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WHITEFLY SUPPRESSION THROUGH RNAi and NANOPARTICLE SYNERGY: RECENT TRENDS AND FUTURE PROSPECTS

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ABSTRACT

Whiteflies (*Bemisia tabaci*) are destructive agricultural pests that cause sufficient damage by sucking sap and transmitting virus vectors. This not only weakens the plant's immunity but also contributes to the spread of plant diseases, resulting in a severe impact on crop yield. The continuous and excessive use of conventional chemical pesticides not only disturbed the environment but also became a source of vertical or resistance in insects. Advances in biotechnology, particularly RNA interference (RNAi), have helped provide an environmentally friendly and species-specific solution for pest management in sustainable agriculture. RNAi technology works by silencing the genes that are essential for whitefly survival and reproduction, increasing its mortality rate without affecting off-target organisms and preventing hazardous residues in crops. However, RNAi delivery is a challenging task due to plant barriers, such as the cell wall and the plant immune system. Encapsulated RNAi in nanoparticles enhanced its solubility and efficiency, making it a more effective approach. This approach not only improved RNAi delivery but also protected it from degradation, ensuring constant activity in plant cells. This review aims to provide a comprehensive understanding of the use of encapsulated RNAi in nanoparticles for controlling whiteflies and promoting sustainability in agriculture.

Keywords: Cotton, RNAi technology, Whiteflies (*Bemisia tabaci*), Nanoparticles

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1. INTRODUCTION

Whiteflies (*Bemisia tabaci*) (order: Hemiptera, family: Aleyrodidae) are tiny insects destroying agricultural production worldwide (Idrees et al., 2024). There are over 1500 species of whitefly, but the population densities of most of them are not high enough to cause potential damage to their host plants. Most of their biotypes, including *Bemisia argentifolii* and *Trialeurodes abutiloneus* are physically similar but with distinct biological differences (White, 2013). Being a sucking pest, whiteflies suck the sap from phloem and food-transporting tissues of stems and leaves of various plant species, which causes direct damage by draining essential nutrients and weakening plants (Cuthbertson, 2013). Additionally, whiteflies are also carriers of a virus that is transferred from plant to plant, leading to major losses in cotton, soybeans, tomatoes, and other crops of agricultural importance (Table 1). Whiteflies are challenging pests because of their rapid reproduction; even a single adult female whitefly can lay up to 110 eggs in a single lifetime (Perring et al., 2018) which hatches in 3-5 days in the cotton growing season (Mohan et al., 2015) and their survival in various environmental conditions.

Traditionally, in agriculture, chemical pesticides have been extensively used to control whiteflies however, the use of too much pesticide had adversely affected the crop production for example, whiteflies had developed resistance against chemical pesticide (Li et al., 2023) by changing their chemistry as it had also been observed in many other insect and pests (Table 2). Moreover, it had disturbed the environment by harming the beneficial insect (Sawant et al., 2022), disturbing the food chain and also had adverse effects on human and animal health (Ali et al., 2021).

In recent years, advances in biotechnology have led to the availability of plant and insect genome sequences (Satam et al., 2023), molecular marker development (Meena et al., 2023), genetic engineering (Moreto Guaitolini et al., 2024) and genome editing (Boti et al., 2023) provided us an environment-friendly and species-specific solution

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Table 1: Whitefly species and their host crops

Common Name	Scientific Name	Host Crops	References
Babul whitefly	*Acaudaleyrodes rachipora*	Many arid zone forestry tree species	(Sundararaj, 2015)
Citrus blackfly	*Aleurocanthus woglumi*	Lemon and Orange	(Nguyen et al., 2007)
Cardamom whitefly	*Aleuroclava cardamom*	Cardamom	(Sundararaj, 2015)
Rice whitefly	*Aleurocybotus occiduus*	Rice and Maize	(Pokhrel and Thapa, 2011)
Coconut whitefly	*Aleurodicus cocois*	Coconut	(Howard et al., 2001)
Arecanut whitefly	*Aleurocanthus arecae*	Arecanut	(Sundararaj, 2015)
Camellia spiny whitefly	*Aleurocanthus camelliae*	Tea	(Kanmiya et al., 2011)
Betelvine whitefly	*Aleurocanthus rugosa*	Betelvine	(Sundararaj, 2015)
Orange spiny whitefly	*Aleurocanthus spiniferus*	Grape, Peach, Guava, and Citrus	(Yamashita and Hayashida, 2006)
Spiraling whitefly	*Aleurodicus disperses*	Chilies, Tomato, and Mulberry	(Srinivasa, 2000)
Giant whitefly	*Aleurodicus dugesii*	Bamboo and Jasmine	(Martin, 2007)
Olive whitefly	*Aleurolobus olivinus*	Olive	(Abd-Raboou and Ahmed, 2011)
Crown whitefly	*Aleuroplatus coronate*	Oak and Chestnut	(Dreistadt, 2016)
Woolly whitefly	*Aleurothrixus floccosus*	Cassava and Guava	(Kerns et al., 2004)
Anthurium whitefly	*Aleurotulus anthuricola*	Anthurium	(Hata and Hara, 1992)
Banded winged whitefly	*Trialeurodes abutiloneus*	Cotton, Soybean and Tomato	(Malumphy et al., 2010)

of pest management for sustainable agriculture (Zafar et al., 2022; Razzaq et al., 2023). RNA interference (RNAi) is the one of the advanced methods for pest management and had been used for controlling various insect and pests (Yan et al., 2021). Naturally, RNAi mechanism is present in all eukaryotic organisms, including insects, where the degradation of complementary messenger RNA molecules leading to the specific silencing of target genes occurred by triggering the double-strand RNA molecules (Xu et al., 2019). RNAi has highly specific mode of action for pest control by targeting the desired genes that essential for specific pest such as whitefly thus minimizing the off-target effects and environmental impacts. Traditional pest control approaches are not species-specific while RNAi is capable of targeting only whitefly species, sparing beneficial insects and non-target organisms (Mamta and Rajam, 2017; Zafar et al., 2020). Further, due to its minimal residues and lack of accumulation in the food chain, RNAi is considered as an eco-friendly method (Vurro et al., 2019; Hunter & Wintermantel, 2021).

Table 2: Insects with vertical resistance against different pesticides

Common Name	Scientific Name	Resistance Against Insecticides	References
Mosquito	*Aedes albopictus*	Pyrethroid, Fenthion; Glyphosate; Deltamethrin	(Hou et al., 2020)
Cotton Whitefly	*Bemisia tabaci*	Bifenthrin; Thiamethoxam; Acetamiprid; Imidacloprid; Chlorpyrifos	(Qiu et al., 2009; Wang et al., 2011; Yang et al., 2014)
Potato Beetle	*Leptinotarsa decemlineata*	Neonicotinoid	(Xiong ManHui et al., 2010)
Pink Bollworm	*Pectinophora americana*	Decamethrin	(Zhao et al., 1995)
Fall Armyworms	*Spodoptera frugiperda*	Indoxacarb	(Hafeez et al., 2021, 2022)
Khapra Beetle	*Trogoderma granarium*	Phosphine	(Siddiqui et al., 2023)
Melon Thrips	*Thrips palmi*	Organochlorine; Organophosphorus; Pyrethroids	(Immaraju et al., 1992; Zhao et al., 1995; Broadbent and Pree, 1997)
Oriental fruit fly	*Bactrocera dorsalis*	Beta-cypermethrin, Cyhalothrin	(Wang et al., 2011)
Rice water weevil	*Lissorhoptrus oryzophilus*	Chlorphenamide	(Liu et al., 2018)
Western flower thrips	*Frankliniella occidentalis*	Spinosad	(Wang et al., 2014)

RNAi delivery in plant is a challenging task due to the strong cell wall of the plants, being the entry point and acting as infiltration barrier. (Zhang et al., 2024). The delivery is also influenced by other complex cellular structures including, plant tissue and growth stages (Nogrady, 2019; Ali Zaidi et al, 2023; Lv et al., 2024). Moreover, the innate immune system of plants is triggered with the delivery of RNAi molecules which reduces its efficiency. To overcome these challenges, the integration of RNAi with nanoparticle delivery systems is one of the best options to enhance its efficiency. RNAi molecules delivered with nanoparticles are more stable, protected from degradation and easily taken up by targeting organisms (Mujtaba et al., 2021) (Fig. 1). Different types of nanoparticles such as liposomes, polymeric and inorganic nanoparticles can transfer RNAi molecules into populations of whitefly by foliar spray, root drenches and injected method (Arjunan et al., 2024).

This review highlights the current knowledge and advances of RNAi technology integrating with a nanoparticle delivery system, to improve agricultural pest control practices for sustainable and environmentally friendly solutions.

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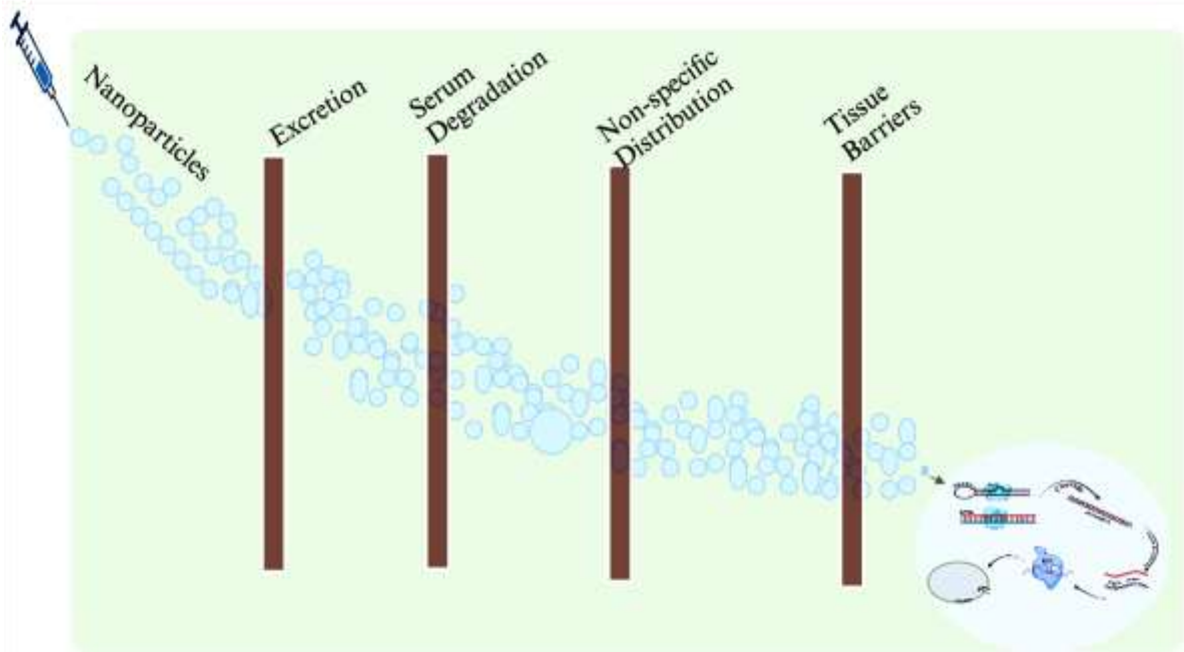

Fig. 1: RNAi molecules delivery via Nanoparticles.

2. Whitefly Biology and RNAi Mechanism

2.1. Life Cycle of Whitefly

Whitefly (*Bemisia tabaci*) go through six stages of development: the egg, the larval instars one, two, three, and four, and the adults (Fig. 2). The eggs are frequently laid in circles (elliptical shape). The young larvae are called crawlers because they have fully formed legs and antennae when they hatch (Perring et al., 2018). They spend several hours searching for a good spot on the leaf to feed after hatching. They stay there until the larval development process start. The legs and the antennae are reduced to one or two segments and become invisible during larval development's second and third stages. The insects finally become flatter and fatter, and its cuticle hardens during the fourth stage of larval development (Saurabh et al., 2021).

The length of the hairs on the leaf determines the length of the hairs on the insect. Longer hairs on the leaf lead to longer hairs on the insect. In another way, we can say that the larva adjusts itself to the leaf's structure. On highly hairy leaves, the larva may occasionally become abnormal as the stiff hairs obstruct the growth (Truman, 2019). During the fourth larval instar, when the pupa development starts, the adult whitefly's red eyes become visible. The easiest stage to differentiate between the various species of whiteflies is pupal; the pupa splits along pre-existing seams on the upper surface to form a T-shaped opening. When whiteflies emerge, they have two pairs of transparent wings. Later, its body and wings are covered in a white waxy powder that gives the wings a distinctive appearance (Kaviyarasu et al., 2017). The undersides of immature leaves are the place where adult whiteflies lay their eggs.

2.2. Mode of Damage

Whitefly (*Bemisia tabaci*) breeds throughout the year and all the developmental stages have been seen overlapping (Sadhana et al., 2024). They damaged the plants in different ways like, the adults suck the leaf sap from phloem tissue by attaching on the lower surface of leaves. They inject toxic saliva into the plants that alters the normal physiological processes and results in plant disorder (Fenemore, 2006). They also produce enormous amount of honeydew and throw it on plants parts. This surgery and sticky material act as an excellent medium for development of sooty mold, which besides giving a sticky black appearance to the plants, interferes in the normal process of photosynthesis (Wang et al., 2017). Whitefly (*Bemisia tabaci*) alone is responsible for the transmission of about 50 viral diseases on the different plants including one of the most destructive cotton leaf curl viruses (CLCuV) (Pan et al., 2018).

2.3. RNA Interference Mechanisms

In many organisms, including whiteflies, there is a powerful and evolutionarily conserved mechanism for gene regulation known as RNA interference (RNAi) (Silver et al., 2021; Niu et al., 2024; Ortolá & Daròs, 2024). RNAi molecules work in two ways: double-stranded RNA (dsRNA) molecules and shorter interfering RNA (siRNA) molecules (Iracane et al., 2024). Through, the RNAi pathway, both kinds of molecules are effective in silencing genes. The dsRNA molecules had targeted entire gene sequences or particular regions of interest. Small RNA molecules, such as microRNA (miRNA) and small interfering RNA (siRNA), guide the RNA-induced silencing complex (RISC) to complementary mRNA molecules, facilitating this process (Sioud, 2021). The Dicer enzyme divides the double-stranded RNA (dsRNA) molecules into siRNA particles. dsRNA are generally 21-23 nucleotides long at the time of entrance into cells (Paturi & Deshmukh, 2021). When mRNA molecules are loaded into an RNA-induced silencing complex (RISC), siRNAs serve as a guide for recognizing sites and attaching them. Once attached, the RISC helps the specific degradation of mRNA transcripts, thereby suppressing the expression of the corresponding gene (Fig. 3) (Mikhed et al., 2015).

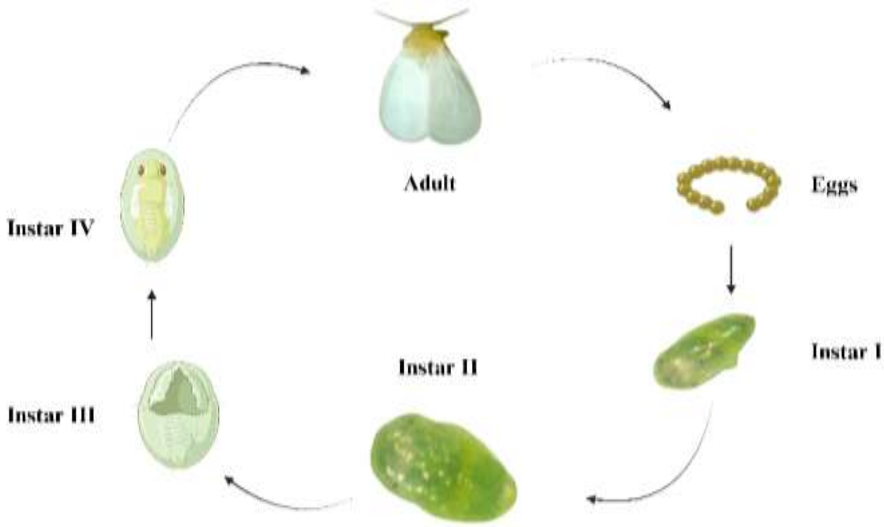

Fig. 2: Life Cycle of Whitefly.

2.4. RNAi a Tool to Control Whitefly

The fast reproduction cycle of whitefly lead to development of resistance against the available chemical pesticides (Table 2). RNAi is one of the effective methods for managing the whitefly population due to its specificity and potency (Shelby et al., 2020). For instance, targeting a crucial gene *V-ATPase* through RNAi in transgenic tobacco resulted in the mortality of whiteflies population (Malik et al., 2016). Neural signaling pathway of whiteflies has been interrupted by targeting the (Acetylcholinesterase) *AChE* genes (Olivera et al., 2003). Growth and development of whiteflies population had been prohibited by targeting (*Ecdysone Receptor*) *EcR* gene (Schwedes et al., 2011; Schwedes and Carney, 2012). RNAi obstructs the growth and survival of whiteflies by selectively targeting genes critical for their immune response metabolism and reproductive processes (Grover et al., 2019). The doubled-standard RNA (dsRNA) molecules introduced into the whitefly cells. These dsRNA molecules are specially designed for target genes, essential for the survival, development, and reproduction of whiteflies (Suhag et al., 2021).

RNAi works better than traditional chemical pesticides by specifically targeting the desired genes in pests, minimizing off-target and non-residual effects in crop plants (Table 3). Additionally, they are easy to design and target multiple genes at once (Traber and Yu, 2023). There are a few disadvantages, including variable efficiency, possible off-target effects, and the delivery to the particular cells. The efficiency and durability of RNAi-mediated molecules can be increased by using long dsRNA constructs that target multiple genes at once (Sharma et al., 2023). A variety of bioinformatics tools and procedures are available to help create siRNAs that are efficient and target-specific as possible. Nucleotide mismatches (Isazadeh et al., 2023) and chemical modification (Li et al., 2024) are used to improve siRNA stability and reduce off-target effects.

Table 3: Use of RNAi against different insects and pest

Sr. No.	Name	Species	Crops	Target Genes	References
1	Western corn rootworm	*Diabrotica v. virgifera*	*Zea mays*	*V-ATPase*	(Li et al., 2015)
2	Colorado potato beetle	*Leptinotarsa decemlimeata*	*Solanum tuberosum*	*Shrub*	(Zhang et al., 2015)
3	American bollworm	*Helocoverpa armigera*	*Arabidopsis thaliana*	*HaAk*	(Liu et al., 2015)
4	Green peach aphid	*Myzus persicae*	*Arabidopsis thaliana*	*MpC001, Rack1*	(Pitino et al., 2011)
5	Whitefly	*Bemisia tabaci*	*Nicotiana rustica*	*V-ATPase*	(Thakur et al., 2014)

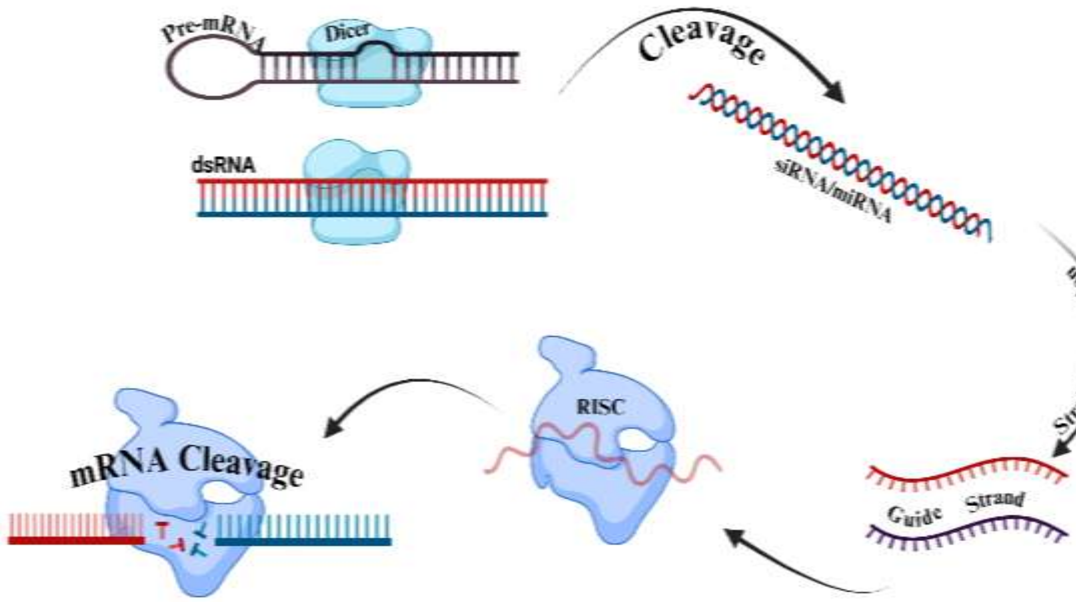

Fig. 3: RNAi mechanism.

2.4.1. Factors Affecting RNAi Efficiency and Delivery: *RNAi* delivery is affected by many factors that hinder the efficiency of the dsRNA uptake and systemic silencing spread in different insects (Zhu and Palli, 2020; Zhang et al., 2023). The selection of target genes must be done very carefully and efficiently, as the genes may have different mechanisms and respond differently to RNAi. More than 150 RNAi experimental results from RNAi of lepidopterans involving 130 genes showed that only 38% were silent at a reasonable level, while 48% failed to be silenced, and 14% were silenced at insufficient levels (Terenius et al., 2011). The design of the dsRNA decides which gene will be silenced; however, off-target effects can occur if siRNAs share sequence similarities with undesired genes. For instance, due to a significant degree of nucleotide similarity between the *Ecdysone Receptor* (*ECR*) genes of *Helicoperva armigera* and *Spodoptera frugiperda* the tobacco plants expressing *HaEcR* dsRNA showed enhanced resistance to *Spodoptera frugiperda* as well (Zhu et al., 2012). This indicated that a single RNAi construct can suppress two or more genes crucial for insects' pests at once, although there is a potential for non-target insect damage and biosafety concerns.

The length of the dsRNA fragments plays a crucial role in the effectiveness of molecular uptake in insects, which is directly involved in the success of target gene silencing. In most of the RNAi experiments, the insects are fed with long dsRNAs (Huvenne and Smagghe, 2010). Some experiments showed that long dsRNAs are more efficiently up taken than siRNAs (Saleh et al., 2006; Bolognesi et al., 2012). This may be due to the fact that a long dsRNA, with 100% match of the target mRNA, after processing into siRNA it had provided a greater diversity of siRNAs available to cause specific suppression of target gene and increase the desired effect (Ali Zaidi et al., 2023).

Moreover, the RNAi stability (Abosalha et al., 2024), formulation (Wang, 2020) and host immune response (Qi et al., 2024) are other limitations of RNAi delivery. RNAi integration with nanoparticle delivery system is safe and secure method which protected dsRNAs from degradation and released it in a controlled manner into plant cells.

2.4.2. Nanoparticles and its types: Nanoparticles are wide class of materials that include particulate substances (Khan et al., 2019), those have one dimension less than 100 nm (Mirzajani et al., 2024). Depending on the overall shape these materials can be zero, one, two or three dimensional (Roy et al., 2024).

On the basis of mode of application, the nanoparticles are divided into different types including organic nanoparticles (Liposomes and Polymeric) and inorganic nanoparticles (Ijaz et al., 2020). Liposome and polymeric nanoparticles are the most adaptable (Date et al., 2007). Liposomes are lipid-based substances that look like vacuoles. The size of these nanoparticles ranges from 100 to 800nm. These have spherical structures and amphiphilic in nature. The cost of manufacturing of liposomes is very high because of lipid leakage. The production of liposomes requires extensive testing. Biodegradability is one of the important benefits of using liposomes which makes them compatible with harmful and nontoxic pigments in the body (Panahi et al., 2017).

Polymeric nanoparticles are solid colloidal particles with a size range of 10–1000 nm, and are made of biodegradable and biocompatible polymers (Yadav et al., 2019). When they reached the target organ, their outer part

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gets dissolved and they showed the therapeutic action (Beach et al., 2024). Biodegradable polymers such as chitosan and polylactic-glycolic acid (PLGA) are used to form polymeric nanoparticles (Daniel, 2021). These nanoparticles can increase the survival and give protection to RNAi molecules.

In agricultural applications, chitosan has emerged as one of the promising natural polymers for the successful delivery of agrochemicals, enhancing the stability of the loaded active drug (Kashyap et al., 2015). It has the ability to chelate inorganic compounds for controlled delivery in plants (Saharan et al., 2015). Encapsulation of agrochemicals in chitosan-based nanoparticles has the many advantages including the ability of chitosan to absorb to plant surfaces prolongs the contact time between the agrochemical and the plant absorptive surface (e.g., epidermis of stems or leaves), chitosan itself plays an important role in plant defense against pathogens, chitosan might stimulate plant development, inducing biotic and abiotic stress responses making plants more tolerant to pathogens (Malerba and Cerana, 2016; Khan et al., 2017; Pascoli et al., 2018).

Inorganic elements could also be a good source of nanoparticles. A 20-nm gold (Au), platinum (Pt), silver (Ag_2), and palladium (Pd) nanoparticles have characteristic wine red color, yellowish gray, black, and dark black colors, respectively (Dreaden et al., 2012). Inorganic nanoparticles usually form a three-dimensional structure, making a covalent bond with the metals (Bronstein and Shifrina, 2011). These nanoparticles can be functionalized with specific ligands or surfaces that changes their interaction with insect cells and increase RNAi absorption (Hanamasagar et al., 2024; Ye et al., 2024; Saini & Sharma, 2025).

2.4.3. Advantages of Nanoparticle Application: Nanoparticles are used for plant growth regulation (Tripathi et al., 2022; Sarkar et al., 2022; Karabulut, 2024), weed control (Carvalho et al., 2023; Khan et al., 2023; Rajpal et al., 2024) and insect control (Cáceres et al., 2019; Nitnavare et al., 2021; Abenaim & Conti, 2023; Agredo-Gomez et al., 2024) (Fig. 4). Integrating RNAi with nanoparticles for whitefly control offers several advantages. The RNAi molecules are stable and long-lasting because they are protected from environmental nucleases. Nanoparticles facilitate RNAi in transportation and absorption into whitefly cells. The effect of RNAi-based approaches has been increased in the presence of nanoparticles by uptake in specific tissues or cells within the whitefly population. The integration of RNAi with nanoparticles has no harmful effects on non-target organisms or the environment.

2.4.4. Integration of RNAi with Nanoparticle Delivery Systems: Integrating RNAi with nanoparticle delivery can stabilize RNAi molecules from denaturation and increase their absorption rate by insects. Previously liposomes (Qi et al., 2024), polymeric nanoparticles (Friesen and Blakney, 2024) and inorganic nanoparticles (Kandasamy and Maity, 2024) are used in nanoparticle formulations for RNAi delivery for insect control.

The choice of proper materials to formulate and encapsulate RNAi is necessary to protect it from degradation, thereby enhancing its efficiency and stability. Lipid-based NPs (LNPs) have been used to deliver therapeutic RNAi (Rietwyk and Peer, 2017; Witzigmann et al, 2020). The majority of the LNPs consist of four main components that include an ionizable lipid, a phospholipid, cholesterol and a poly (ethylene glycol)- conjugated lipid (PEG-lipid) (Rietwyk and Peer, 2017). The ionizable lipid bound with the negatively charged RNAi through electrostatic interactions (Patel et al., 2020). LNPs are prepared by dissolving lipid compositions in water miscible organic solvents like ethanol or acetone, whereas the RNAi is dissolved in aqueous solution, static mixing and micro fluid method has been used for the spontaneous formation of RNAi (Wei et al., 2020).

Polymer NPs had provide the precise control over physicochemical properties of plant using bottom-up chemical approaches, provides a significant advantage over the lipid-based systems (Kim et al., 2017). The RNAi encapsulation involved two main interactions, including electrostatic and hydrophobic. Hydrophobic ionic polymer, such as PLGA, has been encapsulated the RNA through the double-emulsion method to load the siRNA for protecting it from exogenous factors (Cun et al., 2011). The RNAi residency and protection efficiency has been determined by hydrophilic/hydrophobic co-polymer (Li et al., 2019). With the help of intercalation method, siRNA-loaded nanocarriers enhanced siRNA protection from physiological pH (Zhou et al., 2016).

NPs based RNAi have efficient and precise targeting capability due to their ultrahigh sensitivity (Woythe et al., 2021). NPs based dsRNA has been prevented from internalization, enzymatic degradation and undesirable processing by plants RNAi machinery (Šečić and Kogel, 2021).

Spray Induced Gene Silencing (SIGS) efficacy has been improved by encapsulated dsRNA in nanoparticles by taken up through endocytosis into plant cells (Wytinck et al., 2020). RNAi encapsulation in nanoparticles such as chitosan (Gurusamy et al., 2020; Kolge et al., 2023), liposomes (Castellanos et al., 2019), clay nanosheets (Jain et al., 2022) and layered double hydroxide (LDH) (Worrall et al., 2019) has been resulted physical deformation, retarded larval growth and increased mortality of insects. Nanoparticles has prevented dsRNA from salivary degradation and degradation from extreme pH condition (Dhandapani et al., 2021).

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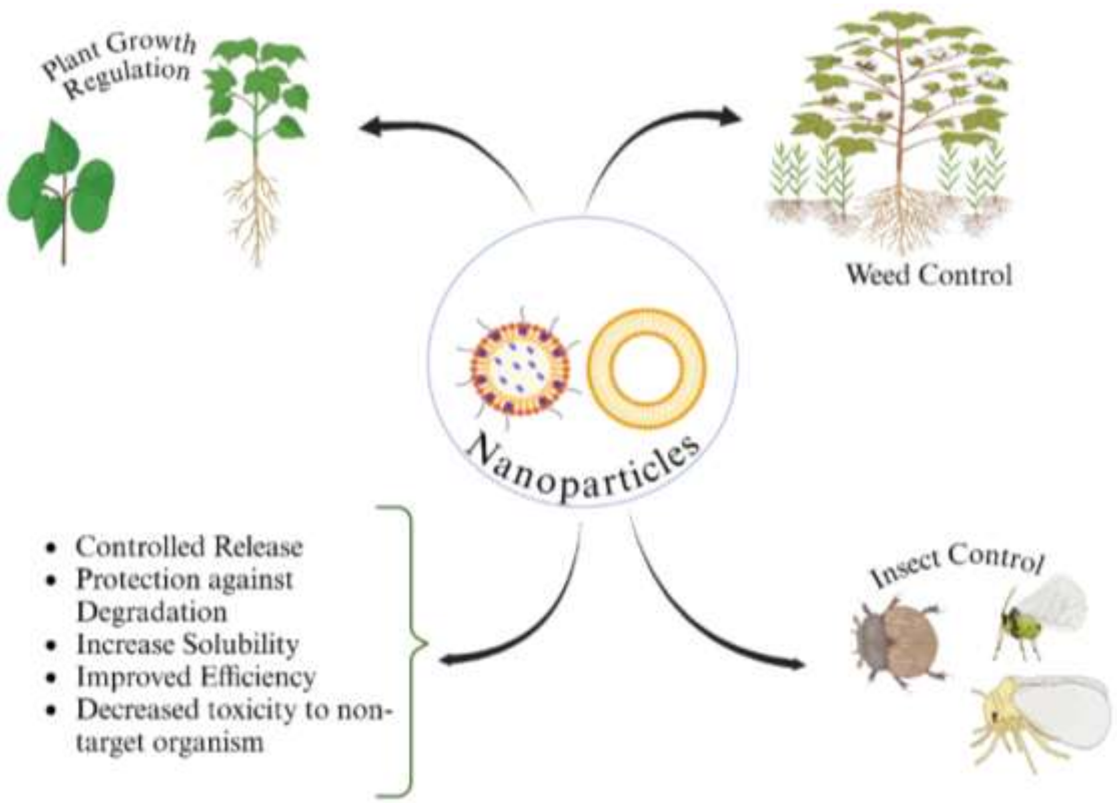

Fig. 4: Advantages of Nanoparticles application.

3. FUTURE PROSPECTS

Future research is needed to improve RNAi delivery system for efficient whitefly control, exploring the novel nanoparticles and their formulation method by developing the RNA interference (RNAi) approaches integrating with nanoparticle delivery systems, whitefly control research has progressed and providing new avenues for investigation. In future significant advancements will achieve to manage the whitefly population. With the help of biotechnology, highly throughput sequencing methods and bioinformatics tools like marker development and mapping association, researchers used to find out new targeting gene in whiteflies population which are helpful in their survival and important for their biological functioning. Researchers are still working on novel strategies for RNAi molecules delivery, such as cell-penetrating peptides, viral vectors, exosomes and via nanoparticles. These advancements open the door to developing RNAi molecules that are more objectively specific and have a stronger effect on whiteflies.

Integrating RNAi-based strategies with other pest management tools, such as biological control agents' cultural techniques and host plant resistance, may result in long-term and sustainable whitefly control. Our focus is enhancing the positive effect of RNAi based approaches integrating with nanoparticles by using integrated pest management (IPM) strategies. These advancements may reduce agricultural losses worldwide and minimizing the negative impact on environment. To ensure the safety and sustainability of these technologies, another research at the environmental risks related to RNA interference-based approaches integrating with nanoparticles for whitefly control is required. In summary new developments in RNA interference (RNAi) technology and nanoparticle delivery systems have allowed for the development of effective and long-lasting whitefly control methods. By applying these developments and looking into new collaboration and integration opportunities scientists can keep developing environmentally friendly and sustainable solution to manage whitefly populations and their impact on global agriculture.

4. CONCLUSION

RNA interference-based approaches, integrated with a nanoparticle delivery system, are beneficial in controlling whiteflies and promoting sustainable agriculture worldwide. Compared RNAi-based approaches with traditional chemical pesticides are precise and environmentally friendly. It is possible to inhibit the essential biological functions of whiteflies without endangering other organisms and the ecosystem. RNAi-based strategies that target specific tissues or cells increase the absorption of RNAi molecules in whitefly populations and prevent the degradation of the

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trigger. However, problems such as variation in suitability and off-target impacts need to be addressed by RNAi-based whitefly control techniques. Further research is needed to mitigate environmental hazards and enhance the suitability of developing RNAi molecule systems and their integration with nanoparticle strategies. Furthermore, it is crucial to create RNAi-based strategies for managing whiteflies and guaranteeing their safe and long-term use in agricultural systems using interdisciplinary cooperation and knowledge exchange between scientists, policymakers, and interested parties. The resolution of vermin problems needs to be addressed with rapid innovation, which means that innovative work costs are essential to leveraging nanoparticle delivery system and RNAi whitefly control. We can develop procedures that promote feasible agriculture, ensure global food security, and protect the health of our environments for future generations by working together.

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