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REVIEW ARTICLE

Green guardians: Harnessing biopesticides for sustainable vegetable pest management

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Abstract

Insect pests pose significant challenges to vegetable crops, causing not only economic losses but also compromising the quality of our food. Shockingly, up to 20 % of globally produced goods fall victim to these insidious invaders. While chemical insecticides have historically bolstered food production, they come with notable drawbacks, including handling risks, residue concerns and negative impacts on non-target species and the environment. Though they have not yet completely replaced chemical insecticides, biopesticides are becoming key in reducing pesticide overuse and promoting safer, residue-free food and environments. Derived from plants and microorganisms, biopesticides offer a safer alternative, ranging from plant extracts to microbial agents such as bacteria, fungi, viruses and nematodes. Additionally, insect hormones and semiochemicals, along with silica-based mineral products like activated clay and rice husk, contribute to eco-friendly pest control solutions. Cutting-edge nano biopesticides also deliver unparalleled pest control with precision targeting and excellent environmental credentials. In this comprehensive exploration, we delve deep into the myriad forms of biopesticides, their commercial availability, modes of action and the advantages and disadvantages in vegetable pest management. Crucially, we illuminate the path toward integrating biopesticides into holistic pest management strategies, which can lead to healthier crops, increased yields and more sustainable agricultural practices. By emphasizing biopesticides, we can promote environmental safety and support a greener future in agriculture.

Keywords

vegetables; insect pests; biopesticides; sustainable management

Introduction

Agricultural pests, including weeds, arthropods, mollusks, plant pathogens and vertebrates, significantly reduce crop output and quality. The rise in pest-related agricultural losses has resulted in a 40 % decrease in potential world crop yields. Insect pests alone contribute to an estimated 10.8 % of global agricultural losses, leading to an annual decline in agricultural output valued at approximately $470 billion (1). Vegetable cultivation faces significant challenges from insect infestations, including fruit flies, diamondback moths, mites, chili thrips, brinjal shoots and fruit borers and tomato fruit borers. Insect pests are responsible for 15-20 % of productivity losses in India's primary food and cash crops (2). These figures underscore the urgent need to adopt sustainable pest management practices and highlight the importance of eco-friendly alternatives to conventional pesticides in the agricultural sector.

Biopesticides offer numerous benefits: they are cost -effective, environmentally friendly, employ a sustainable and targeted mode of action, leave behind no residues and do not contribute to greenhouse gas emissions. However, despite their environmental advantages, biopesticides also face several limitations. They often have a short shelf life, degrade quickly under unfavourable conditions and may exhibit inconsistent efficacy in the field. Their slower action and narrow pest-specific focus can limit their use in large-scale agriculture, where rapid and broad-spectrum control is often necessary (3). Biopesticides work through mechanisms such as inhibiting and destroying the plasma membranes of pathogens and pests as well as interfering with protein translation. As a result, farmers increasingly rely on chemical pesticides to enhance crop production by managing diseases and pests, which are often composed of host-specific polymers. However, the overuse of these pesticides poses significant threats to aquatic ecosystems, harming fish and other marine life.

In contrast to synthetic pesticides, biopesticides are highly precise in targeting specific hosts, have a shorter shelf life are less persistent in soil and the environment and are made from sustainable raw materials, despite several limitations that have affected their acceptability and commercialization (4). Over the past few decades, the development of affordable and effective management options for pests and pathogens has greatly benefited from the exploration of medicinal plants, antimicrobial peptides, natural products and essential oils (5).

Despite advancements in biological pest management strategies and the growing recognition of biopesticides as eco-friendly alternatives to synthetic pesticides, there remains a significant gap in their widespread adoption and commercialization. Key challenges include the fragmented and underdeveloped research on integrating biopesticides with other biological control methods, such as the synergistic use of entomopathogens, botanicals and nano-biopesticides. Additionally, further investigation is needed into innovative delivery systems, including nano-encapsulation and other formulations, to enhance the stability, efficacy and marketability of biopesticides. Addressing these challenges is crucial for promoting the effective use of biopesticides in sustainable agriculture.

The main objective of the current study is to understand the latest advancements in sustainable vegetable pest management, with a particular emphasis on novel biological methods. These methods include entomopathogens, botanicals, insect growth regulators, semiochemicals, inert ash materials and nano-biopesticides to promote sustainable farming (Fig. 1). This study involves examining the various forms of biopesticides, their commercial availability, mechanisms of action and their respective advantages and disadvantages.

2. Microbial pesticides

Microbial pesticides are compounds used to manage pests and are derived from microorganisms, including bacteria, fungi, protozoa, viruses and algae (6).

2.1. Biopesticides derived from bacteria

Bacillus spp. are extensively used as biological control agents in agriculture, functioning through both direct and indirect mechanisms. The direct processes include nutrient supply, hormone level modulation and the

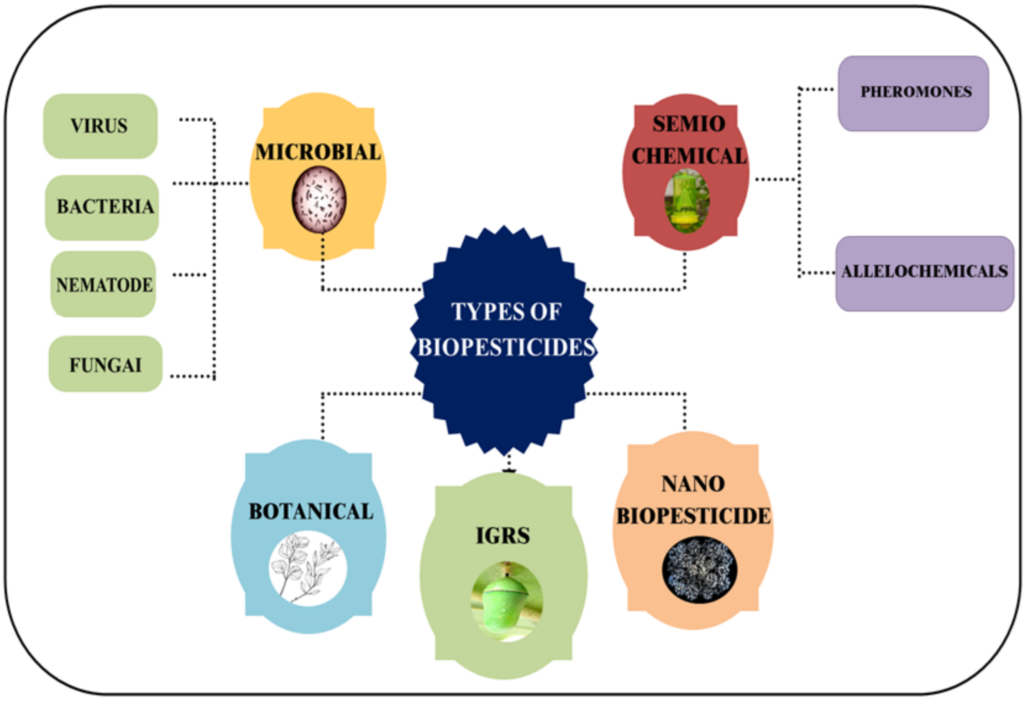


Fig. 1. Biopesticides in insect pest management: This figure represents a flowchart depicting the types of biopesticides. The category includes Microbial (viruses, bacteria, nematodes and fungi), botanicals, semio-chemicals (pheromones and allelochemicals), nano biopesticides and IGRs. Each category is illustrated with a corresponding image that represents its mechanism or source.

secretion of chemical compounds to combat plant infections. Indirect strategies involve inducing resistance and enhancing plant growth. *Bacillus* spp. contribute to plant development by supplying nutrients, modulating hormones, providing resistance to pathogens and promoting overall plant growth (7, 8). *Bacillus*-based biopesticides play a crucial role in managing agricultural pests while simultaneously improving soil quality and health as well as enhancing overall crop growth, yield and quality (9). Commercial bacterial biopesticides products have been widely utilized in the management of vegetable pests (Table 1).

2.1.1. *Bacillus thuringiensis* (Bt) as an effective microbial control agent

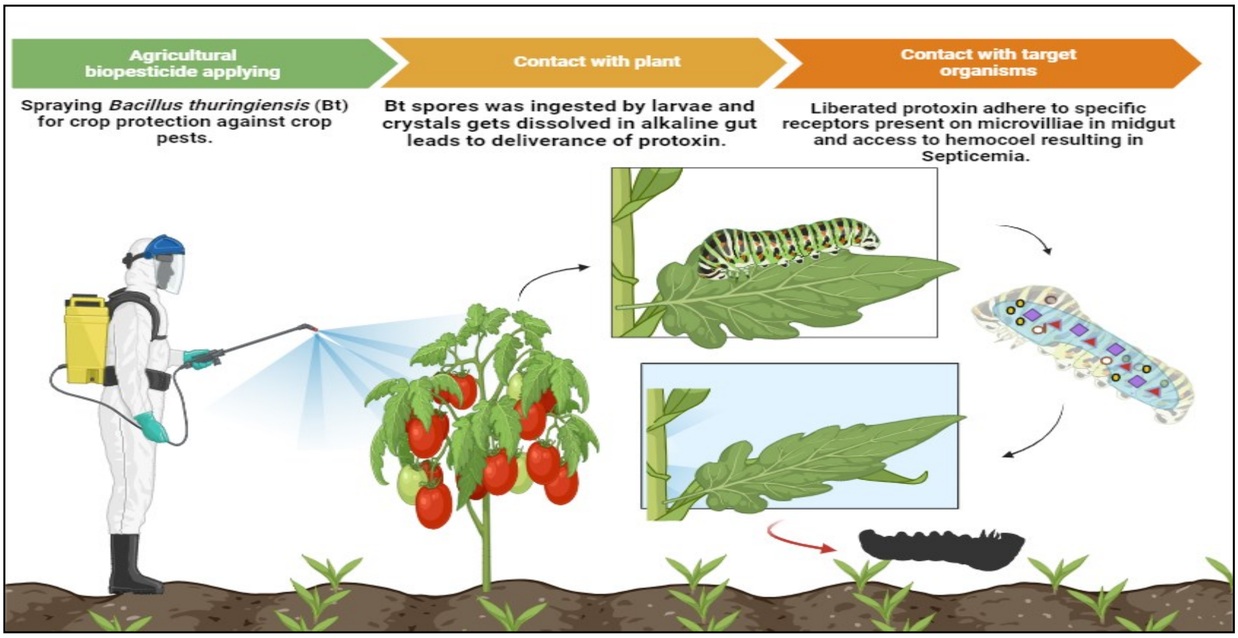
Bacillus thuringiensis (Bt), a gram-positive bacterium, is a well-known bacterial insecticide that has been commercially developed for pest management. Bt acts as an insecticide through the production of poisonous parasporal crystals and endospores. When ingested by insects, these substances dissolve in the alkaline environment of the midgut, releasing delta-endotoxin, a protein that is lethal to insects (10), as shown in Fig. 2. Bt is the most recognized bacterial insecticide and has been developed into various commercial products (11, 12). Business firms and government research institutes collaborate to ensure the widespread availability of Bt products in India. Indigenous Bt isolates, such as DORBt-1, DORBt-5, PDBCBT1 and NBAIIBTG4, have been developed and commercialized using solid-state and liquid fermentation technologies (13). The effectiveness of liquid Bt formulations has been demonstrated in controlling pests like *H. armigera* in pigeon peas and sunflowers across various regions of India (14). Researchers have isolated diverse Bt strains from different ecological niches in India, which exhibit promising insecticidal activity against various pests (15, 16).

2.2. Biopesticides derived from fungi

Entomopathogenic fungi (EPF) play a crucial role in global biological pest control. Mycoinsecticides operate through 6 stages of action: attachment, germination, penetration, invasion, reproduction and host death (17), as shown in Fig. 3.

Table 1. Commercial bacterial products used in insect pest management.

No.	Entomopathogenic bacteria	Commercial name	Target pest	Reference
1.	*Bacillus sphaericus*	VectoLex, VectoMax	*Melolontha*	(92)
2.	*Bacillus thuringiensis* var. *israelensis*	Tacibio, Vectobac®, Teknar®, Bactimos®	*Melolontha melolontha*	(92)
3.	*Bacillus thuringiensis* var. *Kurstaki*	Dipel®, Javelin®,Thuricide®, Worm Attack®, Killer®, Biobit	*Plutella xylostella* *Helicoverpa armigera*	(93)
4.	*Burkholderia* spp.	Yorker, Paceilomyces, Paecil, Pacihit, Bio-Nematon	*Tetranychus urticae*	(94)
			Riptortus pedestris *Spodoptera exigua*	(95)
5.	*Streptomyces* spp.	Neomycin, streptomycin, cypemycin, grisemycin, bottromycins and chloramphenicol	*Spodoptera litura*	(96)



Spraying *Bacillus thuringiensis* (Bt) for crop protection against crop pests.

Bt spores was ingested by larvae and crystals gets dissolved in alkaline gut leads to deliverance of protoxin.

Liberated protoxin adhere to specific receptors present on microvilliae in midgut and access to hemocoel resulting in Septicemia.

Fig. 2. Mode of action of bacterial biopesticides: This figure illustrates the mode of action of *Bacillus thuringiensis* (Bt) as a biopesticide. This process demonstrates how Bt targets pests while being safe for crops.

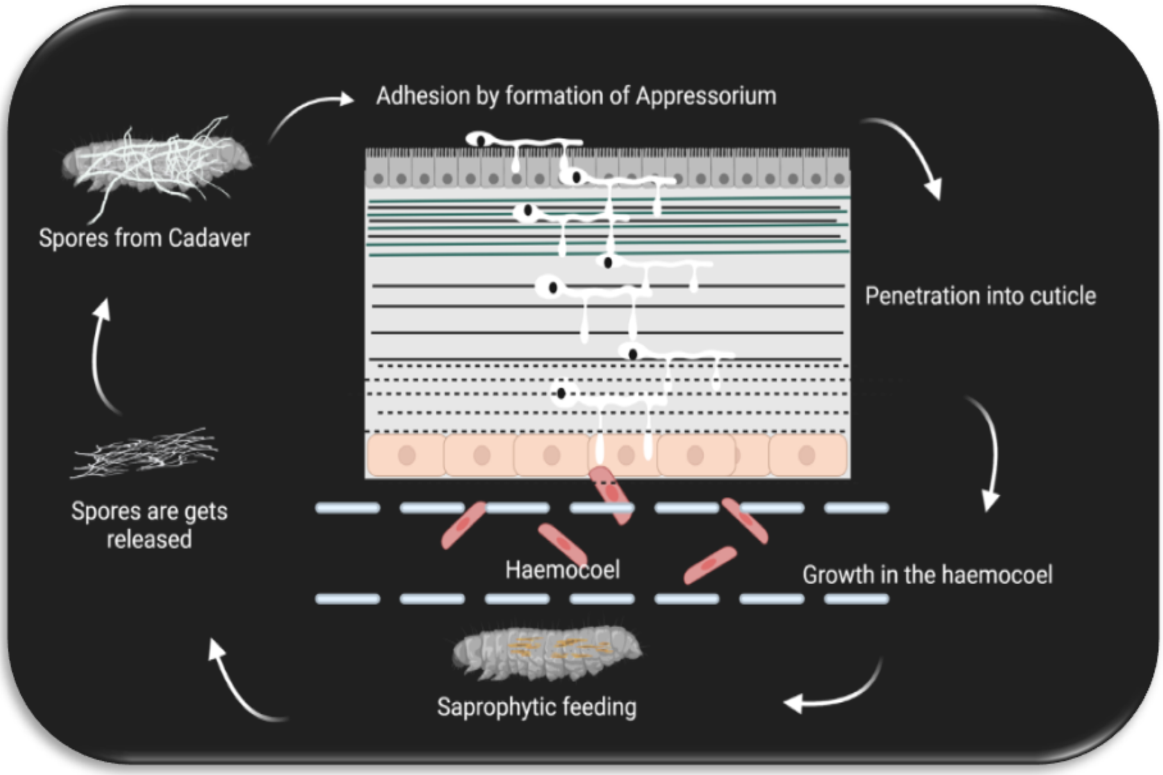


Fig. 3. Mode of action of entomopathogenic fungi: This figure depicts the infection process of fungal biopesticides targeting insect pests. The process illustrates how fungal biopesticides control pest populations through infection and reproduction.

2.2.1. Types of mycoinsecticides

2.2.1.1. *Beauveria* spp.

Studies have shown that commercial formulations of *B. bassiana*-based mycoinsecticides are robust and effective against lepidopterans. *B. bassiana*, which does not favor any specific host has proven effective in crops such as maize, coffee, beans, cabbage, potatoes and tomatoes. Scanning electron microscopy (SEM) investigations on greasy cutworm larvae demonstrated that *B. bassiana* infected them (18). The colonization of *B. bassiana* as an endophyte in natural tomato plants resulted in significant mortality of whiteflies, *Bemisia tabaci* (19). Furthermore, *B. bassiana* has been observed to be effective against various aphid species, including *Lipaphis erysimi*, *Rhopalosiphum padi*, *Brevicoryne brassicae* and *Schizaphis graminum* at concentrations ranging from 10^6 to 10^8 spores/mL (20).

2.2.1.2. *Verticillium* spp.

Lecanicillium attenuatum has been found to be effective against *Plutella xylostella* (21). Certain variants of *L. psalliotae* have been discovered to be harmful to insect pests, such as thrips, when associated with the cardamom plant. Following insect feeding and injury, *L. psalliotae* was observed to react to the volatile compounds generated by cardamom (22). Additionally, some *Lecanicillium* isolates demonstrated reduced efficacy against tomato whiteflies at higher temperatures, highlighting the need to select isolates that are resistant to environmental stressors before commercial formulation (23).

2.2.1.3. *Metarhizium* spp.

Metarhizium exhibits a narrower host range compared to *Beauveria*, being able to infect approximately 200 insect species across seven orders. It can be found in gnats, thrips, flies, root weevils and beetles (24). The effectiveness of the fungus is influenced by various factors, including the timing of conidia application, application temperature, fungus strain, culture medium and application technique (25). Environmental elements such as light, pH, temperature, metal toxicity, nutrient availability and reactive oxygen species (ROS) impact the growth and maturation of *Metarhizium*. Exposure to UV radiation and extreme temperatures has been shown to decrease the pathogenicity of the fungus (26).

The goal of this study was to apply genetic engineering to enhance the method of action of *Metarhizium* (27). Various types of commercial fungal biopesticide products were utilized in the management of insect pests in vegetable crops (Table 2).

2.3. Biopesticides derived from viruses

Several viruses have been approved for insect pest management, with ongoing research aimed at identifying and evaluating novel viruses (28). There are over 60 insecticides on the market based on baculovirus (29). Prior to advancements in molecular biology, baculoviruses were classified into 2 major categories: Nucleopolyhedroviruses (NPVs) and Granuloviruses (GVs), based on the structure of their occlusion bodies (30). NPVs developed for insect pest control include those targeting major caterpillar pests such as *Helicoverpa* spp., which damage cotton and other field crops as well as *Spodoptera* spp., which affect vegetable crops and occasionally *Orgyia* spp. in forest areas (31). NPVs cause infections that eliminate significant pests, including *Spodoptera litura* and *Helicoverpa armigera* (32), with the mode of action of NPVs illustrated in Fig. 4.

Table 2. Commercial fungal products applied in insect pest management.

No	Entomopathogenic fungi	Commercial name	Target pest	Reference
1.	*Beauveria bassiana*	Baeuvesterk, Agritek, B2 Plus, Green Beauveria, Biogaurd	*Thrips tabaci* *Bemisia tabaci*	(97)
			Brevicoryne brassicae *Rhopalosiphum padi*	(98)
			Bemisia tabaci	(84)
			Leucinodes orbonalis	(99)
			Earias vittella	(83)
2.	*Beauveria brongniarti*		*Holotrichia serrata*	(100)
3.	*Verticillium lecanii*	Bio Vertivill, Green Verticill, Verticoz - P	*Lipaphis erysimi*	(101)
			Leucinodes orbonalis	(99)
4.	*Metarhizium anisopliae*	Bio Meta Cure, Green Meta, Plant's Buddy	*Lipaphis erysimi*	(101)
			Melolonthamelolontha	(102)
			Tetranychus urticae	(103)

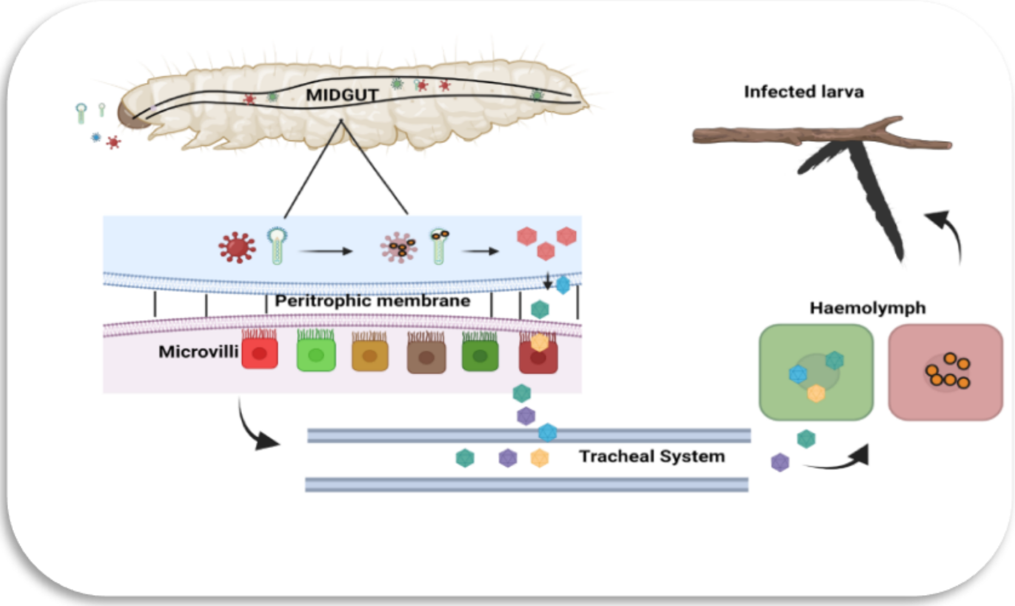


Fig. 4. Mode of action of entomopathogenic viruses: This figure illustrates the infection process of a virus within an insect larva. This process highlights how viral biopesticides target insect larvae.

As for Granuloviruses, the potato tuberworm GV is one of the most commonly used viruses as a microbial biocontrol agent worldwide (33). The diamondback moth, *Plutella xylostella*, has also been effectively controlled using GV (13). Additionally, commercial products containing entomopathogenic viruses for vegetable pest management are listed in Table 3.

2.4. Biopesticides derived from nematodes

The families *Heterorhabditidae* and *Steinernematidae* include the most widely used and effective species of entomopathogenic nematodes (EPNs) (34). These nematodes, such as *Heterorhabditis* spp. and *Steinernema* spp., are associated with symbiotic bacteria from the families *Xenorhabdus* and *Photorhabdus* respectively, which are lethal parasites of many soil-dwelling insect pests (35). The mode of action of EPNs is depicted in Fig. 5. *In vitro* experiments examining the effects of *Steinernema carpocapsae* Mex and *Heterorhabditis indica* LN2 on *Agrotis ipsilon* third instar larvae after 72 h resulted in mortality rates of 80.0 % and 83.3 % respectively. According to a study, *Steinernema thermophilum* was the first species recognized as harmful to lepidopteran eggs (36).

2.5. Botanical pesticides

Botanical pesticides are derived from plants and are used to kill, repel or deter pests (37), as shown in Fig. 6. In addition to their role in plant growth and development, plant secondary metabolites are essential for resistance to both abiotic and biotic stresses. These compounds also play a part in metabolic processes that regulate plant tolerance (38). Most botanical pesticides are applied to control insect pests, which has been the focus of numerous studies. The growing popularity of plant-based insecticides, especially in organic farming, is driven by concerns over chemical pesticides. These concerns include pesticide residues in crop yields, the development of insecticide-resistant pests and the resurgence of previously minor pests becoming major threats (39). Research has shown that EC formulations containing solvent extracts from *Strychnos nux-vomica* L. exhibit oviposition deterrence against *Plutella xylostella* L. Among these formulations, the highest oviposition deterrence was observed in EC formulations containing chloroform extracts from the fruit rind of *S. nux-vomica* L. at a 2 % concentration (40). Various sources of phyto-pesticides and their active ingredients for the effective management of vegetable pests have been listed (Table 4).

Table 3. Commercial viral products utilized in insect pest management.

No.	Entomopathogenic virus	Commercial name	Target pest	Reference
1.	*Nuclear Polyhedrosis Virus*	Sun Bio Hanpv, Heli – cide, Helicop, Spodo - cide	*S. litura*	(104)
			Helicoverpa armigera	(105)
2.	*Granulosis virus*		*Pieris brassicae*	(106)

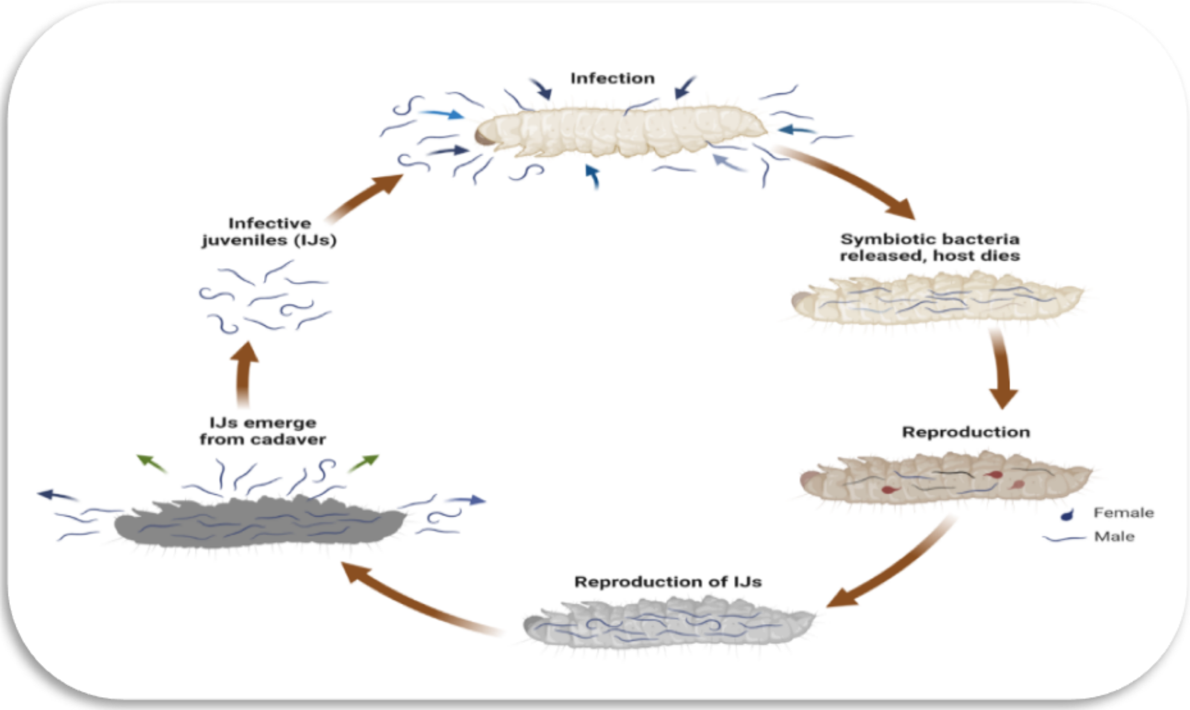


Fig. 5. Mode of action of entomopathogenic nematodes: This figure depicts the life cycle of EPNs, focusing on how they infect and reproduce within insect hosts.

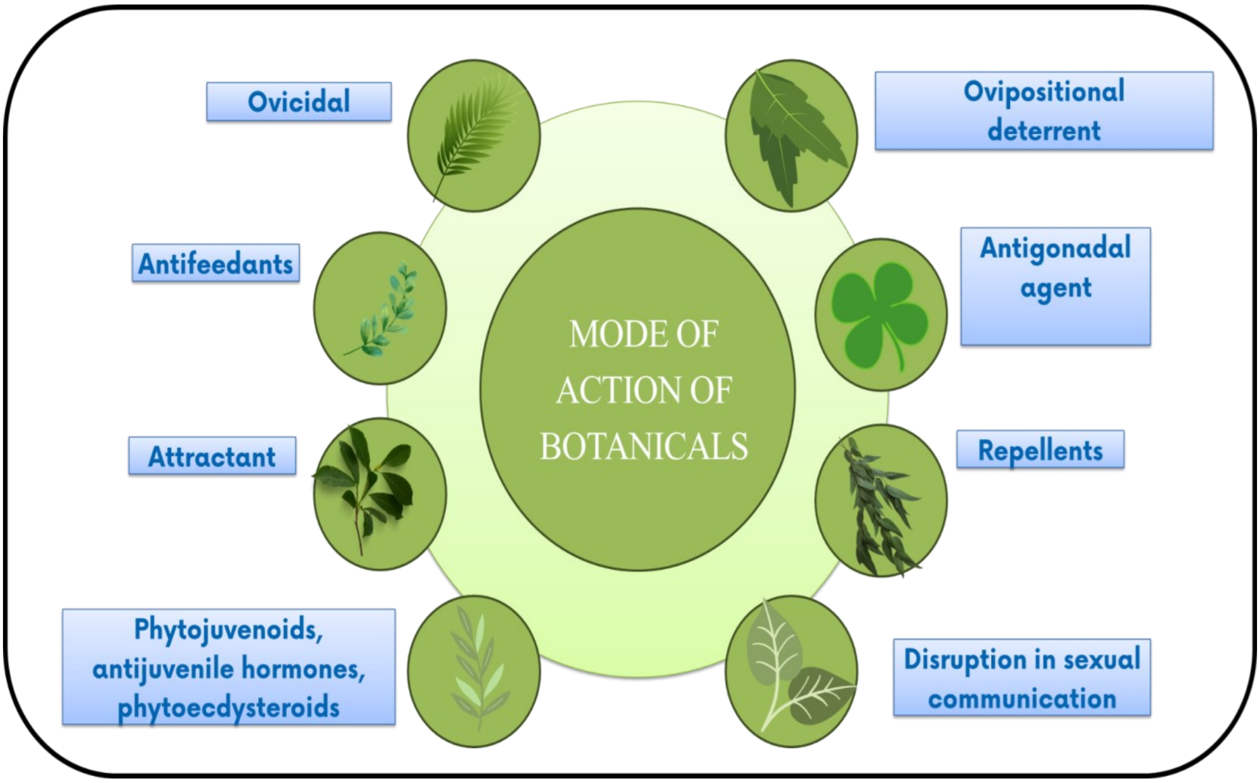


Fig. 6. Mode of action of botanicals: This figure illustrates the mode of action of botanical biopesticides. These mechanisms showcase how botanical compounds can control pest populations through non-toxic, natural means.

Table 4. Source of botanicals with active ingredients comprising insecticidal properties.

No	Scientific name	Common name	Active ingredient	Target pest	Reference
1.	*Justicia adhatoda*	Malabar nut	Salicylic acid, salicylic acid, docosanoic acid, stigmasterol, campesterol, sitosterol and sitosterol-D-glucoside, diterpenoids, ridods and triterpenoids	*Spodoptera litura*	(107)
2.	*Calotropis acia*	Milkweed	Saponins, alkaloids, flavonoids, sugars, terpenoids, phenols, glycosides, tannins, steroids, Cardenolides,	*Lipaphiserysimi, Coccinellaseptempunctata*	(107)
3.	*Ocimumtenuiflorum*	Holy basil	eugenol, ursolic acid, Isothymusin, CA, sinapic acid and Rosmarinic acid	*Aphis* sp., *Tetranychus* spp., *B. tabaci.*	(107)
4.	*Carica papaya*	Papaya	Carpaine, pseudocarpaine, dehydrocarpaine, quercetin 3-(2Grhamnosyl-rutinoside) kaempferol 3-(2G-rhamno-sylrutinoside), quercetin 3-rutinoside, myricetin 3-rhamnoside, kaempferol 3-rutinoside, quercetin, kaempferol	*Spodoptera litura*	(107)
5.	*Azadirachta indica*	Neem	Azadirachtin, nimbin, nimbanene, 6-desacetyl nimbinene, nimbandiol, nimbolide, ascorbic acid, n-hexacosanol	*Aphis* spp., *Tetranychus* spp., *B. tabaci, H. armigera, Meloidogyne incognita*	(37)
6.	*Curcuma longa*	Turmeric	Ar-turmerone and turmerone	*Spodoptera litura*	(108)
7.	*Chromolaena odorata*	Siam weed	Essential oils, Flavonoid aglycones, quercetagetin, kaempferol, acacetin, naringenin, chalcones, quercetin, luteolin, and sinensetin, terpenes and terpenoids, saponin and tannins, organic compound as well as pyrrolizidine, phytoprostane compound, phenolic acids	*Meloidogyne incognita*	(108)
8.	*Derris elliptica*	Derris	Rotenone	*Aphis* spp., *Diabrotica undecimpunctata, Tetranychus urticae*	(108)
9.	*Thymus citriodorus*	Lemon thyme	Rosmarinic acid	*M. incognita, M. javanica*	(108)
10.	*Zingiber officinale*	Ginger	Sesquiterpenes	*B. tabaci, Caliothrips fasciatus*	(108)
11.	*Cymbopogon citratus*	Lemon grass	Citronellal	*Helicoverpa armigera*	(109)

2.6. IGRs as biopesticides

Insect growth regulators are substances that interfere with an insect's ability to grow, develop and undergo metamorphosis. This category also includes synthetic versions of insect hormones such as ecdysoids and juvenoids (41).

2.6.1. Chitin synthesis inhibitors (CSIs)

Chitin synthesis inhibitors (CSIs) are a class of chemicals that disrupt the synthesis of chitin, thereby interfering with the moulting process and killing insects before they reach adulthood. In a study testing four CSIs against okra jassids, their effectiveness in reducing weight, inhibiting growth and development and the mode of entry into the insects' bodies was evaluated. The results showed that, except for chitosan, all selected CSIs were effective in halting the growth and development of jassids, exhibiting both systemic (translaminar) and contact activity (42).

2.6.1.1. Mode of action of CSIs

CSIs significantly inhibit chitin synthesis in embryos, larvae or pupae during critical stages of new cuticle development. This disruption in the essential chitoprotein structure of the insect's exoskeleton severely impairs the moulting process, causing the fragile cuticle to desiccate, ultimately leading to the insect's death (43).

2.6.2. Juvenoids (Juvenile hormone mimics)

One class of insect growth regulators is juvenile hormone-based pesticides, which disrupt the insect's developmental process (44). Juvenoids, a class of chemicals that mimic juvenile hormones, inhibit metamorphosis. Juvenile hormones, produced by neurosecretory cells are byproducts of fatty acid synthesis (45).

2.6.2.1. Mode of action of Juvenoids

Juvenoids are synthetic counterparts of juvenile hormones (JH) and exert an anti-metamorphic effect on insect larvae. Typically, these substances prevent insects from progressing beyond the larval stage, causing additional moults that result in the formation of "super larvae," intermediates between the larval and pupal stages or malformed pupal-adult forms, ultimately leading to death. Juvenoids also act as ovicidal and larvicidal agents, disrupting diapause and preventing insect emergence. Reports suggest that juvenoids can originate from plants, higher animals, bacteria, fungi, yeast and protozoa (41).

2.6.3. Anti-juvenile hormone or precocenes

Juvenoids work by destroying the corpora allata, thus blocking the production of juvenile hormones (JH). When applied to juvenile insect stages, they cause the insects to bypass 1 or 2 larval instars and develop into small, premature adults. These adults die quickly and are incapable of reproduction or oviposition (41).

2.6.3.1. Mode of action of precocenes

The introduction of exogenous juvenile hormone (JH) can counteract the effects of precocenes. Precocenes appear to work by inhibiting the biosynthesis of JH (41).

2.6.4. Ecdysteroids

Moulting hormone (MH), also known as ecdysone, is secreted by the prothoracic glands. In insects, moulting occurs only in the presence of ecdysone. In adult insects, ecdysone levels decline and are eventually eliminated. Synthetic substitutes for ecdysone are available and when applied to insects, they cause the cuticles to rupture, resulting in the insect's death. These substances accelerate development by bypassing several typical processes, leaving the epidermis without a waxy coat or scales. When administered at a concentration of 200 mg/kg, ecdysteroids inhibited feeding in the larvae of *Mamestra brassicae* and *Pieris brassicae*. At a concentration of 100 mg/kg, ecdysteroids inhibited sap-sucking in the adults of *Spiloscelis pandurus*, *D. fulvoniger* and *Dysdercus koenigii* (46).

2.6.4.1. Mode of action of ecdysteroids

In insects, ecdysteroids regulate both metamorphosis and ecdysis. If these reactions are triggered at the wrong time or stage, they can lead to irregular development, altered ecdysis patterns, feeding deterrence and ultimately death (46).

2.7. Semiochemicals as biopesticides

Semiochemicals are chemical signals produced by an organism that influence the behavior of individuals, either within the same species or between different species (47). Plants emit chemical cues to attract pollinators or serve other purposes, which pests may exploit to their advantage (48).

2.7.1. Pheromonal biopesticides

Insects use molecules known as pheromones to communicate with other insects of the same species. These compounds are often structurally similar to those found in tastes and smells (49). A table of commercial pheromone-based biopesticide products and their main components used in vegetable pest management is provided (Table 5).

2.7.2. Pheromone inhibitors

Semiochemicals can disrupt communication channels among insect pests, making them a promising approach for integrated pest management (IPM) programs (50, 51). Females may also utilize pheromone antagonists to enhance their fertility. For instance, female *Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae) use the pheromone antagonist (Z)-11-hexadecenol to prevent non-optimal matings and maximize their reproductive success.

2.8. Mineral based biopesticides

Mineral-derived pesticides primarily consist of silicon-based compounds, such as inert dust, which are chemically inactive yet exhibit insecticidal properties. These substances function by physically damaging the insect's cuticle, leading to desiccation and ultimately resulting in the insect's death. The mode of action of inert dust is illustrated in (Fig. 7).

2.8.1. Diatomaceous earth (DE)

Diatomaceous earth (DE) is a dust that comes in various colors, including grey, yellow, white and red. It consists of fossilized diatoms, which are single-celled algae primarily composed of amorphous silicon dioxide and exist in various shapes and sizes. DE products are produced by mining diatom sediments, which are then crushed into a fine dust containing silicon dioxide. To accommodate different environmental conditions during application, it is recommended to use DE as an adjuvant rather than as an active ingredient (52). A decrease in the population of thrips nymphs and the observed damage to brinjal and tomato plants has been noted. Similarly, a decline in the number of whitefly nymphs was specifically observed in tomato plants (53).

2.8.2. Fly ash

Fly ash, a byproduct of burning coal or lignite in thermal power plants, comprises amorphous ferro-alumino silicate, making it similar to soil, albeit with lower organic carbon and nitrogen content. It can be utilized for various agricultural purposes. Herbal insecticides can be formulated using fly ash, such as combinations of fly ash with 10 % turmeric dust and fly ash with neem seed kernel. The most effective mixture against various test insects, including *Spodoptera* on okra and *Epilachna* on brinjal, was found to be 10 % turmeric dust combined with fly ash. This was followed by fly ash mixed with 10 % dust of *Vitex*, *Eucalyptus* and *Ocimum* (54). Additionally, a pesticide dusting mixture containing up to 40 % fly ash served effectively as a dispersion to address the agglomeration issue associated with crushed white clay. It also proved to be time-efficient, saving energy, labor and natural resources, without adversely affecting the quality and yield of brinjal (*Solanum melongena*) and tomato (*Solanum lycopersicum*) in the trials (55).

Table 5. Commercial pheromone-based products in insect pest management.

No.	Crop	Pest	Pheromone	Pheromone component	Reference
1.	Tomato	*Helicoverpa armigera*	Sex Pheromone (Helilure)	(Z) 11 hexadecanal + (Z) hexadecanal (97:3)	(110)
2.	Tomato	*Spodoptera litura*	Sex Pheromone	(Z, E), 9,11 tetradecanyl acetate + (Z, E) 9,12-dienyl	(111)
3.	Tomato	*Tuta absoluta*	Sex Pheromone (TLM lure)	(3E, 8Z, 11Z)-3, 8, 11- etradecatrien-1-xyl acetate	(112)
4.	Crucifers	*Trichoplusiani*	Sex Pheromone	(Z)-7-dodecen-l-ol acetate	(113)
5.	Cucurbits	*B. cucurbitae*	Marking Pheromone	4-(4-hydroxyphenyl) 2-butanone acetate	(114)

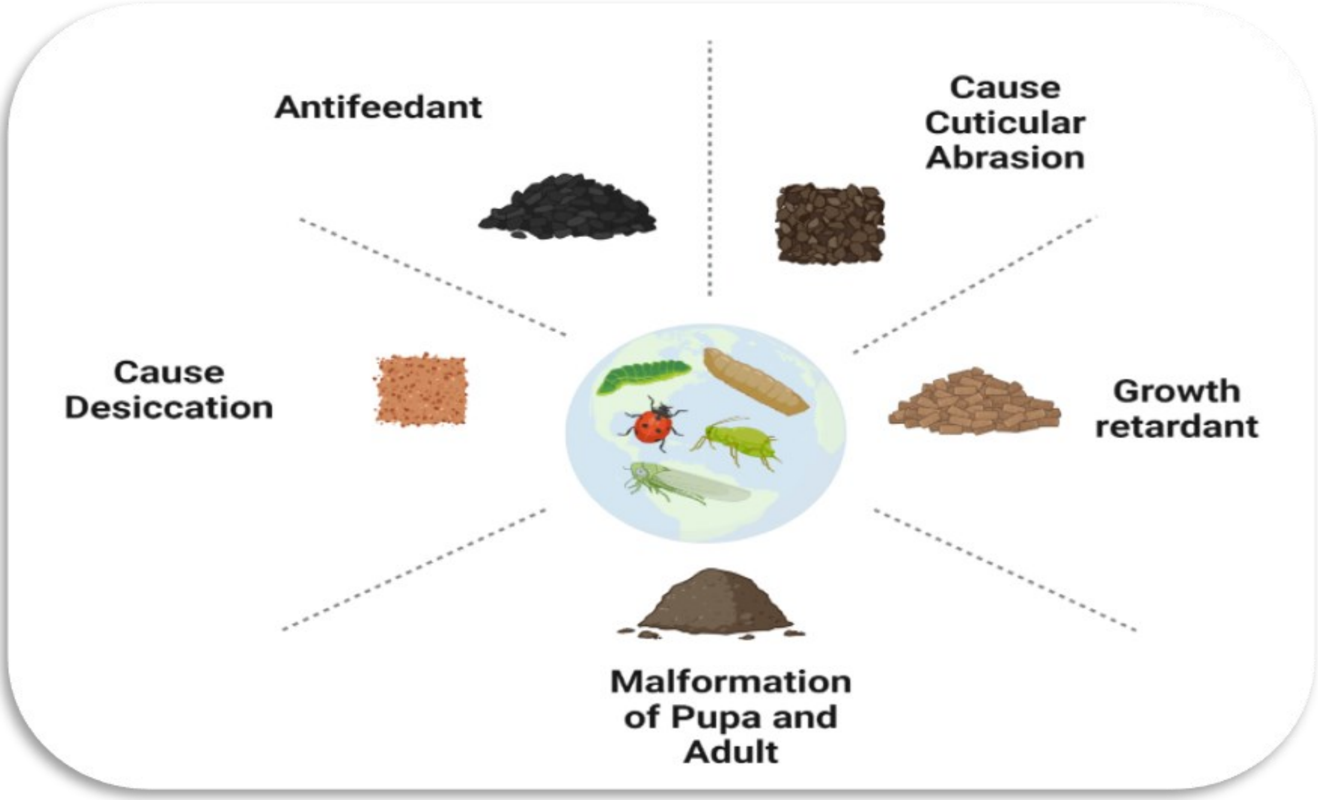


Fig. 7. Mode of action of inert dust: This figure illustrates the mode of action of inert dust. These actions highlight how botanical compounds manage pests using natural, environmentally friendly methods.

2.8.3. Rice husk

In brinjal, the use of rice husk and rice husk biochar treatments resulted in a plant height increase of 24.60 % and 16.95 % respectively, compared to the control treatment. Additionally, the populations of jassids, whiteflies and borer insects were significantly lower in the plants treated with rice husk and rice husk biochar. The reductions were recorded at 33.68-60.62 % for jassids, 19.23-50.92 % for whiteflies and 16.03-75.64 % for borer insects, compared to the control group (56). The research findings indicated that a rice husk ash level of 48 g per polybag was effective in increasing plant height and promoting earlier flowering. Furthermore, a rice husk ash concentration of 72 g per polybag proved to be an efficient method for enhancing the number of plant branches and fruits (57).

2.9. Nanotechnology in pest management

2.9.1. Bio-derived green nanoparticles

Compared to chemical and physical methods, the biological approach provides a more sustainable means of synthesizing nanoparticles. Various plant parts-including leaves, stems, roots, shoots, bark, flowers, seeds and their metabolites-have been shown to be effective in producing nanoparticles with insecticidal and pesticidal properties (58, 59). In addition to these plant parts, bacteria, fungi and waste materials can also be utilized for nanoparticle synthesis. This bio-based approach employs a bottom-up strategy, utilizing dropping and stabilizing agents to facilitate the synthesis process. The synthesis of nanoparticles through biological systems involves three key steps: selecting a suitable solvent medium, choosing a reliable and environmentally friendly reducing agent and selecting a non-toxic substance to serve as a capping agent, which stabilizes the resulting nanoparticles. This process yields nanoparticles with unique and enhanced properties, making them valuable in biomedical and related fields (60). Furthermore, polymeric nanoparticles act as carriers for bio control agents, helping to combat biotic stress in plants (61, 62). The mode of action of nanopesticides is illustrated in Fig. 8.

2.9.2. Botanical-derived nanomaterials against pests

Green-synthesized silver nanoparticles (Ag NPs) derived from neem extracts at a concentration of 1200 ppm demonstrated remarkable efficacy against third instar nymphs and adults of *Bemisia tabaci* (63). The role of gut protease activity in *Helicoverpa armigera* is modulated by leaf extracts from the banyan tree (*Ficus benghalensis*) and the peepal tree (*Ficus religiosa*) when used to fabricate Ag NPs (64). Foliar application of titanium tetrachloride nanoparticles, loaded with neem gum extracts at a concentration of 100 ppm, reduced damage caused by *Spodoptera litura* and *Helicoverpa armigera* by decreasing the activity of detoxifying enzymes in the midgut of larvae (65). In a greenhouse experiment, spraying faba bean leaves with silica dioxide (SiO_2) nanoparticles resulted in 100 % mortality against 3 distinct aphid species, namely *Acyrthosiphon pisum*, *Aphis craccivora* and *Myzus persicae*, at a concentration of 50 ppm (66). Similarly, nanocapsules containing eucalyptus extract achieved 100 % mortality of *Myzus persicae* at the highest concentration of 50 mg/mL after 48 h of exposure (67).

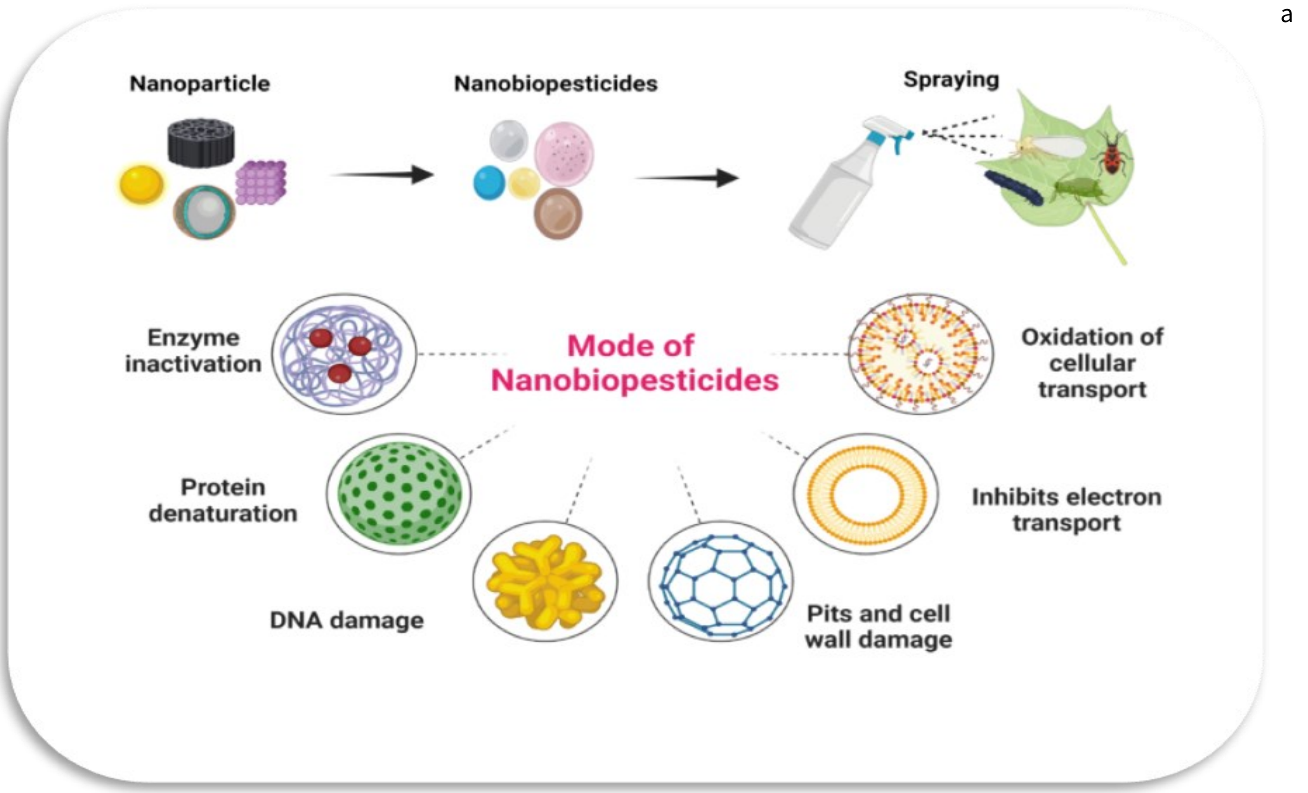


Fig. 8. Mode of action of nano pesticides: This figure illustrates the mode of action of nano pesticides. These mechanisms demonstrate how nano pesticides provide natural pest control solutions.

2.9.3. Nano microbials

Nanoparticles of zinc, silver and copper are commonly used as antibacterial agents in agriculture (68). The population of *Tuta absoluta*, commonly known as the tomato pinworm was significantly reduced under field conditions through the use of *Bacillus thuringiensis* (Bt) nanoencapsulation, which was created by high-pressure homogenization of 100 % glycerol and 2.5 % surfactant (69). The Bt Cry1Ab protein, which operates independently of midgut receptors and can avoid modifications caused by changes in these receptors, may penetrate the midgut cells of *Agrotis ipsilon* more effectively when functionalized with amino acid-functionalized fluorescent nanocarriers (70).

2.9.4. Nanopheromones and Nanoparapheromones

Pheromones are naturally occurring volatile molecules used in eco-friendly biological pest control methods. However, they are susceptible to wind and rain and their stability is compromised by photo-oxidation, auto-oxidation and isomerization. Artificially produced para pheromones mimic the effects of natural pheromones. The most commonly used para pheromone is methyl eugenol, which is derived from clove leaves and primarily attracts tephritid fruit flies, including *Bactrocera* species. Male annihilation strategies are employed to regulate *Bactrocera dorsalis* by attracting males to methyl eugenol. A methyl eugenol-based min-u-gel formulation was developed for spot application in California's male annihilation program to eradicate *Bactrocera dorsalis*. Additionally, geraniol-loaded chitosan/gum arabic nanoparticles attracted the whitefly, *B. tabaci*, by acting as semiochemical, which could potentially be used in trap systems (71).

3. Biotechnological Tools in Pest Management

Gene editing technologies like CRISPR/Cas9 have revolutionized pest management by enabling precise modifications to the genetic makeup of pests. This technique enhances the development of resilient pest populations while minimizing off-target effects, thereby promoting both the efficiency and safety of creating pest-resistant strains. Furthermore, it marks a new era of genetic precision, fostering sustainable coexistence between agriculture and nature for future generations (72). RNA interference (RNAi) technology has transformed pest management by specifically targeting genes essential for pest survival, providing a control method that avoids harming non-target organisms or the environment. Engineered RNA molecules can be used as biopesticides and applied to crops or fields, ensuring targeted pest control while protecting beneficial insects, plants and animals. Successful case studies, such as the use of RNAi against Colorado potato beetles (73), aphids (74) and caterpillars (75), highlight RNAi's effectiveness and its potential for sustainable, targeted pest management in agriculture.

4. Economic aspects

Recent field trial findings demonstrated that *Bacillus thuringiensis* (Bt) was effective against *Helicoverpa armigera* (14, 76, 77), *Earias vittella* (78) and the diamondback moth (79). In the case of *Beauveria bassiana*, it proved effective against *H. armigera* (80, 81), *E. vittella* (82) and *Bemisia tabaci* (19). Additionally, field trials showed that entomopathogenic nematodes (EPNs) were effective against fall armyworms (83) and low-ground pests (84). Synthetic pesticides exhibited the highest effectiveness, resulting in the lowest pest populations, the highest cost-benefit ratios and the greatest marketable yields. In contrast, biopesticides were the least effective, showing higher pest populations, lower cost-benefit ratios and reduced yields (82, 85-90). Biopesticides offer a lower environmental impact due to their reduced toxicity, target specificity and biodegradability, making them safer for non-target species and ecosystems. They minimize residue buildup and the risk of pest resistance, thereby promoting sustainable pest control. However, proper application is essential to avoid potential non-target effects and ensure efficacy (91).

Conclusion and Future Prospects

The future of vegetable pest management focuses on sustainable, eco-friendly techniques, with biopesticides derived from plants, microbes and minerals providing a natural alternative to chemical pesticides. Growing concerns about soil degradation, climate change and the adverse effects of chemicals are driving the incorporation of biopesticides into integrated pest management (IPM) strategies. Key factors in enhancing the efficacy, specificity and adoption of biopesticides include regulatory frameworks, research and education. As the biopesticide market expands, competition encourages innovation. Further research on bio-carrier combinations and biopesticide compatibility is essential, while advancements in precision agriculture and nanotechnology will enhance pest management efficiency and sustainability. Although the introduction of synthetic pesticides initially mitigated significant crop losses caused by pests, their negative environmental impacts have prompted a shift toward biological alternatives. Biopesticides offer significant advantages in terms of environmental safety, biodegradability, effectiveness and integration into integrated pest management programs, making them increasingly essential to pest control systems. The adoption and integration of biopesticides into traditional agricultural practices are influenced by several factors, including the global transition toward sustainable agriculture, supportive regulations, ongoing research and development efforts, educational initiatives, market expansion, crop-specific solutions and advancements in technology. As a critical component of sustainable agriculture, biopesticides are expected to significantly reshape insect pest management in vegetables, promoting a more resilient and environmentally sustainable agricultural sector. Realizing the full potential of biopesticides requires collaboration among farmers, policymakers and industry stakeholders. This cooperative effort is crucial for effectively leveraging biopesticides while balancing environmental stewardship and ensuring food security. However, several challenges hinder the large-scale adoption of biopesticides, including the high cost of refined commercial products, the inability to meet global market demands, variations in standard preparation methods and guidelines and difficulties in determining the correct dosage of active ingredients. Additionally, biopesticides are sensitive to various environmental factors have limited stability and act more slowly compared to conventional pesticides. Despite these challenges, there is optimism that ongoing research and technological advancements will address these limitations in the future.

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Authors' contributions

PVAC: Wrote the first draft of the paper. MS: Conceptualized, reviewed and edited the review paper holistically. AS: Edited the paper and prepared the charts; GP, PJ, EP and RK: Reviewed the paper and shared their inputs for upscaling. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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