from the report.	[181]
Sweet potato	Plant derived pesticides (neem)	The oviposition, egg hatching, and adult eclosion were reduced by 23.1, 53.2, and 26.6% compared to control.	[182]
Okra	Neem essential oils	Neem oil 5% caused 70.77% mortality in *B. tabaci* 72 h after application	[183]
Different crops	Essential oils from aromatic plants	The EOs acted as a repellant, insecticide, and growth inhibitors.	[184]
Tomato	Fermented botanicals from neem, kakawate, marigold, and makabuhay	Marigold was found to be most effective among the four extracts.	[185]

Laboratory	Essential oils and secondary metabolites from lants (cumin, cinnamon, lemongrass and citronella grass.)	Cinnamaldehyde (deterrent at 0.084 mg/L and deadly at 8.4 mg/L) and linalool (retardant at 0.006 mg/L with unknown lethality).	[186]
Y-tube olfactometer	Volatile compounds from six plants species.	There was more than 80% attraction response, more than 62% deterrent effect and more than 80% anti oviposition.	[82]
Tomato	Five different combinations of chemical treatment	100% mortality on treatment 1–4 and 2 whiteflies on treatment number 5.	[187]
	Eugenia Spring ex Mart. foliar extracts	80–97% lethality rates on the insects.	[64]
Okra	Plant extracts	Significant reduction on the whitefly population ranging from 5.19 to 63.17%.	[188]
Tomato	Clove and bitter orange essential oils	The mortality of whiteflies ranged from 70 to 90%.	[189]
Tomato	Essential oils from different plant species	Both adult and egg number decreased to 6.6 ± 0.93, 6.0 ± 2.39 compared to 22.6 ± 2.23 and 70.6 ± 19.29 in the control.	[169]
Potato	Extracts from five plant species viz: neem, licorice, turmeric, pomegranate, and thyme	The most efficient substance was neem oil, with 66.79 and 67.71% reduction of whiteflies density in the two seasons (2014 and 2015).	[190]
Tomato	Plant aqueous extracts	Up to 78% and 72.8% were recorded for ovicidal and mortality rate, respectively.	[60]
Laboratory	Essential oils from lemongrass, cumin, and cinnamon	After 24 h, cinnamaldehyde was the most poisonous (100%) to the whiteflies, followed by geraniol (32.1%) and citronellol (17.1%).	[191]
Laboratory	Essential oils from *Gardenia jasminoides* Ellis and its four primary chemical constituents	The extracts had fumigant activity against whitefly adults (81.48%) and acute toxicity against the larvae (77.28%).	[155]
Eggplants	Aqueous extracts of nine different plant species	Cotton seed extract demonstrated superior effects to pest infestation in eggplant fields.	[192]
Chilli	Aqueous plant extracts	Up to 96.67% mortality rate on the nymph of whiteflies	[64]
Cucumber	Plant extracts and commercial insecticides	Up to 80% whitefly mortality was reported.	[193]
Eggplant	Bio pesticides	Whitefly mortality was highest (83.94%) in n spiromesifen+ imidacloprid and lowest (64.04%) in d dinotefuran.	[194]
Cotton	Essential oils from four different plants	About 30.8% to 64.2% mortality rates were reported.	[195]
Cowpea	Plant extracts (Neem leaves)	Promising results on population reduction in whiteflies, aphids, and pod borer.	[196]
Diets bioassays	French marigold plant aqueous and methanolic extracts	Up to 80% rate and antioviopostion were recorded on whiteflies.	[197]

Common bean	Nanoencapsulated essential oils from the fruits and foliage of *Xylopia aromatic* Lam. Mart.	Up to 98% reduction in oviposition by the whiteflies was recorded on the snap bean leaves.	[198]
Different plants	Lemon peel essential oils	About 99 to 100% mortality rate in both whitefly and mealy bugs.	[199]
Tomato and Strawberry	Neem oils and chamomile extracts	Neem oil lethality (71.3%), chamomile and lechuguilla extracts (62%) while neem oil with cactus pectin led to 60% mortality.	[26]
Tomato and Strawberry	Essential oils of neem	60 to 71.3% mortality was observed.	[26]
Cotton	*Ocimum gratissimum* Lam. and *Cymbopogon citratus* Stapf. volatile compounds	A lower dose of *C. citratus* reduced whitefly number to 3.77 ± 0.51/30 plants, while a high dose of 5% of *O. gratissimum* reduced whitefly numbers to 3.38 ± 0.53/30 plants.	[200]
Laboratory	Plant extract (Avacado Kernel)	The extracts caused a high mortality of 90% in adults and 98.3% in the nymphs of whiteflies.	[201]
Tomato	Ethanolic extracts of Anona species	At 13 days following treatment, fewer eggs (35.00%) had hatched in the LC90 treatment than in the other groups.	[202]

5.1.4. Mechanical Strategies

These methods mechanically interfere between pests and the host plant. Polypropylene sheets are efficient in controlling whiteflies and tomato yellow leaf curl virus (TYLCV) disease incidence in tomatoes [203]. Zucchini plants are cultivated inside low tunnels coated with Agryl sheets to avoid infestation and disease/contamination by the squash leaf curl begomovirus (SLCV), even during peak pest population [204]. Fifty-mesh screens used as greenhouse walls efficiently prevent whiteflies and spread of TYLCV in greenhouse tomatoes [205], and by including a UV-absorbing protection, efficacy of the screens may be significantly improved [206–209]. Although handpicking is not possible in large-scale whiteflies control programs, it may be practiced in kitchen gardening where insects are readily accessible to picking. However, a combination of biological (see Section 5.2) and mechanical strategies can synergistically reduce the whitefly population [210].

5.1.5. Drawbacks of Traditional Strategies

The deployment of traditional practices [87,150] and botanicals [211] may not be supported with scientific evidence of their safety and efficacy. Utilizing crude plant extracts for pest control may be advantageous only for small-scale farmers [212–214] but such pesticides are inconsistent in their efficiency and not validated for efficacy under complicated agro-ecological conditions [99]. Moreover, large quantities of plant-based products and/or extracts may be difficult to obtain to ensure sustainable WFM [215,216].

5.2. Biological Strategies

Biological control is a method in which one type of organism is utilized to limit the population density of another [217–219]. Natural enemies effectively control pests, particularly invasive pests [219]. Natural enemies (predators, parasitoids, and entomophagous fungi) of *B. tabaci* have been thoroughly investigated and reviewed [104,105,220,221]. Over the last 20 years, enormous studies have proven the efficacy of parasitoids, entomopathogenic organisms, and predators in managing destructive insect pests including whiteflies on different agricultural plants [13,222–224].

5.2.1. Predators

There are about 150 species of natural enemies of whiteflies, and only a handful have been extensively investigated [220,221,225]. Coccinellid beetles, lacewings, and phytoseiid mites' prey on whiteflies [223]. Ladybird beetle, *Delphastus catalinae* (Horn), also known as *Delphastus pusillus* (LeConte), is most commonly used for whitefly control in indoor crops [13]. *Delphastus catalinae* substantially reduces whiteflies on tomato. Mirid bug (*Macrolophus pygmaeus* Rambur) when introduced at 6 adults/plant significantly suppressed the whiteflies in watermelon. Under greenhouse conditions, *Nesidiocoris tenuis* Reuter (1 and 4 predators/plant) led to >90% decrease in whitefly densities on tomato, but no effect on the whitefly population was observed in protecting sweet pepper [77]. The effect of a lacewing, *Chrysoperla carnea* Stephens, at 10 adults/plant has been reported to reduce the whiteflies population in greenhouse-cultivated tomato [31]. Integrating *C. carnea* with *Orius albidipennis* Reuter and *Phytoseiulus persimilis* Athias-Henriot reduced the whiteflies count and enhanced the yield of the greenhouse grown cucumber [226,227]. A predatory mite, *Amblyseius barkeri* Hughes or *Amblyseius cucumeris* Oudeman is also effective against the whiteflies on tomatoes in the greenhouse [228].

5.2.2. Parasitoids

Parasitoids *Encarsia* Spp. and *Eretmocerus* spp. (Hymenoptera: Aphelinidae) are the most common parasitoids used for WFM [13,224]. In a study, augmentative release of *Eretmocerus mundus* Mercet and *Macrolophus melanotoma* Costa reduced *B. tabaci* on the eggplant crops in greenhouse [229]. The antagonistic properties of *Encarsia Formosa* Gahan, *Eretmocerus eremicus* Rose and Zolnerowich, and *E. mundus* Mercet have been well studied [228] but among these, *Encarsia Formosa* Gahan is the most common parasitoid deployed on leafy vegetables for WFM under contained conditions. Introduction of low-density *E. formosa* and *E. mundus* has led to 62.0% and 77.9% reduction in whiteflies number, respectively, on sweet potato. *Eretmocerus* species have lately acquired prominence in biological control of whiteflies [228,230,231]. In a similar report, *E. eremicus* substantially reduced whiteflies eggs and nymphs in a greenhouse grown peppermint [232], sweet pepper, tomato [231], and other crops [233]. By combining *E. mundus* with either *Amblyseius swirskii* Athias-Henriot or *Macrolophus caliginosus* Wagner, whitefly densities on sweet pepper and tomato plants can be reduced significantly [77].

5.2.3. Entomopathogenic Organisms

Entomophagous fungi, viruses, nematodes, and bacteria play a critical role in IPM of insect pests [234,235], as a potential substitute to inorganic insecticides, as they are harmless to farmers, non-target species, and the ecosystem [236]. Entomophagous nematode *Steinernema feltiae* Filipjev caused 32% and 28% whitefly mortality on tomato and cucumber, respectively [237]. Co-treatment of tomato with *Steinernema carpocapsae* Wesier and chemical pesticides thiacloprid/spiromesifen results in 86.5% and 94.3% whitefly mortality [238]. The entomopathogenic fungi have been used on a commercial scale for regulation of insect densities [236,239]. There are about 20 species of entomopagous fungi detrimental to whiteflies, but *Beauveria bassiana* (Balsamo-Crivelli) Vuillemin, *Cordyceps fumosorosea* (Wize) Kepler, *B. Shrestha* Brown and G. Smith, and *Isaria fumosoroseus* (Wize) A.H.S have been extensively studied [13,240]. In a study, *B. bassiana* caused 91.8% mortality on 4th instar nymphs (of whiteflies) within 8 days on vegetable crops [241]. Repeated administration of *C. fumosorosea* and *B. bassiana* led to >90% reduction of the insect nymphs on cucumber, cantaloupe melon, and zucchini squash [242]. Under laboratory condition, *B. bassiana* and *C. fumosorosea* caused 71 to 86% mortality of *B. tabaci* nymphs on pea plants [243]. Applications of the *Lecanicillium muscarium* (Petch) Zare and Gams or co-application with the pesticide imidacloprid caused significant mortality of *B. tabaci* [244]. Combined treatments of *C. fumosorosea* and azadirachtin killed 90% of *B. tabaci* nymphs while entomophagous fungi, *Cordyceps javanica* (Frieder. and Bally) Kepler, *B. Shrestha*, and *Spatafora* sp, caused 62.4% nymphal mortality on bean plant [245].

Pirzadfard et al. [246] analyzed the compatibility and the potential of *Orius albidipennis* Reuter (Predator) and *Eretmocerus mundus* Mercet/*Eretmocerus eremicus* Rose and Zolnerowich (parasitoids) on suppression of *Bemisia tabaci* using a choice and non-choice test in the laboratory. In non-choice bioassay, both 5th instar nymphs and adults of *O. albidipennis* were capable of preying on different stages of unparasitized nymphs of *B. tabaci* and nymphs parasitized by *E. eremicus* and *E. mundus.* In choice bioassay, adults of *O. albidipennis* were reported to consume more than the 5th instar nymphs in the combination of unparasitized 2nd instar *B. tabaci* nymphs and pupae of *E. eremicus* and unparasitized 3rd instar nymphs of *B. tabaci* and larvae of *E. eremicus.* A functional response method was deployed by [247] to evaluate the potential of *Orius albidipennis* in the control of whitefly population in cucumber plant under laboratory conditions. The results showed that type ii and iii functional responses were demonstrated by *Orius albidipennis* when fed on the whitefly eggs and third instar nymphs, respectively, while the maximum rate of attack by *Orius albidipennis* was determined as 68.39 eggs and 23.20 third instar nymphs. This indicates the effectiveness of *Orius albidipennis* in managing the population of *B. tabaci* in cucumber plant. The use of mycoinsecticides for the control of whitefly have been reviewed [248], in which they reported that advances in the synthesis and application of entomopathogenic fungi have led to improvements in longstanding whitefly mycoinsecticide products based on *Verticillium lecanii*, and production and registration of many novel products using *Paecilomyces fumosoroseus* and *Beauveria bassiana*. These products were effective in the WFM in both the field and greenhouse cultivated crops. Moreover [249], in their trial designed to measure and compare the contribution and interaction of biological control and insecticides as tactical components within three pest management systems for *Bemisia tabaci* in cotton, reported that the natural enemies (predators and parasitoids) can be used along with synthetic chemicals in an integrated setting to effectively suppress the whitefly population. Gould et al. [250] also presented a collection of reports on classical biological control of *Bemisia tabaci* in the United States in which several entomophaghous fungi, predators, and parasitoids were found to be effective in the management of whitefly infestations on various agricultural plants. The potential of five predatory mites (*Typhlodromus athiasae* (Porath and Swirski), *Neoseiulus barkeri* (Hughes), *Typhlodromips swirskii* (Athias-Henriot), *Euseius scutalis* (Athias-Henriot), and *Phytoseius finitimus* (Ribaga.) on whitefly control was assessed [251]. They revealed that the intrinsic rates of increase (r_m) of the mite species ranged between 0.131 and 0.215 per day, with *E. scutalis* having the highest increase rate. When compared with the rm of *B. tabaci,* the result shows that the mite species have the potential of suppressing local populations of whitefly as they effectively preyed on and reproduced with *B. tabaci.* The events of predation were noted during the oviposition tests using crawlers and eggs where whole contents of these stages were consumed leaving only the transparent exoskeleton. The effect of varying temperature (20–32 °C) on the development and fecundity of *Encarsia acaudaleyrodis* Hayat, a parasitoid of *Bemisia tabaci* was evaluated [252]. They showed that the period of development from egg to adult stage reduced to 9.0 days at 32 °C from 20.3 days at 20 °C. The average oviposition was reported to be 34.2, 54.6, 30.6, and 20.1 eggs at 20, 25, 30, and 32 °C, respectively. The highest value intrinsic rate of population increase of the parasitoid was also found at around 25 °C. This suggests that the moderate temperature (25 °C) is suitable for the activity of *E. acaudaleyrodis* and thus, might be an effective bio-control agent of *B. tabaci* during spring and autumn when such temperatures are prevalent.

Table 4 presents the impact of biological methods in the control of whiteflies on a variety of agricultural crops.

Table 4. Reports on biological strategies for whitefly management (WFM).

Crop Name	Biological Agents Involved	Effects	Reference(s)
	Predators		
Cotton	*Geocoris pallens* Geocoridae	A predator–prey ratio of 0.75 *G. pallens* per 100 sweeps to one *B. tabaci* nymph was recorded.	[253,254]
Cotton, tomato, hibiscus, cowpea, collard	*Delphastus catalinae* (Horn) (Coleoptera: Coccinellidae	High rate of predation on whiteflies with highest effects on cotton and lowest on collard plants.	[255]
Cucumber	*Chrysoperla carnea* (Steph.), *Orius albidipennis* (Reuter) and *Phytoseiulus persimilis* Athias-Henrio	Individual predation suppressed whiteflies density on cucumber with highest effect recorded in the combination of the three predators.	[227]
Tomato	*Dicyphus Hesperus* Knight	About 88.8% decrease in whitefly density was recorded.	[78]
Cotton, cantaloupe	*Hippodamia convergens* Coccinellidae	Nymphal mortality per petri-dish reached 45.5%.	[253]
Cotton ficus hedge	*Delphastus pallidus* Coccinellidae	68.0% and 55.1% eggs and nymph mortality on leaf disc, respectively.	[256,257]
Poinsettia	*Serangium parcesetosum* Coccinellidae	When four individuals/plant were used, *B. tabaci* fatality reached 60%.	[73]
Collards, soybean, and tomato	*Nephaspis oculatus* Coccinellidae	Within 24 h, up to 72.55% average predation on eggs was reported.	[255]
Cotton	*Collops vittatus* Melyridae	*B. tabaci* densities decreased by 86%.	[253,254]
Cotton	*Geocoris punctipes* Hemiptera	There was 36% nymphal predation petri dish. Predation on 4th instar nymphs led to major death of *B. tabaci* in the crops.	[73,258]
Cotton	*Spanagonicus albofasciatus* Miridae	30–50% of the ova or mature females were reactive for *B. tabaci* antigen.	[259]
Cucumber	*Macrolophus caliginosus* Wagner, *Dicyphus tamaninii* Wagner, *Orius majusculus* Reuter, and *O. laevigatus* Feiber.	*D. tamaninii* consumed whitefly effectively at both lower and high densities while *Orius majusculus* and *Macrolophus caliginosus* were ineffective on whiteflies.	[260]
	Entomopathogenic fungi		
Melon, zucchini, squash, and cucumber	*Beauveria bassiana* (Balsamo-Crivelli) Vuillemin and *Cordyceps fumosorosea* (Wize) Kepler	More than 90% suppression of the whitefly recorded.	[242]
Cotton	*Trachelas* spp. Corinnidae	About 33.3% of individuals were reactive for *B. tabaci* DNA causing low species densities.	[253]
Eggplant	*Aschersonia aleyrodis* Aschal.	The rate of egg hatching in treated plants (85.3 ± 61.42) was less than the untreated groups (91.52 ± 2.10). The viability of the 1st (22.56 ± 1.20%), 2nd (39.30 ± 1.88%), and 3rd (39.30 ± 1.88%) instar nymphs were recorded.	[261]

Cucumber, melon, tomato	*Verticillium lecanii* (Zimm) strains	Reduction in whitefly population and symptoms of powdery mildew disease.	[262]
Cotton	*Verticillium lecanii* Zimm, *Beauveria bassiana* (Balsamo-Crivelli) Vuillemin, and *Paecilomyces* spp.	The mortality rate ranged from 57.1 to 100% depending on the strain deployed.	[263]
Eggplant	*Isaria fumosoroseus* Wize	It killed eggs, second, third, and fourth instars at a rate of 91, 90, 86, and 89%.	[264]
Soybean	*Aschersonia aleyrodis* Aschal.	Greatest mortality (99%) reported.	[69]
Cotton and tomato	*Beauveria bassiana* (Balsamo-Crivelli) Vuillemin	The fungi (Bb-01) reduced whitefly eggs by 65.30% and nymphs by 88.82%.	[265]
Cucumber, tomato, melon, and many other crops	*Beauveria bassiana* (Balsamo-Crivelli) Vuillemin	The mean fatality for larvae raised on cotton: 52.3 ± 7.3, cucumber: 91.8 ± 5.8.	[68]
Tomato	*Aschersonia. Placenta* Berk.	The fatality rate varied from 93% to 100%.	[59]
Sweet potato	*Isaria* spp.	LC_{50} and LT_{50} values when exposed to 1000 spores/mm^2: LC_{50}: second instar: 72–118 spores/mm^2; third instar: 166–295 spores/mm^2; fourth instar: 166–295 spores/mm^2.	[70]
Cotton	*Beauveria bassiana* (Balsamo-Crivelli) Vuillemin	The fatality (56%) was observed at a higher dosage (1107 spores/mL)	[266]
Cucumbers	*Isaria fumosoroseus* (Wize) A.H.S	After 7 days of treatment, the 2nd instar was the most susceptible phase, with 83% fatalities.	[33]
Cotton	*Beauveria bassiana* (Balsamo-Crivelli) Vuillemin and *Metarhizium anisopliae* (Metschnikoff) Sorokin with synthetic insecticides	Mortality rate ranging from 62 to 84% was observed.	[267]
Eggplant	*Metarhizium anisopliae* (Metschnikoff) Sorokin, *Verticillium lecanii* Zimm, and *Beauveria bassiana* (Balsamo-Crivelli) Vuillemin	In plots of *B. bassiana, V. lecanii,* and *M. anisopliae,* the average density of whiteflies dropped from 126 ± 2.8 to 62.8 ± 3.3, 130 ± 3.8 to 61.4 ± 2, and 165.6 ± 2.2 to 62.4 ± 3.5, respectively.	[268]
	Entomopathogenic nematodes		
Cucumber and pepper	*Steinernema feltiae* Filipjev and *Heterorhabditis bacteriophora* Poinar	Both life stages of the whiteflies were susceptible to infection by the two nematode species.	[73]
	Parasitoids		
Eggplants	*Metarhizium anisopliae* (Metschnikoff) Sorokin	Mortality rate of up to 84.3% was recorded.	[215]
Hibiscus	*Encarsia noyesi* Hayat, *Idioporous affinis* LaSalle and Polaszek and *Entedononecremnus*	Mean parasitism rates were 28 ± 2% for *Idioporous affinis,* 28.7 ± 1.9% for *Encarsia noyesi,* and 1 ± 0.0% by *Entedononecremnus krauteri.*	[269]

	krauteri Zolnerowich and Rose		
Tomato	*Encarsia formosa* Gahan and *Encarsia sophia* Girault and Dodd (Hymenoptera: Aphelinidae)	Up to 60% parasitism rate was observed on the whitefly population using individual predators.	[223]
Cotton	*Encarsia sophia* Girault and Dodd and *Eretmocerus hayati* Zolnerowich and Rose (Hymenoptera: Aphelinidae)	*Encarsia sophia* had a cumulative host consumption rate (C_0) of 84.1 whiteflies per individual, while *E. hayati* had C_0 of 17.6 whiteflies per individual.	[270]
Cotton	*Eretmocerus hayati* Zolnerowich and Ros	*Eretmocerus hayati* parasitized the entire nymphal phases of the whitefly with 2nd nymphs showing the greatest incidence (62.03%).	[271]
Poinsettias	*Eretmocerus eremicus* (Rose & Zolnerowich) and *Amblyseius swirskii* Athias-Henriot compared to synthetic insecticides	Average density (3.5 ± 1.09) of immature whiteflies per plant were recorded for the IPM.	[25]

5.2.4. Drawbacks of Biological Strategies

Despite being eco-friendly, pollution free, selective, feasible, and cost-effective, biological control measures are associated with farmers' uncertainty in income sustainability, highly unpredictable, and more prone to environmental factors [272]. Severe heat or cold could negatively affect the biological control of whitefly in greenhouses [273]. The implementation of biological control agents in new surroundings necessitates extensive studies to achieve the desired outcomes. Incompatibility with agrochemicals is another challenge since they are specific to a particular species. Undoubtedly, application of agrochemicals causes rapid reduction of pest populations and therefore, farmers find it hard to rely on biocontrol agents (BCAs) over effective agrochemicals [274].

5.3. Biotechnological Strategies for Whitefly Control

Genetic engineering techniques including transgenesis and RNA interference (RNAi) can be effective in regulating whitefly infestations. Transgenic crops harboring/synthesizing pesticidal toxins or lectins are useful in controlling whiteflies [35,275].

5.3.1. Transgenesis and Whitefly Control

One of the early triumphs of plant biotechnology was the development and commercialization of transgenic crops resistant to key insect pests, including whiteflies [35,276,277]. Transgenic tomato and lettuce successfully have been developed to confer tolerance to *B. tabaci* and related viruses [278]. Cotton plants expressing fern protein provided resistance/tolerance against the attack of whiteflies [35]. Such insecticidal proteins have a longstanding record of being safe and cause no harm to humans and other non-target organisms lacking specific receptors for the toxin proteins [276], but are effective against lepidopteran and coleopteran insects. Transgenic plants producing dsRNAs for knocking down target genes in whiteflies caused mortality, retarded growth, and sterility [278]. Whitefly counts were drastically reduced on transgenic tobacco expressing dsRNAs against v-ATPaseA [279] and osmoregulators [73]. Transgenic lettuce expressing dsRNA v-ATPase caused approximately 98.1% mortality of whiteflies [74]. Cotton plants overexpressing gh-miRNA166b downregulate the ATPsynthase gene in *B. tabaci* and reduce whitefly populations [280]. The use of dsRNA detoxification gene in transgenic *Arabidopsis thaliana* knocks-down the *BtBGSTs5* gene in the gut of whiteflies, extends the nymph developmental time, and causes decline in *B. tabaci* densities [281]. Thus, there is a need for robust biotechnological interventions for sustainable management of whiteflies [282].

5.3.2. Exogenous Application of dsRNA to Control Whiteflies

Non-transgenic application, RNAi techniques for controlling pests, can be achieved through foliar spray, submerging leaf tissues in dsRNA solution, soil treatment, or stem injections [283–286]. The RNAi approach effectively mutes the genes in a short period without causing heritable alterations to the genome and have a higher public acceptability. The exogenous delivery of dsRNA particles to tomato seedlings led to dsRNA assimilation by whiteflies, aphids, and mites. However, whiteflies and aphids absorbed less dsRNAs than mites did and siRNAs synthesis from dsRNAs was observed in mites and aphids but not in whiteflies [287]. Spraying of dsRNAs to regulate pest populations is a safe and eco-friendly approach, and dsRNA has short residue period, therefore, it has huge potential for adoption by plant growers [284].

5.3.3. Control of *B. tabaci* through Nanotechnology

The dsRNAs sprinkled on crops or applied using water (to enable plants to uptake through leaves) or soil has a limited life span due to degradation by radiation/microbial cells enzymes, whereas dsRNAs coated onto the layered double hydroxide (LDH) clay nanostructure (BioClay) or carbon nano-tubes of diameter less than 0.1 μm can be complacently reabsorbed into cell membranes [24], stabilize dsRNAs for lengthy continuous delivery, and protect them from proteolytic enzymes. However, such nanomaterials should be recyclable and nontoxic. Foliar spray of nanomaterials to transport dsRNA into the plants, is easy to perform, environmentally friendly, and offers effective protection to crops from pests and pathogens. Nanomaterials laden with insect receptor protein dsRNAs were utilized to manage 3rd instar nymphs of *B. tabaci* through dripping to explore the role of nuclear receptor (NR) genes in insect metamorphosis [281,288]. The nanoencapsulation of *Xylopia aromatica* essential oil was reported to promote its protection from environmental degradation and prolonged biological activity [198]. In a similar report, the nanospheres (nanoencapsulation) of *Zanthoxylum rhoifolium* essential oil caused 95% reduction in the production of eggs and nymphs [289]

Cordyceps fumosorosea-derived zero-valent iron (ZVI) (fungal) nanoparticles have shown significant pathogenicity against *B. tabaci* nymphs and pupae due to prolonged fungal activity by preventing premature degradation [290]. Reports on the impact of biotechnological strategies for the control of whiteflies summarized in Table 5.

Table 5. Reports on the use of genetic engineering strategies for whitefly management (WFM).

Crop Name	Biotechnology Involved	Results	Reference
Cotton	RNA interference using *v-ATPaseA*	After consuming transgenic plants, the transcript level of v-ATPaseA in whiteflies was lowered by up to 62%.	[279]
Cotton	RNA interference using dsRNA	More than 90% mortality rate was recorded 24 h post treatment.	[291]
Lettuce	RNA interference using *v-ATPaseA*	After 5 days of feeding, whiteflies on modified plants die at a range of 83.8–98.1%.	[74]
Tobacco	RNA interference using	Transgenic plants showed tolerance to whitefly compared to untreated plants.	[292]
Cotton	RNA interference using expression of short interfering RNAs (siRNAs)	After 6 days of feeding on modified cotton, 70% mortality rate was recorded.	[73]

Tomato	Nuclear transgenics (transgenic plant)	Due to the toxic and repellency effects of 7-epizingiberene, developed tomato trichomes are resilient to whiteflies.	[293]
Tomato	Plant-mediated RNAi (*A. tumefaciens)*	Up to 50% whitefly mortality.	[294]
Tobacco	Nuclear transgenics (*A. tumefaciens*)	100% mortality of *Bemicia tabaci*.	[66]
Cotton	Transgenic using ZmASN gene under constitutive promoter (*A. tumefaciens*)	There was a 95% death rate for whiteflies.	[295]
Arabidophsis	sRNA (307 bp) detoxifying gene BtGSTs5 is implicated in the neutralization of glucosides in *B. tabaci*	Knockdown of the *BtBGSTs5* gene in the gut extends the developmental time of nymphs and reduces the number of *B. tabaci.*	[281]
Micro-injection (0.1–0.5 µg dsRNA)	dsRNA introduction into whiteflies (0.1–0.5 µg)	Up to 60% success was recorded from the study.	[296]
Micro-injection dsRNA	dsRNA introduction into whiteflies (0.1–0.5 µg)	Up to 70% decrease in whitefly population.	[296]
Micro-injection dsRNA	dsRNA introduction into whiteflies (0.1–0.5 µg)	There was 75% decline in the salivary gland as well 60% reduction in midgut expression.	[296]
Oral feeding	dsRNA introduction into whiteflies (Oral feeding)	Whitefly reproduction as well as survivability decreased significantly.	[278]
Tobacco	dsRNA applied exogenously to plants (0.5 mg/mL)	In 4th instar nymphs of whiteflies, *Cyp315a1* was down-regulated by approximately 80%, while *Cyp18a1* was down-regulated by 46%.	[297]
Citrus and cassava	Exogenous application of modified dsRNA via NRAi methods	Insects' death rate rises from 12–35% in transformed species as related to non-modified ones.	[36]
Tomato	dsRNA applied exogenously to plants	The development of mature whiteflies was dramatically reduced (48.6%) in the pupae produced on Dys-dsRNA-treated plants.	[275]
Tomato	dsRNA applied exogenously to plants leaves.	The dsRNA, were molecularly detected in plants, aphids and mites but not in whiteflies.	[287]
Tomato	Application of dsRNA through the roots	The highest mortality (84%) was recorded at a concentration of 5 (µg/mL).	[298]
Tobacco	Chloroplast transgenics (Transplastomic plants)	*B. tabaci* density decreased by 91–93% in transplastomic plants compared to control plants.	[299]
Cotton	Nuclear transgenics	After six days, nymphs and adults of *B. tabaci* died at a rate of 18.37% and 9.65%, respectively.	[300]
Cotton	Nuclear transgenics	Genetically modified cotton harboring Tma12 gene at a concentration of 0.01% was effective against whitefly (>90% mortality).	[35]
Tomato	RNA interference induced by plants (via siRNA) transgenic	Decreased reproduction and increased lethality by 81.8% to 85.6% respectively.	[5]
Cotton	RNA interference induced by plants (via miRNA) transgenic	Up to 78% mortality rate was recorded.	[280]

Tobacco	Chloroplast-mediated RNAi	The transgenic plants harboring BtACTB had led to 80% mortality rates in *B. tabaci*.	[67]
Tobacco	Artificial miRNA mediated resistance	Abnormal egg hatching and poor nymphal development were observed on the modified plant compared to the control.	[292]
Citrus, cassava	Modified RNAi for dsRNA delivery	There was an increase in the mortality rate of the insects with 12–35% compared to non-modified plants.	[36]
Cotton	Gene silencing (RNAi)	Oral delivery of dsRNA led to 42.5% adult death, decreased fertility (36.57 eggs per female), with 62.50% larval death.	[301]

5.3.4. Disadvantages of Biotechnological Strategies

The public recognition and adoption of genetically engineered crops has provided us with a variety of nutritional, socioeconomic, and medical benefits [261,302]. However, there are public resistances regarding the use and ecological consequences related to the release of genetically modified crops into the environment. Acceptability of farmers and consumers, as well as 'biosafety' are some of the major concerns [257,303]. Furthermore, the cost and time constraints associated with the manufacturing and marketing of transgenic crops have made it difficult for small businesses and government institutions to embrace (practice and implement) this technique for producing transgenic crops [257].

5.4. Synthetic Chemicals

Chemical pesticides are the most commonly used to manage insect pests including *B. tabaci* in open-field crop with high reliance [13,224]. Commonly used pesticides against *B. tabaci* are pyriproxyfen, buprofezen (growth regulators), spiromesifen, spirotetramat (ketoenols), and anthranilic diamides, cyantraniliprole, and chlorantraniliprole (diamides) [13]. Oils, detergents, and soaps have also been widely utilized to combat *B. tabaci* infestation [13,224]. The neonicotinoid imidacloprid is the world's most utilized and very effective pesticide against *B. tabaci.* [101]. Imidacloprid is frequently applied for controlling *B. tabaci* on vegetables, melons, and other crop plants and has been a crucial strategy in the United States [102,103,112,304,305]. Organochlorines, organophosphates, carbamates, pyrethroids, triazines, and neonicotinoids are also extensively used pesticides against sap sucking insects like whiteflies [306]. Despite the fact that the use of chemicals is linked to a negative impact on human and ecological safety [307–309], they have been used globally for managing insect pests on different crop plants (Table 6).

Table 6. Reports on the use of chemicals for whitefly management (WFM).

Crop Name	Pesticides Used	Result	Reference
Tomato and verbena	Buprofezin, teflubenzuron, imidacloprid, and nicotine	Highest mortality (79:8%) was recorded for buprofezin while imidacloprid caused 58:5% lower mortality.	[310]
Cabbage	Seventeen insecticides including abamectin, acephate, acetamiprid, cartap, imidacloprid, malathion, etc.	Cartap caused highest mortality (100%) while trichlorphon had less (4%) mortality.	[311]
Strawberry	Imidacloprid, thiamethoxam, and dinotefuran	Imidacloprid caused adult mortality of 63.58%, thiamethoxam had 41.95% mortality.	[312]
Cotton	Acetamiprid, imidacloprid, bifenthrin, cypermethrin, triazophos, cyhalothrin and rani.	The plots treated with bifenthrin had the highest number of whiteflies per leaf (2.773),	[313]

		followed by imidacloprid (1.83) compared to control plots (5107).	
Cucumber	Imidacloprid, thiacloprid, deltamethrin, pyrethrum, thiamethoxam, and lambda-cyhalothrin	Pyrethrum was the most effective with 90.23% mortality rate followed by thiacloprid+ deltamethrin with 89.57%.	[314]
Eggplant	Four insecticides viz; fipronil, imidacloprid, buprofezin, and thiamethoxam along with emamectin benzoate	Confidor was the most effective with 69.0% whitefly mortality.	[215]
Citrus	Diazinon, endosulfan, imidacloprid	After 10 weeks of pesticide spraying, there was 100% fatality of whiteflies.	[315]
Cotton	Imidacloprid, bifenthrin, chlorpyrifos, and carbosulfan	Carbosulfan led to 40% adult whitefly mortality while chlorpyrifos had the least (25%).	[288]
Cotton	Diafenthiuron, quinalphos, flubendiamide, imidacloprid, thiamethoxam, triazophos, carbosulfan, phosalone, and chlorpyriphos	The whitefly found on treated plants range from 0.13 (fipronil 5 SC) to 2.1 (phosalone 35 EC) per leaf.	[316]
Cluster bean	Clothianidin, thiamethoxam spiromesifen, fipronil, acephate, imidacloprid, and carbosulfan	Spiromesifen was the best treatment with 1.61 whiteflies/3 leaves while imidacloprid had the least effect (3.46) whiteflies/3 leaves.	[317]
Okra	Lambdacyhalothrin	Up to 63.94% lethality at 7 days of treatment. However, a drop (18.99%) in its efficacy was recorded after 15 days of the treatment.	[318]
Eggplant	Thiamethoxam, imidacloprid, acephate, fipronil, thiacloprid, and dimethoate	Total control (100%) was reported using thiamethoxam 25 WG @ 100 g/ha 14 days post treatment.	[232]
Tomato	Transform (sulfoxaflor), polo (diafenthiuron), confidor (imidacloprid), and agrovista	Imidacloprid was the most effective having a mortality rate of up 93.24% 2 h post treatment.	[319]
Tomato	Profenophos, imidacloprid, cypermethrin, and indoxacarb.	Imidacloprid was the most effective treatment with 58.1% mortality while indoxacarb was the least effective (51.40%).	[320]
Cotton	Seven common insecticides: cyantraniliprole, sulfoxaflor, spirotetramat, flonicamid, acetamiprid, etc.	Sulfoxaflor has the highest relative toxicity (13.86%).	[29]
Zucchini	Acetamiprid, pymetrozine with phosphoric soap, and spirotetramat along with azadirachtin	Up to 44% of whiteflies suppression was recorded from the study.	[8]
Eggplant	Actara a 25 WDG, calypso 480 SC, polo, confidor 5 G, and confidor 200 SL	After 14 days, the maximum effectiveness (89.06%) was achieved using actara foliar application.	[321]
Chilli	Spinetoram, novastar (bifenthrin + abamectin), and sulfoxaflor 50 WG	Bifenthrin + abamectin had proven to be the most effective for reducing whitefly populations (84.46%).	[322]
Cotton	Profenofos, cyhalothrin, and imidacloprid	Whitefly mortality of up to 88% was reported from the study.	[323]
Tomato	Dimethoate, imidacloprid, lambda-cyhalothrin, novaluron, imidacloprid, indoxacarb, azadirachtin	Imidacloprid was found to have the lowest whitefly density (2.18 adults/leaf) compared to the control with 5.69 adult/leaf.	[324]

Eggplant	Buprofezin, imidacloprid, fipronil, spinosad, and emamectin benzoate	The use of imidacloprid at a rate of 100 mL/ha have the greatest effect in lowering the whitefly densities with 1.00/leaf 2 weeks after treatment.	[257]
Tomato	Thiocyclam (hydrogen oxalate), acetambrid, and imidacloprid	Abamectin and imidacloprid were the toxic pesticides with 86.98 ± 2.63 and 84.19± 1.56 mortality rate, respectively.	[325]
Okra	Imidacloprid	It was effective against the whiteflies having 3.90 whiteflies/15 leaves 2 weeks after treatment.	[326]
Potato	Emamectin, thiodicarb, diafenthiuron, chlorpyriphos, chlorfenapyr, cryantraniliprole, bifenthrin, and spiromesifen	It was discovered that the insecticide spiromesifen 22.9 SC @ 1.00 mL/l was highly effective against mites and whiteflies.	[30]
Eggplant	Lambda-cyhalothrin	When treated with lambda-cyhalothrin, whitefly average density was dramatically reduced (2.21/leaf 2 weeks after application).	[327]

Drawbacks of Synthetic Chemicals

Development of resistance to chemical pesticides (most commonly used for controlling insect pests) has made the pests management strategies increasingly complex [321,328]. More than 540 insect species have developed tolerance to such chemicals [329] and the reckless use of these chemicals has impacted the human health and the ecosystem [11,330]. Resurgence of invasive pest species and the negative effect of synthetic pesticides on non-target organisms is also a matter of concern [331].

5.5. Pesticide Resistance and B. tabaci Control

The control of whiteflies is based conventionally on synthetic pesticides including carbamates, organophosphates, and pyrethroids [331]. The continuous application of these chemicals in larger quantities has led to the development of resistance by *B. tabaci* [332,333]. Thus, development of insecticide resistance is a major challenge in WFM and once they develop such a resistance, it becomes difficult to control. Recently, several cryptic species viz., MED, MEAM1, Asia I, and Asia II-1 of *B. tabaci* have been reported to have developed high resistance to various groups of insecticides [224,334]. Study of different whitefly populations in major cotton growing regions of India [334] revealed that *B. tabaci* cryptic species Asia-II-7 was the most susceptible and Asia-I and Asia-II-1 most resistant populations showing significant resistance to insecticides imidacloprid and thiamethoxam, monocrotophos, cypermethrin, and deltamethrin. The Asia-I population showed LC50 values of 7x (imidacloprid and thiamethoxam), 5x (monocrotophos), and 3x (cypermethrin) compared to the susceptible population, whereas Asia-II-1 showed LC50 values of 7x (cypermethrin), 6x (deltamethrin), and 5x (imidacloprid) compared to susceptible populations. The study further detected possible potential control failure based on extrapolation of resistance dataset for pyrethroids (cypermethrin), monocrotophos and triazophos in *B. tabaci* populations. Similarly, *B. tabaci* collected from cotton crop of Pakistan, when selected for five generations, showed very high level of resistance against buprofezin (127-fold) and imidacloprid (86-fold) [335]. Pappas et al. [336] reported that *T. vaporariorum* was able to resist the effects of neonicotinoid compounds. *Bemicia tabaci* resistance to a number of pesticides (deltamethrin, thiamethoxam, pyriproxyfen, etc.) has been reported [337,338] and recently, a very low level of resistance to deltamethrin (RF = 4.3) and thiamethoxam (RF = 2.2) was documented in one *B. tabaci* strain from Oman [339]. A review [224] discussed the various strategies for minimizing the level of resistance to pesticides in *B. tabaci,* which include chemical control with selective insecticides, rotational use of insecticides with distinct mechanism of action, mixing insecticides, as well as non-chemical management methods such as the use of cultural approach, host plant resistance, and biological control methods. Other strategies involve growing whitefly-resistant genotypes or application of insect growth regulators such as pyriproxyfen or buprofezin to conserve natural enemies' early stage of crop [112]. Application of "refuges" has been reported to be useful in delaying the development of insecticide resistance [340]. Availability of molecular and gene sequence data of resistant and susceptible *B. tabaci* populations can be very useful for designing effective insecticide resistance management.

Shelby et al. [341] suggested the use of gene silencing via RNA interference (RNAi) for sustainable pest management of *B. tabaci*, focusing on the need for species specificity incorporating both life history and population genetic considerations. They showed that these considerations allow an integrated pest control method, with less negative environmental effects and reduced likelihood of the development of *B. tabaci*-resistant populations. *B. tabaci* through co-evolutionary process have gained the ability to overcome plant defenses by utilizing key element of the plants' arsenal to protect itself from plant defense metabolites [342]. Whiteflies are also known to suppress plant defenses by interfering in plant defense hormones [343] and by inducing specific volatile signals in neighboring plants [344]. Heidel-Fischer et al. [345] suggested that the possibility of herbivores detoxifying plant defense substances is a key factor in their capacity to adapt, and it is becoming clear that the transformation of secondary metabolites by detoxifying enzymes is a very efficient method for whiteflies to deactivate plant toxins. The results demonstrate an unusual evolutionary mechanism/route by which whiteflies gained access to malonylate, a common category of plant defense compounds by acquiring a plant detoxifying gene [346]. The horizontal transfer of BtPMaT1 has been demonstrated to give whiteflies the capacity to bind a malonyl group to phenolic glucosides, making these typical plant-produced secondary metabolites virtually totally harmless. Silencing of BtPMaT1 by small interfering RNAs impaired the detoxification ability of the whiteflies in tomato plants. The studies have suggested that interfering with laterally transferred genes can be a highly effective way to combat pests.

5.6. IPM Strategies

Integrated pest management (IPM) is a worldwide-recognized strategy to reduce the ecological and public health risks posed by synthetic insecticides. The IPM for *B. tabaci* includes use of biocontrol, physical, mechanical measures, and limited use of selected pesticides [331]. Islam et al. [80] reported that the use of neem oil along with *B. bassiana*-mediated biocontrol enhanced the mortality rate of *B. tabaci* larvae on eggplant leaves [80]. The combined impact of different concentrations of neem (1.0%) and *B. bassiana* on *B. tabaci* caused 92.3% mortality of the nymphs. The combined effects (synergism) of biologicals and chemicals in IPM has high potential (73%) for the control of whitefly-transmitted viruses compared to individual methods [105]. Wawdhane et al. (2020) studied the efficacy of synthetic pesticides, phytochemicals, and microbes for WFM and reported that spiroomesifen caused greatest reduction in whitefly counts (82.27%) [37], while amongst the microbes, *Verticillium lecanii* (1 × 108 CFU/mL) was found to be efficient against aphids, whiteflies, and thrips. Table 7 presents the summary of IPM approaches for WFM.

Table 7. Reports on the use of IPM strategies for whitefly management (WFM).

Crop Name	Treatments Deployed	Results	References
Tomato	Plant extracts, tween 20, and biological agent (predator)	Leaf and fruit extracts + tween-20 resulted in death rates ranging from 34.6 to 67.9% for leaf and 53.5 to 74.1% for fruits, respectively.	[347]
Tomato and verbena	Chemical insecticides and entomopathogenic nematode	The combined effect of nematodes and imidacloprid caused 70.9% *B. tabaci* larval mortality.	[309]
Tomatoes	Parasitoids, predators, and insecticides	The most effective treatments were a mix between *Eretmocerus mundus* and *Amblyseius swirskii* with an average of 0.7 ± 0.18 whiteflies per leaf.	[77]
Tomatoes	Chemical insecticides and entopathogenic nematode	The use of nematodes + thiacloprid and spiromesifen resulted in a greater *B. tabaci* lethality (86.5 and 94.3%), compared to nematodes alone (75.2%).	[238]
French bean	Novel insecticides and fatty acids deposits	Fatty acid deposits caused 10.7% adult whitefly mortality, diafenthiuron caused 62.7%, and the combined effect led to 69.7% lethality.	[348]
Ash gourd	Synthetic chemicals, sticky traps, plant extracts, farmers practices, and micronutrients	After 18 days, 100% whitefly inhibition was recorded while the average number of whiteflies per plant was 1.86 after 60 days.	[349]
Tomatoes	Biopesticides and synthetic chemical	Cytraniliprole + lambda-cyhalothrin (50 + 30 g a.i. ha-1) reduced whitefly by 64%. 72% larval mortality was recorded using 0.5% flaxseed + 0.3% sodium bicarbonate.	[350]
Tomatoes	Metallic reflective mulches and insecticides and resistant cultivar	Metallic reflecting mulch drastically decreased the insect density as well as the disease symptoms on tomatoes.	[351]
Tomato	Intercropping and irrigation system	Intercropping along with sprinkling irrigation reduced tomato plants' suitability for *B. tabaci* multiplication.	[110]
Potatoes	Mineral oils and synthetic chemicals	Imidacloprid + thiamethoxam + mineral oils resulted in decrease in *B. tabaci* population (74.5%) and disease incidence (93.0%).	[38]
Cucumber	Botanicals and synthetic insecticides	Thiacloprid + deltamethrin (73.42%), pyrethrum + lambda-cyhalothrin (89.57%), and thiamethoxam + lambda-cyhalothrin (90.29%) mortality were recoded.	[313]
Brinjal	Botanicals and synthetic insecticides	The use of 5% neem extract (NSKE) lowered the population (3.5 whiteflies/leaf) as compared to the control (8.0 whiteflies/leaf).	[142]
Eggplant	Entomoathogenic fungi and plant extracts	Neem (1%) along with *B. bassiana* had the highest effect against both eggs (88.25%) and adult whiteflies (80.15%).	[80]
Soybeans	Different chemical pesticides	There was reduced level of egg hatching greatly to about 4.35% compared to 95% in the control.	[352]
Tomato	Botanical oils and chemicals	Mortality rate of up to 80.5% was reported in the study.	[195]

Tomato	Physical method (use of kaolin, a clay mineral)	90.1–91.6% drop in whitefly number was reported at 5% while 89% and 85.7% were reported for nymphs at 5% *w/v*.	[353]
Cotton	Entomopathogenic fungi and insecticides	A greater death rate (96.78%) was seen when matrine was combined with *L. muscarium* with LC_{50} values of 0.034, 0.063, and 0.21 mg/L.	[354]
Sweet potato	Entomopathogenic fungi and aqueous plant extracts	NATURALIS + *Calotropis procera* had highest mortality rate on eggs (62.6%), nymphs (67%), and adult whiteflies (65.2%).	[355]
Cucumber	Plant extracts and commercial insecticides	The use of the extracts along with the pesticides resulted in up to 80% whitefly mortality.	[193]
Eggplant	Biopesticides and synthetic insecticides	In comparison to the control (11.04), the overall mean number of whiteflies per leaf was significantly lower (3.20 to 5.49) across all treated crops.	[104]
Bt cotton	Chemicals, plant extracts, and entomopathogenic fungi	Spiromesifen had the greatest reduction in whitefly numbers (82.27%, 80.57), then imidacloprid (82.27%, 80.57%).	[37]
Eggplant	Synthetic chemicals, biopesticides	The field treated with imidacloprid 17.8 SL @ 100 mL/ha had the lowest whitefly density (2.40 whiteflies/leaf).	[256]
Tomatoes	Plant elicitors (methyl salicylate) and volatile organic compounds	The plant elicitor was reported to effectively limit whitefly population and enhance production by 11% when used on healthy tomato plants.	[356]
Crop plants	Mixture of cow urine with nettle leaves, wild azadirachta, and holy basil	The concoction was very effective in controlling crop pests at nearly no costs.	[39]
Orange	Different organic pesticides	None of the substances tested resulted in a significant fatality of any of the orange spiny whitefly instars.	[357]
Cotton	Three biopesticides along with synthetic insecticides	Eco-Bb® treated plots caused 60% mortality while Karate® led to 67% whitefly mortality.	[358]
Poinsettia	Integrated using systemic and trans laminar insecticides	Lowest nymph density (1.0 + 0.5) was reported using imidcloprid.	[359]
Tomato	Plant derivatives with the neonicotinoid insecticide	Up to 94.4% mortality rate was recorded.	[202]
Eggplant	Botanicals and synthetic insecticides	The average number of whiteflies was higher in integrated treatments (2.37) and lower in the lambda cyhalothrin treatment (2.21).	[327]
Okra	Biopesticides and synthetic insecticides	On average, there were 3.90 whiteflies per 15 leaves when imdacloprid 17.8% (0.3 mL per liter) was applied to the plants. *Beauveria bassiana* and *M. anisopliae* were found to be less efficient, but still more potent than the control.	[326]

Drawbacks of IPM Strategies

Non-adoption by the users is the biggest drawback in the use of integrated pest management (IPM). Most of the times farmers use insecticides on a recurrent basis and with weak frequency. Farmers cultivate different vegetable crops in small land holding, each requiring its own IPM program, which is not easily adopted by farming community. In such a situation, IPM becomes inappropriate and time-consuming. Similarly, the positive effects of chemical pesticides are much more visible and reproducible than their ill effects, but the environmentalists overlook the pesticides' legitimate involvement in IPM [360].

6. Conclusions

In order to address the global food and health security and sustainable agriculture needs, enhanced crop production is required. However, the damage due to destructive insect pests such as *B. tabaci* is a limitation in such efforts. WFM with heavy reliance on synthetic chemicals causes serious ecological deterioration [361,362]. However, an IPM program applied and adopted in larger scale can restrict damage caused due to *B. tabaci* [238,363]. Transgenic plants and RNA interference (RNAi) strategies are useful in the management of whiteflies. Transgenic plants expressing toxins against whiteflies produced by nuclear or chloroplast transformation have opened new vistas for *B. abaci* control. The use of dsRNA synthesized from insect genomes substantially reduced whitefly population in different crop plants; however, meticulous investigations and joint efforts of academia, government (EPA, GEAC, MoEF) and farmers are needed to advance the practical deployment of these techniques in the fields [363,364].

The deployment of hyperspectral image analysis in conjunction with machine-learning-based evaluations may also provide timely and efficient identification of *B. tabaci* on plants. Even though such techniques are still in infancy (prototype), they hold possibility of rapid screening of insect attack, even at lowest density. Deployment of computerized devices linked to surveillance are more practicable in a large-scale agricultural scheme. Precision management system might minimize pesticide application, product prices, and toxicity to human and animals. It may preserve the natural enemy and pest control program viability. In a nutshell, the use of IPM strategies along with novel biotechnological approaches have tremendous potential to combat the whitefly infestation and its related damages for sustainable agriculture.

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