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Alternative pest control methods

safeFoodTR

"Reducing pesticide use for environmental sustainability and raising awareness of farmers on alternative control methods; Safe Food for Consumers"

[SafeFoodTR]

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Lead Beneficiary: Gaziantep University (Gaziantep, Türkiye)

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1. Introduction

Modern agriculture faces a dual responsibility: to produce sufficient, high-quality food while protecting human health and the environment. For many years, chemical pesticides have played an important role in controlling pests and securing crop yields. However, excessive or improper use of pesticides has led to serious challenges, including environmental pollution, harm to beneficial organisms, pesticide residues in food, and the development of pest resistance.

For these reasons, reducing pesticide use and adopting alternative pest control methods is becoming increasingly important. A key framework for achieving this goal is Integrated Pest Management (hereafter – IPM). IPM is a science-based approach that combines different pest control strategies in a coordinated way to keep pest populations below damaging levels while minimizing risks to people, beneficial organisms, and the environment.

Raising farmers' awareness about reducing pesticide use is therefore essential for achieving sustainable agriculture and ensuring safe food for consumers. Today, farmers are increasingly encouraged to adopt alternative pest control methods that are effective, economically viable, and environmentally friendly. These methods aim not only to control pests, but also to maintain ecological balance, preserve soil and water quality, and protect pollinators and natural enemies of pests.

This training material focuses on the theoretical foundations of alternative pest control strategies that can be integrated into everyday farming practices. Its purpose is to provide farmers with a clear understanding of how different control strategies work and how they complement each other within the IPM framework. The methods discussed include the use of biopesticides such as biochemical pesticides, microbial pesticides, and plant-incorporated protectants as well as biological control using natural enemies, companion planting, cultural methods such as crop rotation, and the use of physical barriers.

By understanding the principles behind these methods and their role within IPM, farmers can make informed decisions about pest control strategies that reduce reliance on chemical pesticides, support environmental sustainability, and contribute to safer food production. The aim of this theoretical training is to build a strong knowledge base that can later support effective and responsible pest management in practice.

2. Biopesticides

Biopesticides are chemicals made from natural organisms or substances used to control or suppress agricultural pests, weeds, and disease-causing agents by specific biological effects. According to the United States Environmental Protection Agency (EPA), biopesticides are made from natural materials like animals, microorganisms, some minerals, and plants [1]. The use of natural substances for pest control is part of long-standing indigenous technical knowledge that has historically been highly effective. However, much of this knowledge has declined with the rise and widespread adoption of chemical pesticides [2,3]. Biopesticides offer a safer alternative, causing less harm to both the environment and human health. Compared with synthetic pesticides, they are generally less toxic, often act on specific target pests, leave little or no residual impact, and are suitable for use in organic farming systems [4,5,6]. The use of biopesticides in crop protection offers many advantages, including reduced pesticide residues in food, which lowers potential risks to consumers. Biopesticides are usually highly selective, affecting mainly the target pests while posing minimal danger to non-target organisms. In addition, most biopesticides degrade rapidly in the environment, and some, such as semiochemicals, are effective even when applied in very small amounts [2,3,6]. EPA divides biopesticides into three major classes: biochemical pesticides, microbial pesticides and plant-incorporated protectants (PIPs) (**Figure 1**) [1,7].

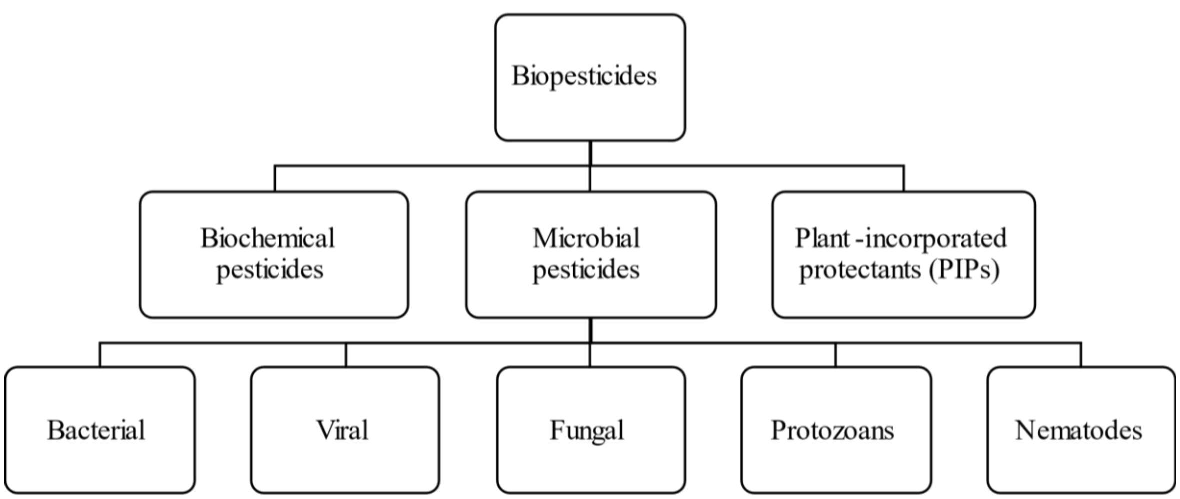

Figure 1. Classes of biopesticides [7]

2.1. Microbial Pesticides

Microbial pesticides are a category of biopesticides derived from microorganisms, including bacteria, viruses, fungi, protozoa, and entomopathogenic nematodes, that contain microscopic living organisms (or their by-products) as the main active ingredient and act against specific plant pests [7]. For example, some fungi control weeds, while others kill certain insects. They reduce pest populations by infecting them and causing disease, competing for nutrients and living space, producing natural toxins, and through other biological actions playing a critical role in IPM strategies and contribute to sustainable agricultural practices by reducing environmental impacts and minimizing the risk of pesticide resistance [9]. Over the past decade, intensive research on microbial biopesticides has resulted in the identification and development of numerous new products and has supported their commercial potential [8].

2.1.1. Bacterial Biopesticides

Bacterial biopesticides are among the most widely used microbial pest control agents. They are primarily applied to manage insect pests, although some are also effective against plant-pathogenic bacteria and fungi. These products typically act on specific groups of insects, including moths, butterflies, beetles, flies, and mosquitoes. For effective control, insects must come into contact with the bacterial agent and, in most cases, ingest it.

Bacteria used in biopesticide production can be grouped into four main categories: crystal-forming spore producers (such as *Bacillus thuringiensis*), obligate pathogens (such as *B. popilliae*), facultative pathogens (such as *Pseudomonas aeruginosa*), and potential pathogens (such as *Serratia marcescens*) [10].

Among the most important crystal-producing bacteria is *B. thuringiensis* and its subspecies *kurstaki, tenebrionis, aizawai*, and *israelensis*, which are widely recognized as highly specific, safe, and effective agents for insect pest control [11]. These bacteria are active against a wide range of insect pests, including larvae of *Lepidoptera* (such as armyworms and diamondback moths), mosquito larvae, black flies, and several beetle species. *B. thuringiensis* is the dominant organism in the biopesticide industry, accounting for nearly 90% of the biopesticide market in the United States. It is the most extensively used bacterial species for commercial insect management and demonstrates effectiveness against diverse pest groups, including lepidopterans, hemipterans, and coleopterans in agricultural systems. *B. thuringiensis* consists of numerous strains, each capable of producing unique insecticidal crystal (Cry) proteins that typically act on specific pest groups. These

Cry proteins function as toxins that, once ingested, bind to receptors in the insect gut, damaging the intestinal lining and disrupting normal digestion. This leads to paralysis of the digestive system, causing the insect to stop feeding and ultimately die from internal damage and starvation. This process disrupts the integrity of the gut wall, leading to leakage of gut contents into the body cavity (hemocoel), septicemia, and rapid cessation of feeding. As a result, the larva typically dies within 24–48 hours (**Figure 2**). Because this mode of action is highly specific, bacterial biopesticides are designed to affect only particular pest species, thereby protecting crops while minimizing harm to beneficial organisms and non-target species [9,10,12].

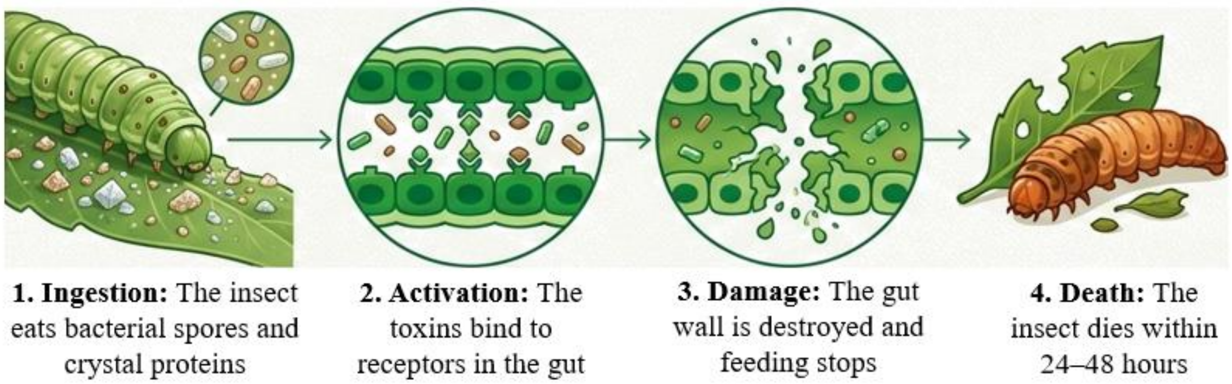

Figure 2. The mechanism of action of *B. thuringiensis* on insect larvae. Source: Generated with ChatGPT (DALL·E) and modified by the author using Microsoft Paint (2026)

As bacterial pesticides, *Pseudomonas fluorescens* (Trevisan), *B. subtilis* (Ehrenberg), and *Pseudomonas aureofaciens* (Kluyver) are also used against a variety of plant pathogens in agricultural practices [13]. Commercial *B. thuringiensis* products are available in various formulations, including dry powders containing spores and crystal toxins as well as liquid suspensions.

Another widely used species, *Lysinibacillus sphaericus*, controls mosquito populations (*Culex* and *Anopheles*) through the production of a binary (Bin) toxin [14]. *Saccharopolyspora spinosa* is also applied in pest management and is effective against insects such as *Aedes aegypti* and *Spodoptera littoralis* [15,16]. In terms of pathogenicity, *Pseudomonas aeruginosa* functions as a facultative pathogen, whereas *B. popilliae* represents obligate pathogenic bacteria involved in biopesticide development [17].

Among these four bacterial groups, crystal-forming spore producers dominate commercial biopesticide formulations. Because of their strong performance, operational reliability, and favourable safety profile, *B. thuringiensis* and *B. sphaericus* are extensively used in insect pest control programs. In addition, some entomopathogenic bacteria form symbiotic associations with entomopathogenic nematodes and possess potent insecticidal activity; these bacteria mainly belong to the genera *Photorhabdus* and *Xenorhabdus* [13]. Commercial formulations of bacterial biopesticides available in the market is presented in **Table 1**.

Table 1. Commercial formulations of bacterial biopesticides [18]

Bacterial biopesticides	**Uses**	**Active ingredient**	**Recommend-ed doses**	**Target organism**
Bactur®WDG	Against foliage-feeding caterpillars	*Bacillus thuringiensis* var. *kurstaki*	0.5 g/lit	Caterpillars
Plant's buddy	It produces endotoxin (parasporal crystal) and exotoxin, which can make the pests stop feeding. The pests all die due to starvation, cell wall rupture and nerve poisoning.	*B. thuringiensis* var. *kurstaki*	10 ml/lit	Lepidopteran caterpillars
SM Srimalar Enterprises®	The active ingredient release enzymes that pierce the stomach lining of mosquito larvae. Also act as effective fungicide	*B. thuringiensis*	2–3 ml/lit	Mosquitoes, Black Flies and fungi
Bio larvicide	The crystal proteins produced by Bt are toxic to certain insect larvae	*B. thuringiensis* var. *kurstaki*	2–3ml/lit	Larvae
Utkarsh BT	Utkarsh BT acts by producing a protein that blocks the	*B. thuringiensis* var. *kurstaki*	2–3 ml/lit	Larvae

Bacterial biopesticides	**Uses**	**Active ingredient**	**Recommend-ed doses**	**Target organism**
	digestive system of the insect, effectively starving it; an infected insect will stop feeding within hours of ingestion and will die within days			
Mahastra	Effective in control of caterpillars	*B. thuringiensis* var. *kurstaki*	5-10 g/lit	Caterpillars
Thuricide®	Effective in control of caterpillars and worms	*B. thuringiensis* var. *kurstaki*	2 - 4 tsp. per gallon	Caterpillars and worms
Bactospeine®	Due to the toxic component, the insect intestines are affected and start decaying, leading to death within 24–72 h	*B. thuringiensis* var. *kurstaki*	1 g/lit	Larvae
Green Heal Larvicide	After entry into the host it paralyzes the digestive tract and cause death	*B. thuringiensis* var. *kurstaki*	5ml/lit	Caterpillars
VectoLex® Granules	A mosquito larvicide produces toxins inside the midgut and cause lysis of cells and larvae death	*B. thuringiensis sphaericus*	4 tsb/272 square feet	Mosquitoes
VectoMax® Granules	A mosquito larvicide produces toxins inside the midgut and cause lysis of cells and larvae death	*B. thuringiensis sphaericus*	30 lbs/ft3	Mosquitoes

Bacterial biopesticides	**Uses**	**Active ingredient**	**Recommend-ed doses**	**Target organism**
VectoBac® WDG	A mosquito larvicide produces toxins inside the midgut and cause lysis of cells and larvae death	*B.thuringiensis* sub sp. *israelensis*	2–8 g/1000lit	Mosquitoes
Teknar® CG	A mosquito larvicide produces toxins inside the midgut and cause lysis of cells and larvae death	*B. thuringiensis* sub sp. *israelensis*	2.5–10.0lbs/acre	Mosquitoes
Gnatrol® SC	Bt protein crystals break down into toxins that bind to, and destroy, intestinal wall and larvae die quickly	*B. thuringiensis* sub sp. *israelensis*		Sciarid fly
Majestene®	Bionematicide affect RKNs life cycle in the plant and kill them	*Burkholderia rinojensis*	9.5 L/ha	Root-knot nematodes (RKNs)
Tracer™ 120 SC	Used primarily for the control of chewing and scratching insects	*Saccharopolyspora spinosa*	0.375 ml/lit	Insects
BioNemagon™	Infects and kills both larvae and adult stage of many plant pathogenic nematodes	*Bacillus firmus*	10–30 kg/acre	Nematodes
Grandevo ® WDG	Shows multiple modes of action: repellency, ingestion, and reproduction disruption.	*Chromobacterium subtsugae*	3 lbs/100 gallons	Thrips Whiteflies

Bacterial biopesticides	Uses	Active ingredient	Recommend-ed doses	Target organism
Novodor@	Produces protein crystals that kills the larvae	*Bacillus thuringiensis* subsp. *tenebrionis*	3 to 4 quarts per acre	Colorado Potato Beetle and Elm Leaf Beetle,
Agree-WP	Strong and effective stomach action leads to death of the insect	*B. thuringiensis* subsp. *aizawai*	0.5–2.0lbs/acre	Loopers, Armyworm

Advantages of bacterial pesticides [12]

- Safe mode of action: Bacterial biopesticides act through biological mechanisms that pose minimal risk to humans, wildlife, and other non-target organisms.
- Target-specific activity: Their action is highly selective, affecting only the intended pest species while preserving beneficial insects.
- Compatibility with IPM: They function effectively alongside other control strategies, including chemical pesticides, within IPM programs.
- Residue-free protection: These products do not leave harmful residues on crops, allowing application even close to harvest.
- Sustained environmental presence: Many bacterial biopesticides can persist and re-establish naturally in the environment, providing continued pest suppression across subsequent growing seasons.

Disadvantages of bacterial pesticides [12]

- Narrow target activity: Microbial insecticides act on specific insect species or small pest groups. While this ensures selectivity, non-target pests may remain unaffected and continue to damage crops.
- Sensitivity of beneficial organisms: When predators and parasitoids are used in biological control programs, incompatible chemical pesticides can harm these beneficial agents, making careful product selection essential.

- Environmental dependence: Their biological activity is strongly influenced by factors such as ultraviolet radiation, high temperatures, and weather conditions, which can reduce effectiveness. To protect microbial agents from sunlight degradation, treatments are often most effective when applied in early morning or late evening.
- Formulation and handling requirements: Microbial pesticides require specialized formulations, proper storage, and strict adherence to label instructions to maintain organism viability and performance.
- Production and availability constraints: Year-round mass production of biological agents is technically demanding, limiting large-scale availability.
- Regulatory and market limitations: Regulatory requirements and restricted product availability often reduce adoption compared with conventional chemical pesticides.
- Field performance conditions: Successful pest control depends on suitable temperature, humidity, and rainfall to support survival and multiplication of the biocontrol agents.

2.1.2. Viral Biopesticides

Several virus families are known to infect insects; however, viruses belonging to the family *Baculoviridae* are considered as the most commercial viral biopesticides used to control insect pests [19,20]. Baculoviruses belong to a group called *entomopathogenic viruses,* which means they infect only insects and other small arthropods. Unlike chemical pesticides, baculoviruses are safe for humans, animals, and beneficial insects, making them an environmentally friendly option for pest control [21] and ideal candidates for inclusion in IPM programs [19].

Baculoviruses contain genetic material made of double-stranded DNA and are protected by special protein structures called occlusion bodies. These structures allow the virus to survive in the environment until it is eaten by a suitable insect host. The occlusion bodies help the virus to survive outside the host [22]. Once inside the insect, the virus multiplies and eventually kills the pest. There are three main types of baculoviruses [12]: NPVs (nuclear polyhedrosis viruses); CPVs (cytoplasmic polyhedrosis viruses); GVs (granulosis viruses). They differ in the size and structure of their protective protein coats, but all work by infecting and killing insect pests.

Baculoviruses are highly specific, mainly targeting caterpillars of moths and butterflies that damage crops such as cotton, rice, vegetables, maize, and beans. A well-known example is *Helicoverpa zea* nucleopolyhedrovirus (HzNPV), one of the first successful viral insecticides, used to control pests in crops like soybean, maize, tomato, and sorghum. Although other insect-infecting viruses exist, baculoviruses are the most widely used in agriculture [12,23].

Viral biopesticides act in a manner similar to bacterial agents and must be ingested by insect larvae to initiate infection and subsequent disease development. After ingestion, the virus particles penetrate the intestinal lining and begins replication within susceptible tissues, leading to a systemic infection of host cells. During the final stage of infection, the insect body breaks down and liquefies, releasing large numbers of occlusion bodies that can infect other insects when consumed. The process of granulovirus-based infection and replication in the host insect is shown in **Figure 3**. Once a virus enters a susceptible cell, replication occurs either in the nucleus or in the cytoplasm and proceeds through three main stages: an early phase (0–6 hours), a secondary phase (6–24 hours), and a very late phase (24–72 hours). During the final stage, the virus produces protective protein structures known as occlusion bodies, which contain multiple viral particles. These structures enable the spread of infection and can trigger natural epizootics that substantially reduce pest populations [12,23].

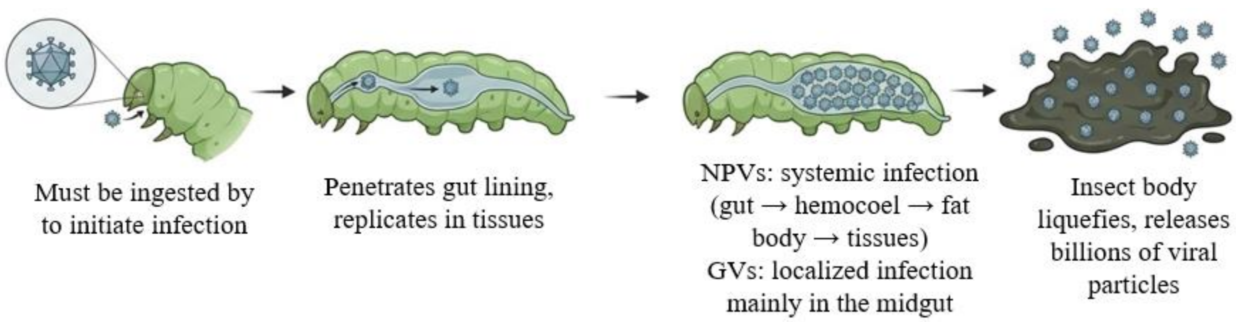

Figure 3. Mode of action of a granulovirus-based biopesticide against a larva. Source: Generated with ChatGPT (DALL·E) and modified by the author using Microsoft Paint (2026)

At the time of death, a single caterpillar may contain more than 10^9 occlusion virus bodies, even when the initial infective dose was as low as 1,000 particles. Under favourable environmental conditions, susceptible pests may be killed within 3-7 days; however, when conditions are less suitable, mortality may be delayed for up to 3-4 weeks.

Granulovirus-based biopesticides are mainly applied to control larval stages of *Lepidopteran* pests, particularly species such as the codling moth (*Cydia pomonella*) and the diamondback moth (*Plutella xylostella*) [24]. Viral biopesticides are very specific, meaning they target only certain pests and do not harm other insects. They can greatly reduce pest populations. Some examples of viral products used in agriculture include viruses that control cotton bollworms (*Helicoverpa zea*), beet armyworms (*Spodoptera exigua*), and codling moth (*Cydia pomonella*). A list of commercial viral biopesticides is provided in **Table 2**.

Table 2. Commercial formulations of viral biopesticides [12]

Target pest	**Host**	**Products available**
NPV of *H. armigera* (HaNPV)	*Helicoverpa zea* *H. armigera*	Biokill-H, BioVirus-H, Heli-Cide, Heliokill, Heliman-NPV, Helixus, Jas Viro-H, Helicop, Heligard, Somstar-Ha
NPV of *S. litura* (SINPV)	*Spodoptera litura* *S. exigua*	BioVirus-S, Jas Viro-S, Spodo-Cide, Spodopterin, Somsta-SL
Nuclear polyhedrosis for Gypsy moth	Gypsy moth caterpillars	Gypchek virus
Tussock moth NPV	Tussock moth caterpillars	TM Biocontrol-1
Pine sawfly NPV	Larvae of pine sawfly	Neochek-S
Granulosis virus for Codling moth (GV)	Codling moth caterpillars	Madex, Carpovirusine, CYD-X

Sunlight presents a limitation, as occlusion bodies quickly lose effectiveness when exposed to ultraviolet radiation in the 280–320 nm range [25]. However, research indicates that plastic greenhouse coverings can reduce this effect by blocking more than 90% of UV-B radiation, thereby increasing infection rates in larvae [26].

Because of their highly selective mode of action, baculoviruses infect only their designated target pests. They do not generate toxic compounds or metabolites that would pose risks to human health. Furthermore, baculoviruses gradually lose activity when exposed to ultraviolet radiation, which prevents the build-up of active residues on harvested produce. Owing to these characteristics, plant protection products based on baculoviruses are exempt from maximum residue level (MRL) requirements under European legislation, such as Regulation (EC) No 396/2005. In line with this regulatory approach, the Organisation for Economic Co-operation and Development (OECD) has determined that baculoviruses are safe for both users and consumers and are non-toxic to plants, aquatic organisms, and mammals. In the United States, baculovirus-based products fall under the oversight of the Environmental Protection Agency (EPA) [27].

Because the target insects must consume the virus through plant tissues, granulovirus-based biopesticides should be applied to the parts of the crop, where feeding normally occurs. For instance, when larvae feed on leaves, the treatment should be directed onto the foliage. Overall, the use of granulovirus products follows practices similar to those for conventional chemical pesticides. These biopesticides are most commonly formulated as liquids and can be applied using standard spraying equipment. In some cases, they are also available as dusts or powders for alternative application methods.

Advantages of viral pesticides [12]

- Safe interaction with non-targets: Viral biopesticides act only on specific pest species and do not harm humans, beneficial insects, or other non-target organisms.
- Sustained pest control: Target insects do not develop resistance, allowing viruses to remain effective over long periods.
- Compatibility with IPM: They can be easily combined with other control measures, including chemical insecticides, within integrated pest management programs.
- Environmental persistence: After application, the viruses remain active in the environment and continue to naturally suppress pest populations.
- No secondary outbreaks: Their targeted action prevents the emergence of secondary pest problems.
- Residue-free protection: They leave no chemical residues on crops, eliminating the need for a pre-harvest waiting period.

Disadvantages of viral pesticides [12]

- Narrow target activity: Viral biopesticides act only on specific pest species and cannot control multiple pests simultaneously, unlike broad-spectrum chemical pesticides.
- Delayed mortality: After infection, the virus requires time to multiply inside the insect, so pest death occurs gradually rather than immediately.
- Environmental sensitivity: External factors such as ultraviolet radiation, high temperatures, and other harsh conditions can inactivate the virus and reduce its effectiveness in the field.

2.1.3. Fungal Biopesticides

Fungal biopesticides are widely used for the control of insect pests, plant pathogens, and even certain weeds, alongside other biological agents. Their mode of action varies according to the fungal species involved and the type of pest being targeted. One key advantage of fungal biopesticides over many bacterial and viral alternatives is that they do not need to be ingested to be effective, as they can infect pests through direct contact. After the fungus enters the insect's body, it grows internally, producing toxins that cause paralysis and ultimately lead to the insect's death. Among entomopathogenic fungi, four genera are most widely used: *Beauveria*, *Isaria*, *Metarhizium*, and *Paecilomyces* [28]. The species *Beauveria bassiana* is particularly effective against pests such as whiteflies, thrips, and aphids. When applied to insects, the fungus penetrates their bodies, and within a few days, the infection results in mortality.

Fungal biopesticides based on naturally occurring fungi or their cellular components. These fungi infect their targets by attaching to the host surface through adhesive spores. After attachment, the spores germinate and produce fine filamentous structures that penetrate the insect cuticle. During this process, the fungi release powerful hydrolytic enzymes and toxic compounds that disrupt internal physiological functions, ultimately causing the death of the host [29]. Following host mortality, fungal growth extends outward from the cadaver, producing new spores that enable further spread and continuation of biological pest suppression [30]. Mode of action of fungi-based biopesticides, highlighting the steps by which these biopesticides attack target insect pests is shown in **Figure 4.**

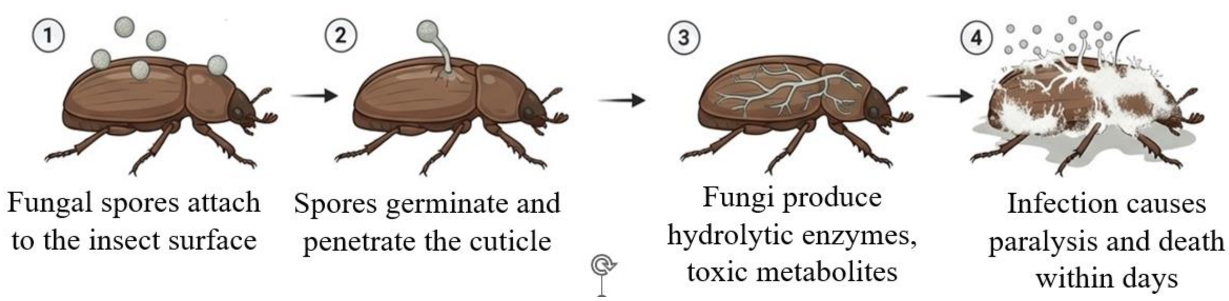

Figure 4. Mode of action of fungi-based biopesticides. Source: Generated with ChatGPT (DALL·E) and modified by the author using Microsoft Paint (2026)

The most common commercial fungal biopesticides available in the market are from *Beauveria bassiana*, *Metarhizium anisopliae*, *Nomuraea rileyi*, *Trichoderma viride*, *Paecilomyces farinosus* and *Verticillium lecanii* which are valued for their low cost, environmental safety, and strong ability to reduce the harmful effects associated with chemical pesticide use [2,18,31]. Among these, *B. bassiana* and *M. anisopliae* are widely used for their broad-spectrum activity against pests including aphids, beetles and their grubs, grasshoppers, leaf and plant hoppers, pod borer, cutworms and other lepidopteran and coleopteran pests [12]. These agents are commonly applied in the form of conidia (spores) or mycelial preparations, which subsequently sporulate after application, allowing for prolonged pest suppression in treated environments [32]. Stages of infection of the *Asiatic rhinoceros* beetle (*Oryctes rhinoceros*) larvae by a *Metarhizium fungus* is shown in **Figure 5**.

Figure 5. Stages of infection of the *Asiatic rhinoceros* beetle (*Oryctes rhinoceros*) larvae by a *Metarhizium fungus*. Credit: Image by Milksloong via Wikipedia Commons, CC BY-SA 4.0 [33]

Fungal biopesticides offer strong potential as environmentally friendly tools for controlling a wide variety of insect and mite pests. One of their key advantages in biological control is their high selectivity: they primarily affect target pests while sparing beneficial organisms such as pollinators and natural predators. In addition, these products typically do not interfere with the growth or development of other helpful soil organisms, including earthworms and springtails. As a result, fungal biopesticides are well suited for use in IPM programs and sustainable farming systems, where they support biodiversity and reduce environmental impact [9]. Moreover, a number of fungal species have already been successfully produced on a large scale and formulated as commercial mycoinsecticides, enabling their broader adoption in pest management practices [34]. Fungal biopesticides developed or being developed for the biological control of pests is presented in **Table 3**.

Table 3. Commercial formulations of fungal biopesticides [2]

Product	**Fungus**	**Target pests**	**Producers, companies and countries**
BIO 1020	*Metarhizium anisopliae*	Vine weevils	Licensed to Taensa, US
Bio-Blast	*Metarhizium anisopliae*	Termites	EcoScience, US
Biogreen	*Metarhizium anisopliae*	Scarab larvae in pasture	Bio-care Technology, Australia
Bio-Path	*Metarhizium anisopliae*	Cockroaches	EcoScience, US
Boverin	*Beauveria bassiana*	Colorado beetles	Former USSR
Conidia	*Beauveria bassiana*	Coffee berry borers	Live Systems Technology, Colombia
Corn Guard	*Beauveria bassiana*	European corn borers	Mycotech, US
Engerlingpilz	*Beauveria brongniartii*	Cockchafers	Andermatt, Switzerland
Jas Bassi	*Beauveria bassiana*	Colorado beetles	Shri Ram Solvent Ext. Pvt., India
Jas Meta	*Metarhizium anisopliae*	Sugarcane spittle bugs, termites	Shri Ram Solvent Ext. Pvt., India
Jas Verti	*Verticillium lecanii*	Whiteflies and thrips	Shri Ram Solvent Ext. Pvt., India
Laginex	*Lagenidium giganteum*	Mosquito larvae	AgraQuest, US

Product	Fungus	Target pests	Producers, companies and countries
Metaquino	*Metarhizium anisopliae*	Spittle bugs	Brazil
Mycotal	*Verticillium lecanii*	Whiteflies and thrips	Koppert, The Netherlands
Mycotrol WP	*Beauveria bassiana*	Whiteflies, aphids, thrips	Mycotech, US
Naturalis-L	*Beauveria bassiana*	Cotton pests including bollworms	Troy Biosciences, US
Ostrinil	*Beauveria bassiana*	Corn borers	Natural Plant Protection (NPP), France
Pae-Sin	*Paecilomyces fumosoroseus*	Whiteflies	Agrobiossa, Mexico
PFR-97	*Paecilomyces fumosoroseus*	Whiteflies	ECO-tek, US
Proceol	*Beauveria bassiana*	Army worms	Probiagro, Venezuela
Schweizer Beauveria	*Beauveria brongniartii*	Cockchafers	Eric Schweizer, Switzerland
Vertalec	*Verticillium lecanii*	Aphids	Koppert, The Netherlands

Notable improvements in pest control have been reported when fungal biopesticides are applied in combination with conventional insecticides, often resulting in substantially higher pest mortality. For instance, research indicates that the joint use of *Beauveria bassiana* with reduced insecticide doses improves control of the Colorado potato beetle, while its combined application with neem oil is effective against eggs and nymphs of tobacco thrips [32,35,36].

In addition to insect control, fungal-based products are also employed as mycoherbicides for the management of invasive plant species. Examples include *Cylindrobasidium l*aeve for controlling *Acacia mearnsii* (black wattle) and *Colletotrichum acutatum* for the management of *Hakea sericea* (silky hakea), supporting integrated approaches to alien and invasive species control [9].

Advantages of fungi-based biopesticides [12]

Broad infection capability: Entomopathogenic fungi act through direct contact and cuticle penetration, allowing them to infect a wide range of pests in fields, storage environments, and soil -broader than most bacteria or viruses.

- Efficient biological production: Key fungal agents such as *Beauveria*, *Metarhizium*, *Lecanicillium*, and *Isaria* can be mass-produced through simple fermentation on low-cost substrates, enabling scalable application.
- High effectiveness and specificity: These fungi provide strong pest control while targeting specific insect species.
- Environmentally friendly: They offer a sustainable alternative to chemical pesticides with minimal impact on ecosystems.

Disadvantages of fungi-based biopesticides [12]

- Strict environmental requirements: Fungal activity is strongly influenced by environmental conditions. High humidity (above 80%) is necessary for spore germination and successful penetration of the arthropod cuticle.
- Sensitivity to temperature and UV light: Extreme temperatures and exposure to ultraviolet radiation can significantly reduce fungal survival and effectiveness.
- Challenges in formulation: Producing and stabilizing delicate conidia or long-lasting resting stages is technically demanding.
- Higher cost: Compared with other microbial control methods, fungal biopesticides are generally more expensive.

2.1.4. Protozoans as Biopesticides

Protozoans, also called microsporidia, a group of spore-forming unicellular parasites that live inside insect cells. They can infect pest insects such as moths and grasshoppers, so they can be used in IPM. Examples include *Nosema* and *Vairimorpha* species. These organisms are very specific to certain pests and weaken insects over time. However, they work slowly, so protozoan biopesticides are not used as widely as bacterial, viral, or fungal biopesticides. Protozoans can cause chronic and debilitating effects on their targets, but their success rate is lower compared to other biopesticides [12].

The microsporidian *Nosema pyrausta* is a common and significant pathogen of the European corn borer (*Ostrinia nubilalis*), acting as a natural population regulator by negatively impacting larval development, adult longevity, and reproductive success [37].

Protozoans spread by spores, which are the infective form for many insects. Microsporidia can infect insects only when their spores are ingested. When an insect eats the spores of *Nosema*, the spores germinate in the midgut and release sporoplasm, which penetrates the gut cells in the insect. The parasite then enters the insect's cells and spreads through to the other tissues and organs of the body. The infection then spreads, where the organisms multiply, damaging organs and tissues and causing septicemia that eventually weakens or kills the insect. New spores are produced inside the infected insect. When these spores are released and eaten by another insect, the infection continues and can spread through the pest population [38]. Studies on *Nosema pyrausta* infection in the European corn borer (*Ostrinia nubilalis*) have shown that this protozoan can spread within host populations through both horizontal and vertical transmission (**Figure 6**). In horizontal transmission, protozoan spores enter the host when they are ingested. Once inside, the spores multiply within the midgut, generating large numbers of new spores. These remain in the insect's body and are later expelled with the feces. Although the infected insect eventually dies, the released spores remain viable in the environment and can be consumed by other larvae, thereby continuing the infection cycle. If spores are ingested by a female larva, the pathogen may be transferred to the next generation through vertical transmission. In this case, the reproductive tissues of the adult female become infected, resulting in the production of contaminated eggs. These eggs hatch into infected larvae that ultimately die from *Nosema* infection, releasing viable spores into their surroundings and enabling further spread of the disease [39].

The best-known commercially registered example of protozoan biopesticide is *Nosema locustae*, which is used to control grasshopper populations (a list of commercial protozan biopesticides is shown in **Table 4** [40]. It is particularly effective when applied to nymphal stages and can cause mortality within about six weeks. Another important microsporidian, *Nosema pyrausta*, is known to kill larvae of the European corn borer and to reduce both adult lifespan and reproductive capacity [39,12].

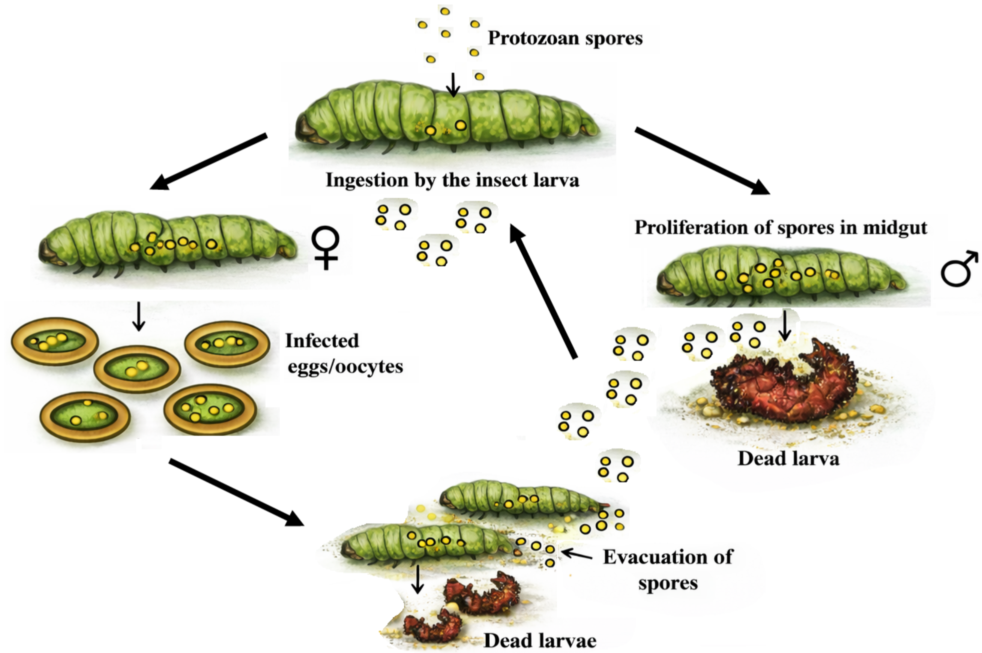

Figure 6. Mode of parasitism of entomopathogenic protozoan against lepidopteran insects. Source: Generated with ChatGPT (DALL·E) and modified by the author using Microsoft Paint (2026)

Table 4. Commercial formulations of protozoa-based biopesticides [40]

Protozoan	Host range	Products
Nosema locustae	European corn borer caterpillars, grasshoppers and Mormon crickets	NOLO Bait, Grasshopper attack

2.1.5. Entomopathogenic Nematodes as Biopesticides

Entomopathogenic nematodes are tiny roundworms that live in the soil, mainly in the thin water layer around soil particles. They infect insect pests by finding them through signals such as carbon dioxide, movement, and chemicals released by the insects and kill insect pests [12]. Nematodes have a special symbiotic relationship with certain insect pathogenic bacteria (*Xenorhabdus* spp. and *Photorhabdus* spp.) having great insecticidal potential [39]. These bacteria live inside the nematodes without causing them harm, but they are highly toxic to insect pests and play a key role in killing the host [41].

Nematodes invade the host pests as infective juveniles (**Figure 7**). When nematodes come into contact with their host, they enter its body through natural openings such as the mouth, breathing holes, or anus. Once inside, the nematodes release these bacteria that produce toxins and cause an infection inside the pest and within 24-48 h after infection they kill the host. These bacterial symbionts then proliferate (multiply in the insect hemolymph) with the release of virulence factors and toxins which help in the weakening of the host [39]. The nematodes reproduce in the insect's body and are released once it dies due to the infection. Released nematodes can infect more individuals and kill the insect within a few days. The nematodes feed on the dead insect, multiply inside it, and produce new young nematodes. The new nematodes then leave the dead insect and search for another host, continuing the control of pests.

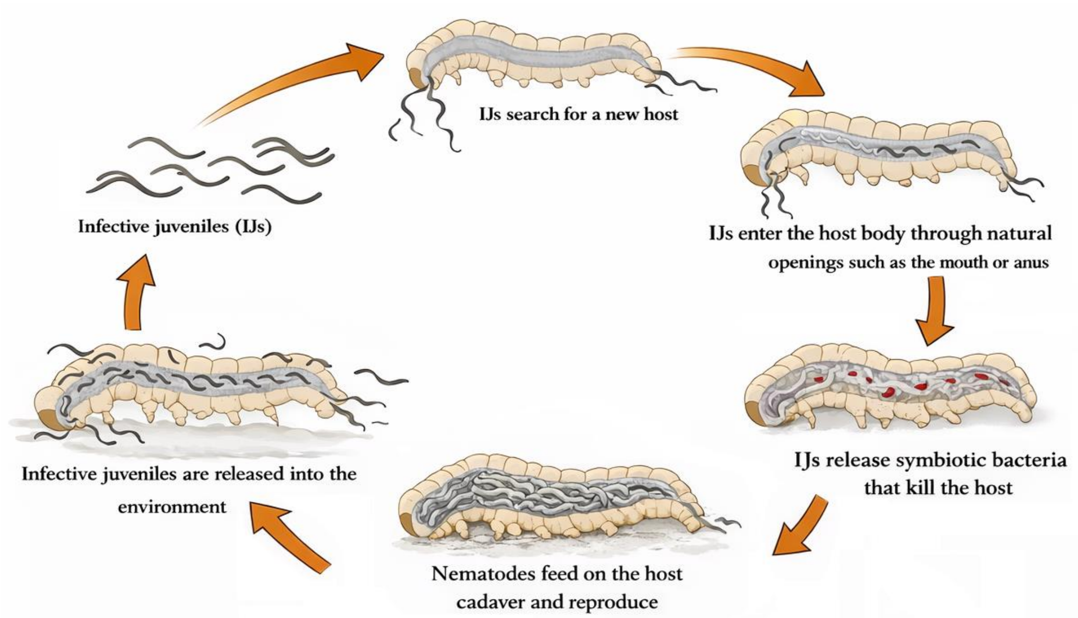

Figure 7. Mode of parasitism of nematodes in insects. Source: Generated with ChatGPT (DALL·E) and modified by the author using Microsoft Paint (2026)

Two main groups, *Steinernematidae* and *Heterorhabditidae*, are commonly used in agriculture as biological pest control agents (bionematicides) [12]. The nematode *Steinernema feltiae* is effective against soil-dwelling pest larvae, including fungus gnats and leaf miners. Similarly, *Heterorhabditis bacteriophora* is used to control vine weevil (*Otiorhynchus sulcatus*), as it can infect and kill both the larval and pupal stages of this pest [41]. These nematodes help reduce soil-dwelling insect pests and are an important part of environmentally friendly pest management. List of commercially available entomopathogenic nematodes-based biopesticides is provided in **Table 5**.

Table 5. Commercial formulations of entomopathogenic nematodes-based biopesticides [12]

Entomopathogenic nematodes	**Host range**	**Commercial products**
H. bacteriophora	Effective against root weevils, cutworms, fleas, borers and fungal gnats. Effective against black vine weevil populations by 56–100%	BioSafe, Larvanem, Nemaplant, NemaShield-HB, Nematop, Nematech-H, Nematriend-H, NemaTrident-C, Nema-green, Optimem-H
H. indica	*H. armigera*, *Conogethes punctiferalis*, *Athalia proxima*	Soldier, Nema power, GrubTerminator, Grubcure, Calterm, Armour
H. downesi	Black vine weevil	NemaTrident-CT
Steinernema feltiae, S. riobrave	Effective against black vine weevils, strawberry root weevils, cutworms, cranberry girdler and termites	Biosafe, Ecomask, Hortscan, Guardian, Millenium, Nematac C, NoFlea, Savior WG, Scanmask, Termask, Vector
S. carpocapsae	Borer beetles, caterpillars, crane fly, moth larvae, coconut rhinoceros beetle	Capsamen, Carpocapsae-system, Exhibitline SC, Optimem-C, NemaGard, Nemastar, NemaTrident-T, NemaRed, NemasyS-C, Palma-life

The application of nematodes differs from that of predators and parasitoids. Before use, nematodes must be mixed with water and then distributed onto the crop or soil. Common application methods are spraying, soil drenching, drip irrigation.

Spraying. Because nematodes are very small, they can be applied to soil or foliage using standard sprayers.

Soil drenching. The nematode - water mixture can be poured directly onto the soil, allowing the nematodes to move downward and locate pest insects.

Drip irrigation. Nematodes can also be introduced through irrigation systems. In this case, suitable filters must be used to prevent clogging while ensuring the nematodes remain viable.

Advantages of entomopathogenic nematodes [12]

- Safe to use: They are harmless to people, animals, plants, and the environment. No protective clothing or re-entry time is needed, and they leave no chemical residues.

- Effective against soil pests: They control pests such as cranberry girdler, black vine weevil, root weevil, cutworms, webworms, wood-borer and armyworms.
- Work well in moist soil: Nematodes survive best in wet, shaded soil and are protected from strong sunlight and high temperatures.
- Compatible with other products: They can tolerate short exposure (2-24 h) to many chemical and biological insecticides, fungicides, herbicides, fertilizers and growth regulators, so they can be used in integrated pest management programs.

Disadvantages of entomopathogenic nematodes [12]

- Sensitive to environment: They are easily damaged by sunlight (UV) and high temperatures.
- More expensive: They usually cost more than chemical insecticides.
- Need repeated use: After killing pests, nematode numbers drop, so re-application is often needed.
- Only work in soil: They cannot control insects that live on leaves or above the ground.
- Short shelf life: They must be stored and used quickly.
- Special application needed: They should be applied early morning or evening, and the soil must be watered before and after application to help them move into the soil.

2.2.Biochemical Pesticides

Biochemical pesticides are a category of biopesticides obtained from natural sources with the same structure and function as a naturally occurring chemicals and manage pests through non-toxic mechanisms. They are commonly grouped into plant-derived extracts, semiochemicals, and insect growth regulators [7]. These chemicals work by modifying insect's physiology and control pests without directly killing them [42].

2.2.1. Plant-Derived Extracts

Phytochemicals, also referred to as botanical or herbal pesticides, are substances of plant origin (plant-based extracts and essential oils) and have gained recognition as environmentally friendly alternatives to synthetic insecticides for effective pest management. These natural products contain diverse bioactive compounds that can function as attractants, repellents, or feeding deterrents, interfering with insect host recognition, egg-laying behaviour, and feeding activity [7,43].

Each phytochemical has a unique chemical structure and fulfils diverse biological roles in plants, including protection, stimulation of growth, and reproduction [44]. Botanical extracts and essential oils are derived from various plant parts, including fruits, bark, leaves, and seeds. They are mainly used for controlling insect pests, although some also exhibit activity against plant diseases [12]. Because they contain numerous bioactive components with antiparasitic, antibacterial, antifungal, antiviral, and insecticidal activities, phytochemicals are increasingly regarded as promising alternatives to synthetic pesticides. Most of these compounds are plant secondary metabolites, including (1) terpenes, which comprise phytovolatiles and glycosides, and (2) sterols and phenolic substances such as phenolic acids, lignin, tannins, and alkaloids as well ass and nitrogenated compounds that exhibit pesticidal activity. Secondary metabolites play a central role in plant defence against insect pests by functioning as toxins, growth regulators, repellents, and feeding deterrents (antifeedants) [45]. They can also function by inhibiting respiration and causing metabolic dysfunction. Phytochemicals can be isolated from plant materials using techniques such as solvent extraction, microwave-assisted extraction, and ultrasound-assisted extraction, depending on the types of compounds present [46]. Pesticidal action of some essential oils is shown in **Table 6**.

Table 6. Pesticidal action of some essential oils [2]

Essential oil	**Mode of action**
Insecticides and Growth Regulators	
Eugenol	Termiticide, fumigant, feeding detergent, and toxic to many species
Orange oil extracts from citrus peel (containing 92% d-Limonene)	96 and 98% mortality of Formosan subterranean termite (*Coptotermes formusanus* shiraki) within five days
Citronellal, eugenol, menthol, pulegone, and thymol	Moderate active against various mites
Diterpene, 3-epicaryotin	Reduces growth of European corn borer
Menthol	Reduces growth of European corn borer
1, 8-Cineole from *Artemisia annua*	A potential insecticide
Turmeric plant oil	Very useful in pest control

Essential oil	**Mode of action**
Fumigants	
Pulegone, linalool, and limonene	Effective fumigants against rice weevils
Mentha citrata oil containing linalool and linalylacetate	Significantly toxic to rice weevils
Trans-anethol, thymol, 1, 8-cineole, carvacrol, terpineol, and linalool	Fumigants against *Tribolium castaneum*
Anethol combined with 1, 8-cineole (1:1)	Reduces the population of *T. castaneum*
Antifeedants	
Thymol, citronellal, and a-terpineol	Effective as feeding deterrent against tobacco cutworm
1, 8- Cineol	Antifeedant against *T. castaneum*
Terpenoid lactone	Antifeedant against granary weevil
Essential oil of marjoram and rosemary oil	Antifeedant against onion thrips
Essential oils from *Elsholtzia densa* and *E piulosa*	Antifeedant against third instars of *S. litura*
Repellents	
Monoterpenes, eremophilane sesquiterpenes, eremophilane sesquiterpenes derivatives from the heartwood of Alaska yellow cedar	Active against *Ixodes scapularis* and *Aedes aegypti* adults
Carvacrol	Active against ticks, fleas, and mosquitoes
Citronellal	More effective than eugenol and cineole against mosquitoes
Essential oils from *Cinnamomum* species	Effective mosquito larvicides
Fruit oil of Piper retrofractum	High repellence (52-90%) against *T. castaneum* at 0.5-2% concentration
Oviposition Inhibitors and Ovicides	
1, 8-Cineole and marjoram at concentrations of 1.0%	Reduce oviposition rate by 30-50%

Essential oil	**Mode of action**
Calamus oil	Prevents oviposition of *Callosobruchus maculatus*
Garlic oil	Oviposition deterrent, toxic to eggs
Essential oil of *Aegle marmelos*	Reduces 99.5% egg hatching in *Spilosoma obliqua* at 250 mg 250 egg
1-carvone	Completely suppresses the egg hatching of *T. castaneum* at 7.22 mg/cm^2 surface treatment
Carvacrol, carveol, geraniol, carvones, linalool, menthol, terpinol, thymol, fenchone, menthone, pulegone, thujone, verbenone, cinnamaldehyde, citral, citronellal, and cinnamic acid	Ovicides against *Musca domestica* egg
Attractants	
Geraniol and eugenol	Effective attractants used in traps to lure Japanese beetles
Methyl-eugenol	Used to trap oriental fruit flies
Cinnamyl alcohol, 4-methoxy-cinnamaldehyde, geranylacetone, and a-terpineol	Attractants to adult corn rootworm beetles
1, 8-Cineole	Attractant to western flower thrips
Terpenes and geraniol from lemon essential oil	Attractants to thrips, fungus, gnats, mealybugs, scale, and Japanese beetles
Cis-jasmone	Effective attractant to adult *Lepidoptera*
Sandalwood oil, basil oil, grapefruit oil, and other aromatics	Attractants to greenhouse whitefly

Essential oils are generally safer for people and animals than chemical pesticides when used correctly, although some must be handled carefully. Their effectiveness often comes from a combination of many natural compounds working together, not just one ingredient. The quality of an oil can varies depending on the plant part used, how it is extracted, where it is grown, and the season [47].

One of the most widely used botanical insecticides is neem oil, obtained from the neem tree *Azadirachta indica*. Its active constituents, particularly azadirachtin and solanine, disrupt insect development and suppress feeding [48]. Neem products can control various insects, including mealybugs, aphids, thrips, whiteflies and locusts. When azadirachtin enters an insect body (by ingestion or physical contact), it prevents it from feeding or growing normally. It also has repellent properties [49].

Commercially available biochemical pesticides typically include 3% neem oil formulations or 5% neem seed kernel extract concentrates, which are applied at approximately 25 kg ha^{-1} to control major agricultural pests [12]. Research has shown that combining neem oil with the entomopathogenic fungus *Beauveria bassiana* can provide strong control of sucking pests in vegetable crops [50]. However, the concentration of azadirachtin must be carefully optimized to prevent negative effects on non-target organisms [51]. Another important plant-derived insecticidal compound is pyrethrin, extracted from chrysanthemum flowers *Tanacetum cinerariifolium*. Pyrethrins act primarily by deterring herbivorous insects from feeding and have been widely studied for their insecticidal properties [52]. Other active compound is thyme oil, which is extracted from the leaves of the thyme plant and contains thymol as one of its main active compounds. It is effective in pest management by repelling insects and also shows activity against certain fungal plant diseases [49]. As well commonly used plant-based biopesticides include, Nicotine (from *Nicotiana species*), Pyrethrum (from *Dalmatia pyrethrum*), Ryanodine (Rayania; from *Ryania speciosa*) [12]. Commercially available biochemical plant-based pesticides are provided in **Table 7**.

Table 7. List of commercially available biochemical pesticides [12]

Plant source	**Target pest**	**Commercial name/compounds**
Azadirachta spp., *Nicotiana* spp.,	Aphis craccivora, bollworms, aphids, jassids, thrips, whitefly, leaf folder, pod borer, fruit borer, leafhopper, diamondback moth	Essential oils, nicotine, azadirachtin, salanin, nimbin, (leaf, seed, kernel) nimbecidin, bionimbecidin

Plant source	**Target pest**	**Commercial name/compounds**
Chrysanthemum cinerariaefolium *Lonchocarpus* spp. *Ryania* spp.	Crawling and flying insects such as cockroaches, ants, mosquitoes, termites	Pyrethrium, rotenone, ryanodine
Artemisia annua	*Helicoverpa armigera*	Essential oils from leaf and seed
Vinca rosea	*Helicoverpa armigera*	Essential oils from leaf and seed
Ocimum basilicum, *Salvia Officinalis*	*Aphis craccivora* Koch, *Agrotis ipsilon*	Essential oils form aerial parts leaves
Citrus spp.	Fleas, aphids, mites, paper wasp, house cricket	D-limonene linalool
Schoenocaulon officinale	Bugs, blister beetles fly, caterpillars, potato leafhopper	Sabadilla dust
Adenium obesum	Cotton pest	Chacals Baobab (Senegal)

Herbal pesticides work in several ways. They can enter an insect's body through the outer skin, be breathed in, or be eaten with food. Once inside, they affect the insect's body functions, chemical processes, and nervous system. Some of these substances block the insect's breathing openings (spiracles), causing the insect to suffocate. At the cell level, herbal pesticides disturb how signals are sent in the insect's body by damaging ion channels and pumps in cell membranes. They also affect the insect's hormone system, especially the hormones responsible for growth and development, which can lead to deformities. Other effects include shorter mating time, fewer eggs being produced, and lower egg survival. Certain compounds in essential oils, such as monoterpenes, act on the insect's nervous system by blocking an important enzyme (acetylcholinesterase) needed for nerve signals. This causes paralysis and eventually kills the insect. These substances may also interfere with the production of DNA, RNA, and proteins in insect cells [12] (**Figure 8**).

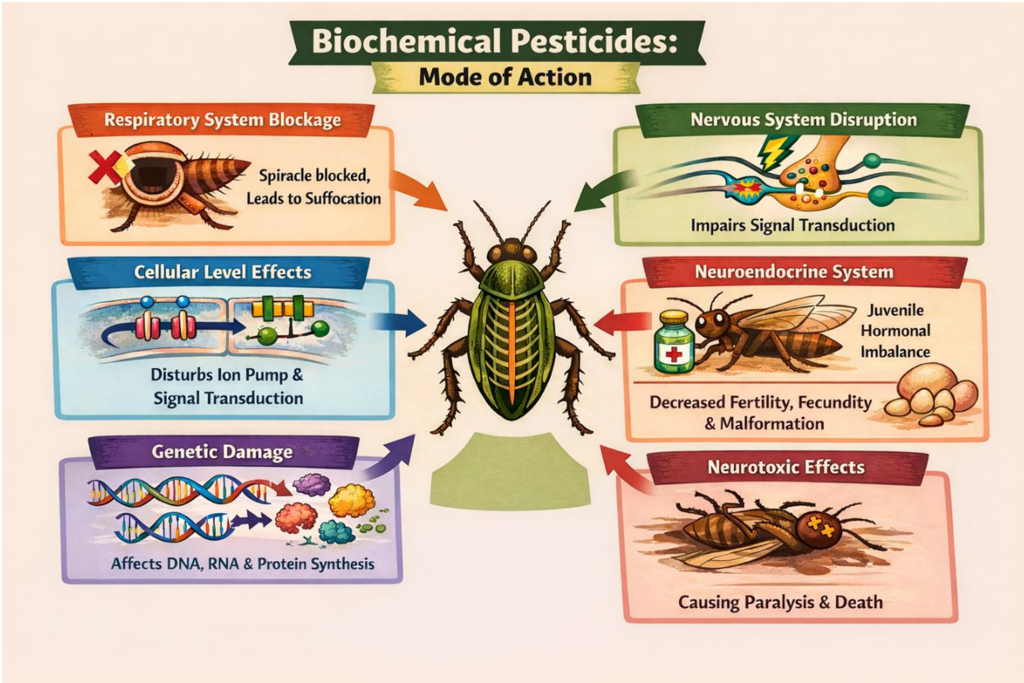

Figure 8. Mode of action of biochemical pesticides. Source: Generated with ChatGPT (DALL·E)

2.2.2 Semiochemicals

Semiochemicals are chemical compounds produced by organisms naturally that allow them to communicate with one another by chemical signals. They help insects communicate with each other about food, danger, and mating. Semiochemicals can be used in pest management to monitor and control pests. They do not directly kill pests. Rather, they influence how pests communicate and interfere with their usual behaviour.

There are two main types of semiochemicals: *pheromones*, which work between insects of the same species, and *allelochemicals*, which work between different species [49, 53].

Among *pheromones*, releaser pheromones produce immediate behavioural changes in the receiving organism. This group includes sex pheromones, aggregation pheromones, alarm pheromones, and trail pheromones. Some pheromones change behaviour of pests immediately. For example, aggregation pheromones attract insects to a food source, alarm pheromones warn others of danger and make them move away, trail pheromones help insects follow a path, and sex pheromones help males and females find each other for mating. Synthetic versions of sex pheromones are widely applied to control pests. They are commonly used for pest monitoring, disrupting mating behaviour, and large-scale trapping of insect populations. Artificial sex pheromones are used to check how many pests are in a field, to confuse insects so they cannot mate, and to trap large numbers of pests. This helps reduce pest populations without using harmful chemical sprays [12].

Allelochemicals are substances released by one organism that can be detected and responded to by individuals of another species. The four types of allelochemicals are allomones (beneficial to the transmitter), kairomones (beneficial to the recipient), synomones (beneficial to both), and apneumones (from non-living sources). For example, kairomones are typically derived from plants and act as attractants for pests. They are primarily used for pest monitoring within IPM programs. The semiochemical kairomone is used to control the coffee berry borer by mimicking the aroma of ripe coffee berries, thereby attracting female insects. When combined with trapping systems, it enables effective monitoring of infestation levels and supports timely decision-making for pest control measures [49].

Various behavioural and physiological effects of semiochemicals are known; however, their influence on pest behaviour in pest management mainly occurs through three mechanisms [49]:

- *Attraction***:** the semiochemical serves as a bait, drawing pests to a specific location where they can be captured.
- *Mating disruption/confusion:* the semiochemical interferes with pest orientation and communication, preventing individuals from locating mates. Consequently, reproduction is reduced and the pest population declines.
- *Repulsion:* certain semiochemicals drive pests away from crops, thereby protecting plants from damage.

Farmers and pest managers can use semiochemical to monitor, attract, repel, or confuse pests without relying only on chemical pesticides. To apply both conventional and alternative pesticides effectively, continuous monitoring of pest populations is essential. One additional approach is the use of semiochemicals that suppress insect feeding. However, the most commonly used and practical method is the application of semiochemicals to attract pests into traps, where they are captured and eliminated. This approach helps reduce pest populations while also decreasing the need for chemical spraying [54].

The application of semiochemicals depends largely on the product formulation and its mode of action. In most cases, they are placed in dispensers that gradually release the active compound into the surrounding environment. These dispensers may take the form of vials, small sachets, rubber tubes, capsules, or similar devices. For example, pheromone-releasing capsules designed to attract the tomato leaf miner can be placed inside traps to capture the insects drawn to them (**Figure 9**). To ensure effectiveness, semiochemical dispensers must be strategically positioned in the field. In many cases, they are combined with trapping systems to enable pest control or monitoring. Since the active compounds disperse only over a limited distance, multiple dispensers are usually required to provide coverage across an entire field. A semiochemical (pheromone) dispenser attached to a branch to disrupt the reproduction of sweet corn pests is shown in **Figure 10**. List of commercially available semiochemicals is given in **Table 8**.

Figure 9. A pheromone dispenser attracting adults of the tomato leaf miner in a delta trap. Credit: Image by CABI, licensed under CC BY-NC-SA 4.0 [55]

Figure 10. A semiochemical (pheromone) dispenser attached to a branch to disrupt the reproduction of sweet corn pests. © Eugene E. Nelson via Bugwood.org [55]

Semiochemicals can be used for two main purposes: direct and indirect control. Key strategies include [49]:

- *Mass trapping and attract-and-kill*: semiochemical dispensers are placed inside traps or incorporated into trapping devices, such as pheromone-coated sticky traps. In this way, pests are either removed from the population (*mass trapping*) or eliminated (*attract-and-kill*).
- *Mating disruption*: sex pheromone dispensers are distributed strategically throughout the field to prevent pests from locating mates.
- *Detection and monitoring*: traps baited with pheromones or kairomones are used to detect pests or estimate population density, helping determine the most appropriate moment to control pest.

Table 8. Commercially available semiochemicals

Product name (Producer, country)	**Pests**	**Action**
Pherogen Spray FAW® (Provivi do Brasil Serviços Agrícolas Ltda, Brasil)	Fall Armyworm (*Spodoptera frugiperda*)	is based on sex pheromones that prevent males from finding females to mate. As a result, the population of Fall Armyworm gets smaller. Fall Armyworm is one of the most destructive agricultural pests worldwide, particularly affecting maize, soybean, cotton, and other crops.
Pherodis® (Koppert B. V., The Netherlands)	To attract male moths, beetles, mealybugs and flies to traps	is a product containing sex pheromones that attract males of the tomato leaf miner. To control the pest, the product works in combination with a trap. For early detection of pests
Bio Broca® (Bio Controle - Métodos de Controle de Pragas)	Coffee berry borer (*Hypothenemus hampei*)	is a semiochemical that contains a kairomone. It can manage the coffee berry borer. In this case, the kairomone imitates the smell of ripe coffee fruits and attracts females of the pest. By using Bio Broca® together with a trap for monitoring the level of coffee berry borer infestation and decide when to act.

Advantages of pheromones [2]

- High efficiency at low doses: Very small amounts of pheromones are sufficient to attract and control large insect populations, making the method cost-effective.
- Environmentally safe: Pheromone-based devices are non-toxic and pose no risk to ecosystems or human health.
- High species specificity: Only the target pest is affected, while non-target and beneficial organisms remain unharmed.
- Long-range attraction: Pheromone traps attract insects over long distances, enabling efficient control with reduced labour input.

- Reliable population monitoring: They provide a simple and accurate tool for tracking pest population dynamics.
- Versatile surveillance use: Pheromone techniques are suitable for monitoring pest movement and entry points.
- Early detection of invasive species: They support rapid identification of new or invasive pests, enabling timely prevention and control strategies.

Limitations of pheromone-based technologies [2]

- Limited coverage across pest species: Pheromones have not yet been identified or developed for all economically important pests.
- Sex-specific action: Due to their high specificity, many sex pheromones attract only one sex (typically males), while the other sex may continue to cause crop damage.
- Requirement for specialized expertise: Successful implementation requires trained personnel with technical knowledge and skills, which are often provided by governmental or specialized agencies rather than individual farmers.
- Not suitable for short-term control: Pheromones do not provide immediate pest suppression like chemical pesticides and are therefore best applied as part of long-term IPM strategies.
- Sensitivity to environmental factors: Pheromone technologies are technically demanding and influenced by temperature, wind, rainfall, and pressure, necessitating careful handling during production, storage, transport, and field application.

2.2.3. Insect Growth Regulators

Insect growth regulators (IGRs) are insecticides that interfere with the growth and development of insects. They disrupt the development and reproduction of insects by mimicking or blocking natural hormones. They do not kill insects immediately but prevent them from maturing or reproducing, leading to population decline over time. They work against different insects like mosquitoes, fleas, and cockroaches. Types of IGRs and their modes of action are summarised in **Table 9.** They mainly include juvenile hormone analogues (JHAs), ecdysteroids analogues, and chitin synthesis inhibitors (CSIs) [2, 56].

Table 9. Commercially available IGR's formulations [2]

IGR	**IGR compound/ trade name(s)**	**Mode of action**	**Target pests**	**Benefits**
Juvenile hormone analogues (JHAs)	Methoprene (Altosid) Hydroprene (Gencrol) Kinoprene (Enstar AQ) Fenoxycarb (Insegar 25 WG) Pyriproxyfen (NyGuard, Admiral 10 EC)	Mimics juvenile hormone (JH), preventing insects from molting into the adult stage. Affected insects remain in the larval or nymph stage and eventually die.	Fleas, mosquitoes, cockroaches, ants, stored product pests.	Effective for long-term control in insect life cycles. Safe for humans, pets, and beneficial insects. Works well in liquid, aerosol, bait, and fogging formulations.
Chitin synthesis inhibitors (CSIs)	Diflubenzuron (Dimilin) Chlorfluazuron (Atabron) Flufenoxuron (Cascade) Hexaflumuron (Consult 10 EC) Lufenuron (Match®) Bistrifluoron (Xterm) Novaluron (Pedestal, Mosquiron) Noviflumuron (Recruit III) Teflubenzuron (Nomolt SC) Triflumuron (Alsystin) Fluazuron (Acatek) Flucycloxuron (Andalin)	Prevents insects from producing chitin, an essential component of the exoskeleton. Causes molting failure, leading to death.	Mosquitoes, cockroaches, fleas, termites, and stored product pests	Stops insects from reaching adulthood and reproducing. Works well in baits, sprays, and granules.

IGR	IGR compound/ trade name(s)	Mode of action	Target pests	Benefits
	Buprofezin (Applaud) Etoxazole (TetraSan 5 WDG) Cyromazine (Larvade, Neporex) Dicyclanil (Clikzin)			
Ecdysoids also called moulting hormone (MH)	Tebufenozide (Mimic) Methoxyfenozide (Runner 24% SC) Halofenozide (Mach 2) Chromafenozide (Matrif FI, Matric DI)	Interferes with ecdysone, the molting hormone. Prevents insects from transitioning between life stages.	Whiteflies, aphids, caterpillars, thrips, mosquitoes	Organic and botanical-based option. Works well in Integrated Pest Management programs. Repels and disrupts feeding in some insects.

Juvenile hormone analogues (Juvenoids, JHA mimics). Juvenoids are synthetic compounds that imitate juvenile hormone and are among the most effective hormonal insecticides. They prevent normal metamorphosis in immature insects, forcing them to remain in a juvenile state (preventing insects from molting into the adult stage). As a result, insects undergo abnormal moulting, producing oversized larvae or malformed intermediate stages between larva, pupa, and adult, which are not viable. *Methoprene* is a widely used JH mimic effective against hornfly larvae, stored tobacco pests, greenhouse homopterans, red ants, and leaf-mining flies in vegetables and ornamental plants.

Ecdysteroid analogues (Ecdysoids). These compounds mimic the natural insect hormone ecdysone. When applied to insects, they disrupt normal cuticle formation, producing a defective outer covering. Development is abnormally accelerated, skipping essential growth stages, which results in an integument lacking protective layers such as wax or scales. This leads to dehydration, vulnerability, and ultimately death.

Chitin synthesis inhibitors (CSIs). Compounds in the benzoylphenyl urea group block chitin production by inhibiting the enzyme chitin synthase. Important examples include *diflubenzuron (Dimilin)* and *penfluron*. These insecticides interfere with moulting, cause malformation of mouthparts, prevent adults from emerging properly from the pupal case, and often result in death. They also exhibit strong ovicidal activity. CSIs are registered in many countries and are widely used against pests of soybean, cotton, apples, fruits, vegetables, forest trees, mosquitoes, and stored grain insects.

Natural compounds such as *anti-juvenile hormone compounds (precocenes)* and *neem-based natural IGRs* are used as well.

Anti-juvenile hormone compounds (precocenes). Precocenes found in plants like *Ageratum houstonianum*, that disrupt insect development by causing premature metamorphosis (precocious metamorphosis) and sterility, acting as potential insecticides by targeting the corpora allata (JH-producing glands). Precocenes damage the glands that produce juvenile hormone, thereby disturbing normal insect development. When applied to immature insects, they cause premature development into undersized adults that are unable to reproduce and die shortly afterward.

Neem-based natural IGRs. Extracts from neem leaves and seeds contain azadirachtin as the main active component. When applied to insects, these compounds inhibit growth, cause deformities, reduce survival, and lower reproductive capacity, making them effective natural insect growth regulators.

Application timing is important with insect growth regulators. Products have a brief period of residual activity, and exposure to ultraviolet light can affect longevity, so repeat applications usually are warranted. Insect growth regulators are most active on the early life stages of insects that undergo complete metamorphosis (egg, larva, pupa, and adult). They should be applied as soon as susceptible life stage(s) are noticed, thoroughly covering all plant parts.

Advantages of IGRs

- Provide extended residual activity, remaining effective for weeks or even months.
- Interrupt the insect life cycle, helping to prevent future pest outbreaks.
- Pose minimal risk to humans, pets, and non-target organisms.
- Can be used alongside conventional insecticides to achieve a combined mode of action.

- Help slow the development of resistance to pesticides in pest populations.

2.3. Plant-Incorporated Protectants

Plant-incorporated protectants (PIPs) are pest-control substances that are produced directly by plants after specific genetic material has been introduced into their DNA [57]. For example, scientists can insert a gene that codes *Bacillus thuringiensis* Cry protein into a crop. Once modified, the plant continuously produces this protein, which is toxic to certain insects when they feed on the plant [7]. First-generation insecticidal PIPs were Cry proteins expressed in genetically modified crops containing transgenes from the soil bacterium *B. thuringiensis*; next-generation double-stranded ribonucleic acid (dsRNA) PIPs have been recently approved. In this strategy, pests ingest double-stranded RNA molecules that trigger the breakdown of essential messenger RNA within their cells, ultimately suppressing growth or causing mortality [57].

In the United States, PIPs are regulated as pesticides by the US Environmental Protection Agency (EPA). The agency oversees both the pesticidal protein itself and the genetic material that allows the plant to produce it, rather than regulating the entire plant [58]. Before a PIP is approved for use, the EPA conducts a detailed risk assessment to ensure that it does not pose unacceptable risks to human health or the environment [59]. PIP active ingredients registered 1995-2025 are available in US EPA web page [60]. List of commercially available PIPs is provided in **Table 10**.

Table 10. List of plant-incorporated protectants against crop pests [12]

Plant	Gene incorporated	Resistance to insect	Commercial name
Cotton	Cry1Ac toxins from *Bacillus thuringiensis*	Cotton and tobacco bollworm	Bollgard
Maize	Cry1Ab, 1F, 9c toxins from *Bacillus thuringiensis*	European corn borer	Yieldgard, Knockout, Herculex I, Starlink, Maximizer
Rice	Cry1C from *Bacillus thuringiensis*	Leaf folders (*Cnaphalocrocis medinalis*) and stem borers	Trait in development

Tobacco	QB protein of photosystem II from mutant Amaranthus	Atrazine resistant	
Brinjal (Eggplant)	Cry1Ac from soil *Bacillus thuringiensis*	Shoot and fruit borer (*Leucinodes orbonalis*)	Bt Brinjal
Tomato	Cry1Ab gene of *Bacillus thuringiensis*	Second instar larvae of *H. armigera* and *S. litura*	Bt tomato

3. Biopesticides Formulations

In most instances, biopesticides are formulated in a manner similar to conventional synthetic pesticides, which makes them convenient for farmers to apply using standard equipment. However, because biopesticides are derived from living organisms, maintaining their biological viability during formulation and storage is essential. Biopesticide products consist of both active ingredients and inert or inactive components. The active ingredient is responsible for controlling the target pest, while inert ingredients serve to improve the stability, application efficiency, and overall performance of the product. In essence, a pesticide formulation is a combination of these active and inactive substances [12]. Based on formulation type, biopesticides are generally classified into two main groups [12,61]: dry and liquid formulations.

3.1. Dry Formulations

Dry formulations include dustable powders, granules, seed dressing, wettable powders, and water-dispersible granules.

In *dustable powders* formulations, the active ingredient typically makes up about 10% of the product and is applied by adsorbing it onto finely milled mineral carriers such as talc or clay, with particle sizes generally between 50 and 100 μm. The remaining components include inert substances that serve as ultraviolet protectants, adhesive agents (stickers) to improve adherence to surfaces, and anticaking agents to prevent clumping.

Granular formulations usually contain between 2% and 20% active ingredient, which may either be coated onto the surface of the granules or absorbed into their internal structure. To regulate the release rate of the active substance after application, granules can be further coated with resins or polymer layers. These products are primarily used for controlling soil-dwelling insects, weeds, and nematodes and are taken up through plant roots. Granules generally consist of coarse particles ranging from 100 to 600 μm and are manufactured from materials such as kaolin, silica, starch, polymers, groundnut residues.

Seed dressing is a biopesticide formulation in which the active ingredient is blended with a powdered carrier and suitable inert materials to ensure effective adhesion to the seed surface. These powders are applied by tumbling or mixing the seeds with the formulation so that the product evenly coats the seed coat. In addition, seed-dressing products often include colorants, typically red pigments, which serve as a safety marker to clearly identify treated seeds and prevent accidental use for food or feed.

Wettable powders are finely milled dry formulations that are applied after being mixed with water to form a suspension. They are produced by combining active ingredients with dispersing agents, surfactants, synergists, melting agents, and inert carriers. Because these products generate dust, strict safety precautions are required during manufacturing and application to reduce potential health risks. Despite this, wettable powders are valued for their long shelf life, good compatibility with water, and suitability for use with standard spraying equipment.

Water-dispersible granules are designed to be suspended in water and address many of the limitations associated with wettable powders. They are essentially dust-free and offer improved storage stability, making them safer and more convenient to handle.

3.2. Liquid Formulations

Liquid formulations include emulsions, suspension concentrate, suspension emulsion concentrates, oil dispersion and capsule suspension formulations, ultra-low-volume liquids.

Emulsion formulations are intended to be diluted with water prior to application and may be either oil-in-water or water-in-oil systems. The selection of suitable emulsifying agents is essential to ensure product stability and prevent separation. In water-in-oil emulsions, where oil forms the outer phase, losses due to evaporation and spray drift are reduced, improving application efficiency.

Suspension concentrates are produced by dispersing finely milled solid active ingredients within a liquid medium, typically water. Because the solid particles are not dissolved, continuous agitation is required before and during application to ensure uniform distribution. These formulations generally contain particles in the range of 1–10 μm, and the small particle size facilitates better penetration into plant tissues, thereby enhancing biological effectiveness. Suspension concentrates are widely used due to their relatively low risk to both operators and the environment.

Suspension-emulsions combine the characteristics of both emulsions and suspension concentrates. They represent a technically demanding formulation, as a stable emulsion phase must be successfully integrated with a suspended solid phase to produce a homogeneous and physically stable product. Careful formulation and thorough stability testing during storage are essential to ensure that the final product remains uniform and effective over time.

Oil dispersion formulations are prepared using a process similar to that of suspension concentrates, with the key difference being that the solid active ingredient is dispersed in an oil-based medium rather than in water. Potential instability issues can be minimized through careful selection of appropriate inert components that enhance formulation stability.

In *capsule suspension* formulations, active ingredients are enclosed within microcapsules and dispersed in a stable liquid medium that is diluted with water prior to application. Encapsulation materials such as gelatine, starch, cellulose, and other polymers are commonly used to protect biological agents from unfavourable environmental conditions. One of the most widely applied techniques is interfacial polymerization, which enables the production of small-sized, highly efficient formulations, particularly for fungal biopesticides.

Ultra-low-volume formulations are highly concentrated products that are applied without prior dilution in water. These formulations are easy to transport and can be prepared using suspended biological control agents as the active component, making them suitable for applications requiring minimal spray volumes.

3.3. Biopesticide Application Methods

The performance of biopesticides is influenced by several factors, including their biological activity, formulation, and the method of application. Several methods are commonly used to ensure optimal performance of biopesticides, including the following [62]: seed treatment, seedling dipping, foliar application, aerial application, soil drenching, microbigation.

Seed treatment is one of the most efficient and widely used approaches for applying biopesticides. This method involves coating seeds with beneficial biological agents, such as bacteria, fungi, or viruses, prior to planting. Once applied, these agents form a protective layer around the seed, helping to shield emerging seedlings from soil-borne pathogens and insect pests during germination and early growth.

Seedling dipping (root dipping) method consists of immersing the roots of seedlings in a biopesticide suspension for a specified period prior to transplanting. It is commonly used to protect young plants from soil-borne pathogens. For instance, *Trichoderma* spp. and *Pseudomonas fluorescens* are frequently applied using this technique.

Foliar application is one of the simplest and most commonly used methods for applying biopesticides, particularly for managing pests and diseases that affect above-ground plant parts. This approach involves spraying biologically derived products directly onto leaf surfaces using equipment such as handheld sprayers, backpack sprayers, or boom sprayers. Once applied, the active ingredients are rapidly absorbed or remain on the leaf surface, enabling plants to quickly respond to insect pests and microbial pathogens. Foliar treatments are especially effective against insects, fungal pathogens, and bacteria that colonize plant surfaces, helping to reduce pest populations before substantial crop damage occurs. A key advantage of this method is the precise delivery of biopesticides to the areas where pest pressure is greatest.

Aerial application refers to the distribution of agricultural treatments using aircraft or unmanned aerial vehicles (drones), allowing large areas of farmland to be treated efficiently while reducing labor requirements and ensuring even coverage. This approach is valued for its speed, accuracy, and operational efficiency, contributing to effective pest control, improved crop performance, and reduced soil compaction. The success of aerial spraying is strongly influenced by environmental conditions. Low wind speeds (below 10 mph) are required to limit spray drift, moderate temperatures help prevent rapid evaporation, and relative humidity above 50% promotes adequate droplet adhesion to plant surfaces. Consequently, early morning and late afternoon are generally the most suitable periods for application.

Soil drenching is a practical method for delivering biopesticides directly into the root zone using water-based solutions. This approach allows beneficial microorganisms and bioactive substances to move into the soil, where they can suppress pests while supporting overall plant health. The effectiveness of soil drenching depends on suitable environmental and application conditions.

Microbigation refers to the delivery of biological pest control agents through irrigation systems. This approach combines pest management with soil health improvement by introducing beneficial microorganisms and entomopathogenic nematodes that suppress harmful pathogens, strengthen plant resistance, and support sustainable agricultural practices. By integrating biopesticide application with irrigation and nutrient delivery, microbigation ensures that active agents reach both the root zone and, in some cases, above-ground plant parts, making it particularly effective for controlling soil-borne diseases and enhancing microbial diversity in agroecosystems. The controlled application through irrigation systems prolongs the activity of biopesticides in the soil, decreasing the need for repeated treatments. To ensure effective delivery and prevent clogging of irrigation equipment, microbial biopesticides should be prepared with suitable stabilizers and surfactants. Optimal operating conditions include maintaining water pH between 5.5 and 7.0 to avoid precipitation and blockage, keeping water temperature within the range of 18–25 °C to support microbial activity, and using filtration systems with mesh sizes of 100–200 microns to remove debris. Microbial agents such as *B. thuringiensis* and *Trichoderma* spp. are particularly well suited to this method because of their effectiveness against soil-borne pathogens and insect pests.

Trunk injection is a targeted method for applying biopesticides in which pest control agents are introduced directly into the trunk or stem of woody plants. When injected into the xylem, the active substances are carried throughout the plant by the transpiration stream, providing systemic protection against insect pests such as borers and against fungal diseases. This technique is particularly useful for treating trees and high-value perennial crops where foliar spraying or soil drenching may be ineffective, impractical, or pose environmental risks. A major benefit of trunk injection is its high delivery efficiency combined with minimal environmental impact. In contrast to aerial spraying or soil applications, this method prevents spray drift, limits operator exposure, and reduces contamination of non-target organisms. As a result, trunk injection is widely employed in forestry, urban tree management, and commercial crop production, including in plantations of avocado and citrus. Biopesticides applied through trunk injection commonly include microbial agents, plant-derived extracts, and carrier compounds that support movement within the vascular system. Entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* act by infecting insect pests and interfering with their physiological processes. In addition, botanical products, including essential oils such as mint and cinnamon, have demonstrated the ability to translocate within plant tissues and provide protective effects against pests.

A consolidated overview of the several application methods, outlining their respective strengths, weaknesses, opportunities, and threats is provided in **Table 11**.

Table 11. SWOT analysis of selected modes of biopesticides application [62]

Element	Aerial application	Foliar spray	Soil drenches	Seed treatment	Seedling root dip	Microbigation	Trunk injection
Strengths	Rapid coverage of large areas; ideal for inaccessible terrains	Quick biopesticide uptake; direct targeting of pests on leaves	Targets root-zone pathogens; long-lasting effects	Early plant protection; lower chemical use	Prompt protection at transplanting; easy to apply in nurseries	Promotes soil health; effective distribution	Precise delivery; minimal environmental exposure
Weaknesses	High risk of drift; expensive equipment and training required	Short residual effect; can cause leaf burn if misapplied	Potential for leaching; labor-intensive for large fields	Limited to early-stage protection; affects germination if overdosed	Labor-intensive; limited to small-scale or transplant crops	Requires compatible irrigation setup; risk of clogging	Precise delivery but limited to woody plants
Opportunities	Integration with drones and GPS for precision farming	Nanoformulations for delivery; sustainable bioformulations	Slow-release formulations; integration with fertigation systems	Enhancing seed vigor; precision seed coating technologies	Use of beneficial microbes for improved establishment	Expanding use in organic farming; synergy with fertigation	For high-value crops/trees; advancement of auto-injection tools

Threats	Negotiating regulatory restrictions	Drift and runoff risks; pest resistance development	Soil structure impact; groundwater contamination	Resistance buildup	Root damage risk	Biofilm formation in systems	Tree injury risk
Case study notes	Agricultural UAVs are extended to crop monitoring, soil and field analysis, and bird control	Drone-assisted foliar spray in agriculture reduces the need for manual labor by up to 50%	Soil drenching helps manage root-knot nematodes, fungal pathogens, aphids, and scale insects	The most reported types of seed coating are seed dressing, film coating, and pelleting	Phosphorus is critical for seedling root dip success in plant wellbeing	Conidial suspensions (10^6 conidia ml^{-1}) pass drippers unclogged regardless of size, remaining viable	Highlight of potentially systemic acquired resistance (SAR) induction by these essential oils

4. Beneficial Insects - Natural Enemies of Pests as Biocontrol Agents

Natural enemies such as parasitoids and predators are widely used to control insect and mite pests in crops. Most parasites and disease-causing agents, along with many predators, show a high degree of host specificity and usually target only a narrow range of closely related pest species. Integration of natural enemies into IPM programs forms the cornerstone of success, ensuring population suppression, crop vitality, and reduced chemical use [63]. These beneficial organisms can be native or introduced species with a particular preference for specific pests, making them highly effective in reducing pest numbers without causing harm to the environment or other non-target organisms [64].

Parasitoids are insects that develop on or inside a single pest insect and eventually kill it. They lay their eggs on or inside the pest's body. When the larvae hatch, they feed on the pest's internal tissues and body fluids. The pest dies as the parasitoid completes its development. The most important parasitoids used in agriculture belong to the *Ichneumonidae* and *Braconidae* wasp families. Some parasitic wasps and flies attack caterpillars and can also control other pests such as aphids. Tachinid flies are especially useful because they parasitize many pests, including caterpillars, beetle larvae, and adult insects. For biological control to work well, parasitoids should: target specific pests, reproduce effectively and adapt to different weather and field conditions.

Predators are free-living insects or mites that hunt and eat pests throughout their lives. They are usually larger than their prey and can consume many pests over time. Predators actively search for pest insects on crops or remain in one place and attack when prey comes within reach. After locating a pest, the predator captures, kills, and consumes it. Sometimes both immature and adult stages of predators feed on prey, for example, ladybirds; however, sometimes only one of the life stages is predatory, such as lacewings that only predate as larvae [49]. Common and effective predators include: *Brumoides* (ladybird beetles), *Chrysoperla* (green lacewings), dragonflies and damselflies, parasitic wasps, predatory mites and others. These beneficial insects are strong predators that feed on many common pests, including aphids, whiteflies, thrips, mealybugs, and spider mites [12]. When they are released into a greenhouse, they help create a natural balance by keeping pest populations at low and manageable levels [65]. Some pests and their common natural enemies are provided in **Table 12**.

Table 12. Some pests and their common natural enemies [66]

	Natural enemies				
Pests	**Lacewings**	**Lady beetles**	**Parasitic flies**	**Parasitic wasps**	**Predatory mites**
Aphids	X	X		X	
Carpenterworm, clearwing moth larvae				X	
Caterpillars (e.g., *California oakworm*)	X		X	X	
Cottony cushion scale		X	X		
Elm leaf beetle			X	X	
Eucalyptus longhorned borers				X	
Eucalyptus redgum lerp psyllid				X	
Giant whitefly	X	X		X	
Glassy-winged sharpshooter	X			X	
Lace bugs	X	X		X	
Mealybugs	X	X		X	
Psyllids	X	X		X	
Scales	X	X		X	X
Slugs, snails			X		
Spider mites	X	X			X
Thrips	X			X	X
Weevils, root or soil-dwelling				X	
Whiteflies	X	X		X	

4.1.Ladybugs

Ladybugs (ladybird beetles) are a good example. They are well known for feeding on aphids, one of the most damaging greenhouse pests. A single ladybug can eat dozens of aphids in one day, making them a very effective tool for pest management. They are usually applied using small plastic containers with live adult insects inside. In cases of heavy infestation, about 5,000–8,000 ladybugs per acre may be required. Studies have shown that using ladybugs can reduce aphid populations by more than 50% in most situations [67].

Adult ladybugs (**Figure 11, right**) are easy to recognize when they have the familiar red or orange bodies with black spots. However, their immature stages (**Figure 11, left**) are much harder to identify, and many beneficial larvae or pupae are mistakenly destroyed because they are not recognized as helpful insects. Both larvae and adults' prey on many small insects and will attack any pest stage that is small enough for them to capture.

Figure 11. Immature life stage (left) and adult life stage (right) of a ladybug. © CABI (left) and Gilles San Martin via Flickr CC BY-SA 2.0 (right) [41]

4.2. Lacewings

Lacewings may look fragile, but they are excellent hunters, especially against aphids and small soft-bodied insects. The development of lacewings goes through four distinct life stages. It begins with the egg stage: the eggs laid individually on thin silk stalks. After about five days, the eggs hatch and the larval stage begins. This stage lasts approximately two to three weeks. During this period, the larvae maintain the same overall appearance but grow steadily in size as they feed. Once fully developed, the larvae spin a silken cocoon and enter the pupal stage, remaining inside for about 10–14 days while they undergo transformation. The final stage is the adult lacewing, which can be recognized by its large, delicate, lace-like wings (clear or light brown), long antennae, and soft body measuring about 12–20 mm in length [68].

While adult lacewings primarily feed on nectar and pollen, their larvae are powerful natural enemies of pests (**Figure 12, left**). Equipped with long, needle-like mouthparts, the larvae actively hunt, seize, and consume small, soft-bodied insects. This strong predatory capacity, combined with the possibility of rearing them in large numbers, has made lacewings a reliable and widely adopted option for augmentative biological control. In crop management, lacewing larvae are commonly introduced to suppress aphid populations, as a single larva can eliminate roughly 200–400 aphids during its development. Beyond aphids, lacewings are also effective against mealybugs, leafhoppers, spider mites, and several other economically significant pests and their eggs (**Figure 12, right**).

Lacewings are available for purchase as eggs, larvae, or adults, and the most suitable form depends on the goal of the treatment. Eggs are simple to distribute in the field, but because they require time to hatch, they are most appropriate for preventive use rather than immediate pest suppression.

Figure 12: Lacewing larva eating an aphid (left) and western been cutworm eggs (right). Photo by: Cristhian Ochoa (left) and John Obermeyer (right) [68]

4.3.Parasitic Wasps

Most parasitic wasps are very small and easily overlooked, and species that attack insect eggs are even tinier - often nearly microscopic. As a result, farmers and gardeners are frequently unaware that these parasitoids are actively helping to suppress pest populations. Occasionally, they may be observed moving rapidly across leaf surfaces, tapping with their antennae as they search for chemical cues left by potential hosts. Parasitic wasps lay their eggs on or inside other insects, most commonly in the egg or larval stages of the host. The developing wasp larva grows either inside or on the surface of the host insect, ultimately killing it. Typical signs of parasitism include weakened caterpillars with emerging parasitoid larvae or dead hosts from which a cocoon is suspended. These wasps play a vital role as natural enemies of many agricultural pests, including caterpillars, beetle grubs, whiteflies, and aphids [69].

4.4.Predatory Mites

Predatory mites like *Phytoseiulus persimilis* and *Neoseiulus californicus* are highly specialized and are particularly effective against spider mites, which are tiny but can cause serious crop damage if not controlled [63]. *Phytoseiulus persimilis* is a specialist predator of spider mites across multiple life stages, including eggs, larvae, and adults. It is extremely effective in controlling outbreaks under warm and humid conditions. This red predatory mite consumes large quantities of spider mites daily. A generalist predator, *Neoseiulus californicus* tolerates broader environmental conditions and feeds on low densities of spider mites, making it ideal for preventive control.

Advantages of using predatory mites [63]

- Precise pest control: Predatory mites attack spider mites at every stage of their life cycle.
- Safe for beneficial organisms: They provide a natural control method without harming pollinators or other beneficial species.
- No resistance issues: Unlike chemical treatments, pests do not develop resistance to biological predators.
- Residue-free: Their use leaves no chemical residues, helping growers comply with residue limits and organic production standards.
- IPM-friendly: Predatory mites can be easily integrated with other biological agents and selective pesticides within an IPM program.

4.5. Parasitic Flies

Several species of parasitic flies are known to attack insect pests. In many cases, eggs are deposited directly on the surface of the host. Following hatching, the larvae penetrate the host body and ultimately cause host mortality. Unlike most parasitic wasps, however, parasitic flies lack the elongated ovipositor used to insert eggs into host tissues [69].

4.6. Application of Predatory and Parasitoid Macrobials in Biological Control

Predators and parasitoids are typically introduced directly into the crop environment, eliminating the need for specialized application equipment. They may be released either in their immature, non-predatory stages (for example, as eggs) or in active predatory stages. Immature organisms require time to develop before becoming effective in pest suppression, whereas individuals released in their predatory form can begin controlling pests immediately. Several delivery methods are commonly used to introduce predators and parasitoids into the field [49]:

- *Slow-release (breeder) sachets*: These sachets contain both beneficial organisms and a food source, allowing them to survive, reproduce, and be released gradually over an extended period. The sachets are typically attached to crop plants, enabling continuous dispersal of the biocontrol agents over several weeks.
- *Release cards*: This method is frequently used for *Trichogramma* parasitoids. Parasitoid eggs are affixed to cards, from which adults later emerge and seek out host pests. The cards are hung or secured directly onto plants.
- *Bottles*: Some predatory species are supplied in containers from which they can be manually dispersed by emptying the contents onto the crop.
- *Perforated bags*: In this method, beneficial organisms are packaged in bags with small openings. When suspended on plants, predators or parasitoids gradually exit through the perforations and spread into the crop canopy.

To get the best results from predatory insects and parasitoids, it is important to help them survive and work in your fields or greenhouses. When these beneficial insects are healthy, they can multiply and control pests for a longer time. Key good practices [49]:

- *Avoid spraying chemicals*: Do not use chemical pesticides in areas where beneficial insects are released. Many pesticides kill both pests and helpful insects.
- *Provide extra food*: Plant flowering strips or cover crops to give beneficial insects nectar and pollen. You can also use special food products when pest numbers are low.
- *Offer shelter*: Keep hedgerows, field borders, or other natural areas. These places protect beneficial insects from harsh weather and give them a place to live.

5. Companion Planting

Companion planting is one specific type of polyculture, under which two plant species are grown together that are known, or believed, to synergistically improve one another's growth. Growing two or more plant species together so that one plant helps protect another from insect pests. Companion plants can: confuse pests, repel pests, attract pests away from the crop and attract beneficial insects (predators and parasitoids). This strategy is widely utilized by organic growers as part of IPM [70].

Insect pests use different signals to find and choose their host plants. Therefore, understanding how a pest searches for its crop is very important when selecting an effective companion plant. Pests locate host plants using mainly two types of signals: smell and sight. Smell (chemical cues) is used at long distances, when insects follow plant odours carried by the wind, while sight (visual cues) becomes important at closer range, when insects use the plant's size, shape, and colour to decide where to land and lay eggs. Because of this, a good companion plant should work in one or more of the following ways: disrupt plant odours, so the pest cannot detect the crop easily; hide or mask the crop visually, making it harder to recognize; combine both effects, confusing the pest by smell and sight at the same time.

5.1. Plants That Draw Pests Away

Trap crops are plants grown specifically to attract pest insects away from the protected crop, drawing them to a separate area where they can be managed more easily. It works, when a very attractive plant is planted near the main crop and pests prefer the trap crop and move there instead of the main crop. Farmers may monitor the trap crop and destroy or treat only the trap crop, rather than the whole field. Trap crops must be more attractive than the main crop and planted in the right place (often field borders). There are many successful examples of trap cropping in practice (**Table 13**).

The need to manage pests within the trap crop itself can be reduced by using so-called "dead-end" trap crops. This approach relies on plants that are highly attractive for egg laying, but do not allow the pest's offspring to develop successfully. For example, the diamondback moth (*Plutella xylostella*), an important pest of Brassica crops, readily lays eggs on the G-type of yellow rocket (*Barbarea vulgaris*). However, the larvae are unable to survive on this plant because it contains feeding-deterrent compounds, such as monodesmosidic triterpenoid saponins, which prevent normal development.

Table 13. A few successful examples of trap cropping by companion plants [70]

Main crop (protected)	**Pest**	**Trap crop used**	**Type of trap crop**	**Key reason / Note**
Cotton (California)	*Lygus* bugs	Alfalfa	Standard trap crop	Nearly eliminated insecticide spraying by concentrating pests in alfalfa
Soybean	Mexican bean beetle	Snap bean	Standard trap crop	Beetles strongly preferred snap beans over soybean
Potato (Belorussia, >50 years)	Colorado potato beetle	Early-planted potato	Standard trap crop	Early potatoes protected later plantings for decades
Brassica crops	Diamondback moth	*Barbarea vulgaris* (G-type)	Dead-end trap crop	Larvae could not survive due to toxic saponins
Potato	Colorado potato beetle	*B. thuringiensis* modified potato (early planted)	Dead-end trap crop	Early-arriving beetles killed by *B. thuringiensis* toxins
Cauliflower (Finland)	Pollen beetle (*Meligethes aeneus*)	Chinese cabbage + marigold + rape + sunflower	Diverse trap crop	Multi-species trap more attractive than single species

Main crop (protected)	Pest	Trap crop used	Type of trap crop	Key reason / Note
Broccoli	Crucifer flea beetle	Pacific gold mustard + pac choi + rape	Diverse trap crops	Three-species mixture gave highest crop protection

Trap crop effectiveness can be improved by using several plant species at the same time. Diverse trap crops combine plants with different chemical traits, physical structures, and growth patterns, making them more attractive to pests than single-species traps. The success of trap crops depends on a number of variables, such as the physical layout of the trap crop (e.g., size, shape, location) and the pests' patterns of movement behaviour. Trap crops are most effective when they remain attractive for a longer period than the main crop and when they are used against mobile pests that can easily move between trap crops and the protected plants [70].

5.2.Plants That Repel

Some plants release smells that disturb pest behaviour and reduce egg laying. Plants with aromatic properties release volatile oils that can disrupt pest behaviour, including host plant location, feeding, movement, and mating, which can lead to reduced pest populations. For example, herbs such as basil grown alongside tomatoes have been reported to repel both thrips and tomato hornworms. Plants belonging to the genus *Allium* (such as onion and garlic) have also been shown to possess repellent properties against a wide range of insects and other arthropods, including moths, cockroaches, mites, and aphids. In addition, many studies have identified numerous companion plants with repellent effects against pests of Brassica crops. These companion plants include sage, rosemary, hyssop, thyme, dill, southernwood, mint, tansy, chamomile, orange nasturtium, celery, and tomatoes. Similarly, intercropping tomatoes with cabbage has been suggested as a mean to reduce infestations of the diamondback moth, while ragweed (*Ambrosia artemisiifolia*) has been used to repel the crucifer flea beetle (*Phyllotreta cruciferae*) from collards (*Brassica oleracea* var. *acephala*), both of which are widespread pests of Brassica crops.

The effectiveness of a repellent plant depends on both the behaviour of the insect and the plant species involved. Consequently, a plant that repels one pest may not be effective against another.

In addition, many studies evaluating the repellent properties of plants have been conducted under laboratory conditions, which do not always accurately reflect how these plants perform in the field. Repellent effects are not always reliable. Results depend on the pest species and field conditions. Repellent plants work best as part of a combined strategy, not alone [70].

5.3.Plants That Mask

Companion plants can release volatile compounds that mask the odors of the main crop and thereby disrupt the pest's ability to locate its host plant. Because it is harder for pests to find the crop, this results in reduced pest landing, egg laying, and damage to the crop. For example, the ability of the cabbage root fly (*Delia radicum*) to locate its host plants was disrupted when the crop was surrounded by a diverse mixture of plants, such as spurrey (*Spergula arvensis*), peas (*Pisum sativum*), rye-grass (*Lolium perenne*), and clover [70].

5.4.Plants That Camouflage or Physically Block

In addition to affecting pests by smell, companion plants can protect crops by hiding them visually and by creating physical barriers that interfere with pest movement and egg laying. Tall or dense plants may block pest movement and flight. Common barrier plants such as maize, sunflower, sorghum and dill may be used by plant in rows or strips between crops as barrier plants to limit pest movement into the crop. They are especially useful against flying insects [70].

5.5.Combinations of Companion Planting Techniques

In some farming systems, different companion planting methods are combined to improve pest control. One successful example is the "push–pull" system (**Figure 13**), widely used in Kenya to control stem borers in maize. In this system repellent plants ("push") are planted within the crop to drive pests away. These include plants such as molasses grass and desmodium. Trap crops ("pull") are planted around the field to attract pests away from the crop. These include Napier grass and Sudan grass. The pests are pushed out of the maize and pulled into the trap crop, where they cause less damage [70]. This method is now used by thousands of farmers in East Africa and has been shown to reduce pesticide use, improve pest control, increase crop yield, and support sustainable farming [71].

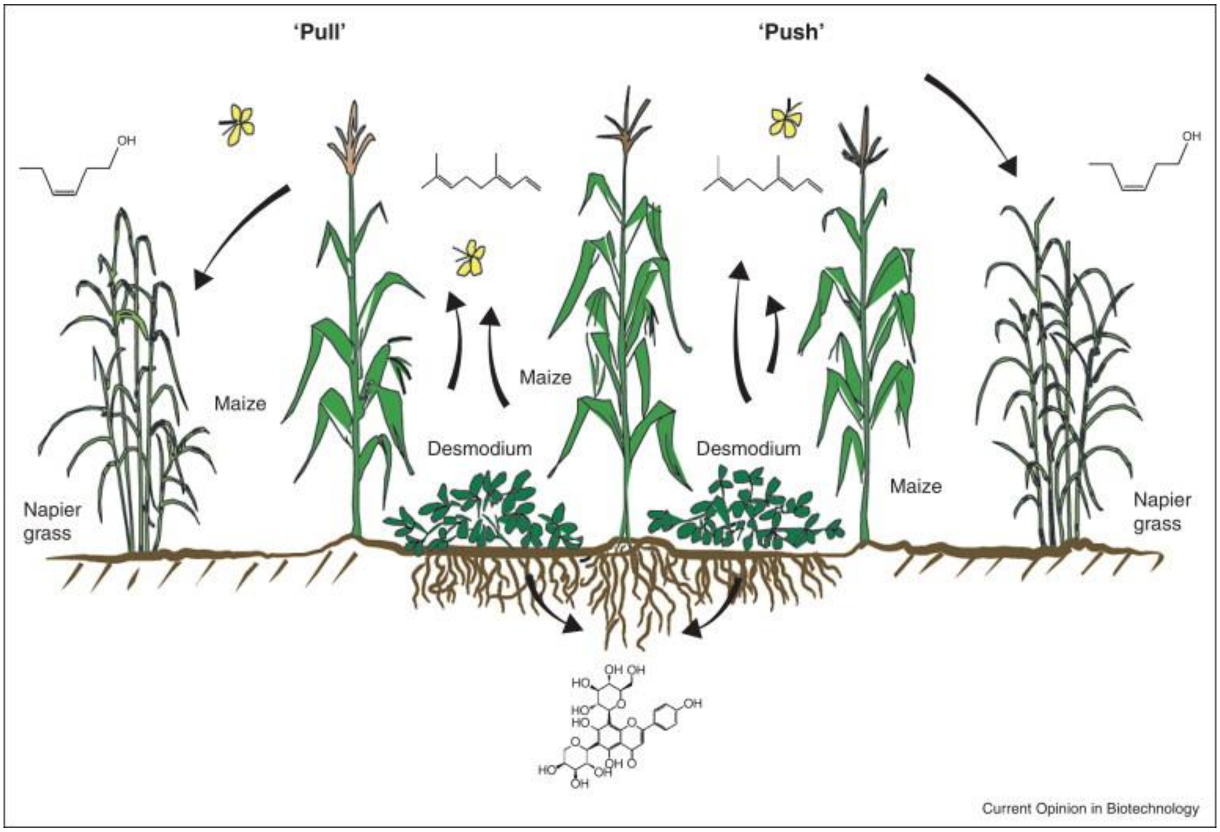

Figure 13. “Push–pull” farming system. Licensed under CC-BY 4.0 [71]

5.6.Plants That Attract Beneficial Insects

Pest populations can be controlled by strengthening the activity of locally occurring natural enemies. This can be achieved by introducing non-crop vegetation, such as flowering plants known as insectary plants, into the cropping system to support and attract beneficial insects. Flowering plants provide nectar, pollen and shelter, this increases populations of beneficial insects such as lady beetles, lacewings, parasitic wasps and other. These insects naturally kill aphids, caterpillars, and other pests. Recommended insectary plants: dill, coriander, buckwheat, phacelia, alyssum [70].

5.7.Use of Companion Plants to Reduce Aphid Infestation

Companion planting can reduce pest numbers and pesticide use, increase beneficial insects and improve sustainability. Best results come from correct plant choice, good field design and combining several methods. Examples that illustrate how companion plants can reduce aphid infestation by repelling insects, masking host odours, and lowering the attractiveness of the main crop is given in **Table 14**. It also highlights the main mechanisms involved, such as repellence, odour masking, and reduced host attractiveness [72]. Companion planting works best as part of IPM.

Table 14. Examples of studies that evaluated the altering effect of companion plant on host plant for different species of aphid [72]

Species of aphid	**Host plant**	**Companion plants**	**Proposed mechanisms**
Myzus persicae	*Capsicum annuum*	*Allium schoenoprasum*	Masking odors; Repellency; Reduces the attractiveness of hosts
Brevicoryne brassicae	*Brassica oleracea Bentley F1*	*Tagetes patula nana; Calendula officinalis*	Repellency
Myzus persicae	*Nicotiana tabacum*	*Allium sativum*	Repellency; Deterrent effect
Myzus persicae; Aphis gossypii	*Solanum tuberosum*	*Allium sativum*	Repellency; Reduces the attractiveness of hosts
Myzus persicae	*Capsicum annuum*	*Ocimum basilicum; Rosmarinus officinalis; Lavandula latifolia*	Repellency; Reduces the attractiveness of hosts
Brevicoryne brassicae	*Brassica oleracea*	*Allium cepa*	Reduces host-finding ability
Brevicoryne brassicae	*Brassica oleracea*	*Secale cereal*	Reduces host-finding ability
Aphis fabae	*Vicia faba*	*Satureja hortensis; Ocimum basilicum*	Deterrent effect; Repellency
Aphis citricola	*Pyrus communis*	*Satureja hortensis; Ocimum basilicum*	Repellency

Species of aphid	Host plant	Companion plants	Proposed mechanisms
Lipaphis erysimi	*Brassica napus*	*Allium cepa; Allium sativum*	Repellency; Deterrent effect; Disrupts behavior
Macrosiphum rosae	*Rosa chinensis*	*Tagetes patula*	Repellency; Allelopathy change
Rhopalosiphum padi	*Hordeum vulgare*	*Cirsium vulgare*	Allelopathy change; Reduces the attractiveness of hosts

6. Crop Rotation

Crop rotation is the practice of growing different crops on the same field in a planned sequence over time, instead of planting the same crop every year, for example: year 1: wheat; year 2: legumes (peas, beans); year 3: root crops (potato, beet) [73]. To make crop rotation effective it is important to avoid growing the same crop or crop family in the same field every year and to ensure the rotation between cereals, legumes, root crops and oilseeds. This approach improves soil fertility, helps control pests and diseases, and supports stable crop yields by disrupting pest life cycles and balancing soil nutrients through the varied demands of different crops.

By rotating crops, farmers interrupt the life cycles of pests and diseases that build up when the same crop is grown continuously. Many pests and diseases are crop-specific. They survive in the soil or plant residues and increase when the same crop is grown repeatedly. Changing the crop makes the field unfavourable for pests that depend on one specific plant.

Western corn root worm larvae are vulnerable to crop rotation of alfalfa. For this reason, crop rotation would be an actual way for controlling corn pest. Diverse cropping systems of plant could be designed in various ways that affect the insect population, agronomically. The manipulation of vegetation affects the insect's population through field margins, species composition managing and other types of shelter belts. Moreover, insect dynamics is greatly influenced by the weed diversity, which remains in form of weed borders, alternate rows or supply weeds certain period of crop growth. Cabbage aphids, flea beetles, diamondback moth, cabbage butterfly, wheat midge, red turnip beetle, wheat stem maggot and wheat stem sawfly are a few of the many insect pests that can be regulated with diverse crop rotations [74].

7. Physical Barriers

Physical controls are pest management methods that use physical or mechanical means to prevent, reduce, or manage pest infestations. These methods include the use of barriers, traps, and manual removal of pests.

Barriers are physical obstacles that prevent pests from reaching plants. Common examples include insect netting to protect fruit trees from birds and fine mesh covers or fencing to keep rabbits and other animals out of vegetable fields and gardens. Barriers are most effective as a preventive measure, especially when installed before pests appear. However, they may not protect against all pest species, and installation can be costly or labour-intensive. If pests manage to enter inside the protected area, their population can increase rapidly in the absence of natural enemies. Barriers can be applied against aerial pests (fruit flies, vegetable flies, whiteflies, thrips, aphids, thecla, etc.), birds, fruit bats and certain fungi.

Trapping is another method used to capture and remove pests from the environment. Typical examples include slug traps in gardens and pheromone traps for moths in greenhouses and fields. In many commercial farming systems, traps are used mainly as a monitoring tool to detect the presence and population level of pests rather than as a method for complete control. Traps may also capture non-target organisms, such as beneficial insects, lizards, frogs, or other useful animals, so their placement and type must be carefully selected.

Manual removal involves physically removing pests from plants. This can range from hand-picking caterpillars from leaves to vacuuming aphids from shoots or spraying plants with a strong jet of water to dislodge insects. Some farmers use sticky tape to remove pests from leaf surfaces, but this should be done with caution, as it may damage the plant’s protective waxy layer (cuticle). Although manual removal can be time-consuming, it is a simple, low-cost, and chemical-free method that is especially useful for small-scale farming and early infestations [75,76].

Effective physical control methods can protect crops throughout the entire production cycle, from crop emergence to postharvest handling. However, postharvest conditions are especially well suited for physical control, because the environment is more confined, the stored products are of high economic value, and the use of insecticides is often inappropriate or even prohibited.

Mechanical and physical controls have relatively little impact on natural enemies and other non-target organisms and are compatible with biological controls. They can be rapid and effective, and are well suited for the home landscape [75]. Physical barriers are an important part of IPM because they reduce pest pressure without harming beneficial organisms or the environment. Examples of passive physical control methods are shown in **Table 15**.

Table 15. Examples of passive physical control methods [75]

Method	**Main target pests / situation**	**Main advantage**
Trenches	Walking insects (e.g. Colorado potato beetle)	Intercept migrating insects and reduce field invasion
Fences	Low-flying insects (e.g. cabbage flies)	Exclude pests from crops without chemicals
Organic Mulch	Colorado potato beetle, aphids	Enhances natural enemies and reduces pest damage
Artificial Mulches	Thrips, aphids, plant bugs	Modify light reflection to repel insects
Particle Films	Psyllids, aphids, leafhoppers, moths	Disrupt feeding and egg laying; improve fruit quality
Inert Dusts	Stored-grain beetles and moths	Cause dehydration; safe for stored products
Trapping	Fruit flies, moths, orchard pests	Reduces pest entry and supports monitoring
Oils	Aphids, mites, scales, psyllids	Suffocate soft-bodied pests; low risk to beneficials
Soaps/Surfactants	Aphids, mites, soft-bodied insects	Destroy cuticle and cause drowning; low residues

8. Biopesticides in Integrated Pest Management

Integrated Pest Management (IPM) is a long-term, environmentally responsible approach to pest control that relies on understanding ecosystems and using a combination of methods rather than depending solely on chemicals. It brings together biological, cultural, physical, and chemical practices, with pesticides applied only when necessary and as a last option. The goal is to reduce risks to human health, crops, property, and the environment while maintaining effective and economical pest control. It focuses on long-term prevention through monitoring, understanding pest life cycles, and implementing tactics like habitat modification, using resistant varieties, and encouraging natural predators, rather than relying solely on reactive chemical treatments, making it economically viable and environmentally sound.

According to EPA [77], IPM is not a single pest control method but, rather, a series of pest management evaluations, decisions and controls. In practicing IPM, growers who are aware of the potential for pest infestation follow a four-tiered approach. The four steps include:

Set section thresholds. Before any control measures are applied, IPM sets action thresholds – the pest population level or environmental condition at which intervention becomes necessary. Seeing an occasional pest does not automatically require treatment. Instead, decisions are guided by the point at which pests are likely to cause economic or unacceptable damage, ensuring that control actions are justified and timely.

Monitor and correctly identify pests. Not every insect, weed, or organism is harmful; many are harmless or even beneficial. IPM emphasizes regular observation and accurate identification of pests so that management choices are appropriate and based on real need. This approach prevents unnecessary pesticide use and reduces the risk of selecting the wrong type of control method.

Prevention. Prevention is the foundation of IPM. The goal is to manage crops, landscapes, or indoor environments in ways that reduce the chances of pest outbreaks. In agriculture, this may include practices such as crop rotation, using resistant plant varieties, and planting clean, pest-free material. These strategies are often highly effective, economical, and pose minimal risk to people and the environment.

Control. When monitoring and thresholds show that pests must be managed and preventive measures are no longer sufficient, IPM evaluates available control options based on both effectiveness and safety. Priority is given to methods with the lowest risk, such as targeted approaches (e.g., pheromones to interfere with mating) or physical and mechanical techniques like trapping or manual removal. If these measures do not provide adequate control, more intensive methods, including carefully targeted pesticide applications, may be used. Broad, non-selective pesticide spraying is considered only as a last option.

9. Recommendations

To achieve effective pest control while reducing reliance on chemical pesticides, farmers are encouraged to apply alternative control methods as part of an Integrated Pest Management (IPM) strategy. The following practical recommendations can help maximize the effectiveness of biopesticides and other non-chemical approaches:

1. Monitor fields regularly

Inspect crops frequently to detect pests at early life stages. Early identification allows timely intervention and improves the effectiveness of biological and biochemical control methods.

2. Apply control measures only when necessary

Do not treat fields based on the presence of a few pests. Use action thresholds to decide when pest populations are likely to cause economic damage and require intervention.

3. Choose the right product for the right pest

Select biopesticides and biological control agents that are specifically effective against the target pest. Always confirm pest identification before application.

4. Apply biopesticides under suitable conditions

Environmental factors strongly influence biopesticide performance. Apply products:

- Early in the morning or late in the evening to avoid strong sunlight
- When temperatures and humidity are suitable for the biological agent
- When rain is not expected shortly after application.

5. Follow label instructions carefully

Respect recommended doses, application timing, storage conditions, and compatibility guidelines. Incorrect use can reduce effectiveness and waste resources.

6. Ensure proper coverage and ingestion

Many biopesticides must be eaten by pests to work. Apply treatments to the plant parts where pests feed and ensure thorough coverage of leaves, stems, or soil as required.

7. Combine multiple IPM methods

Best results are achieved by combining biopesticides with other approaches such as:

- Crop rotation and resistant varieties
- Companion planting and trap crops
- Physical barriers and trapping

- Natural enemies

Avoid relying on a single control method.

8. Protect beneficial insects

Avoid broad-spectrum chemical pesticides, especially when releasing predators or parasitoids. Maintain flowering plants, field margins, and shelters to support natural enemies.

9. Check compatibility with chemical pesticides

If chemical control is unavoidable, choose selective products that are compatible with biological agents. Avoid tank-mixing products unless compatibility is confirmed.

10. Plan for repeated applications when needed

Some biopesticides have short residual activity. Be prepared for follow-up applications, especially during periods of high pest pressure.

11. Keep records and evaluate results

Record pest levels, weather conditions, treatments used, and outcomes. This helps improve decision-making in future seasons and supports long-term farm sustainability.

10. Conclusions

Modern agriculture must balance the need for effective pest control with the responsibility to protect human health, the environment, and biodiversity. This training material demonstrates that reducing reliance on synthetic chemical pesticides is both feasible and practical when alternative pest control methods are applied within the framework of Integrated Pest Management (IPM).

Biopesticides, including microbial, biochemical, and plant-incorporated protectants, provide effective tools for pest suppression while minimizing risks to non-target organisms, beneficial insects, and ecosystems. Their high specificity, low toxicity, and limited environmental persistence make them particularly suitable for sustainable and organic farming systems. When correctly selected and applied, biopesticides can significantly reduce pesticide residues in food and slow the development of pest resistance.

Biological control using natural enemies such as predators, parasitoids, and entomopathogenic organisms plays a key role in maintaining pest populations below damaging levels. Supporting these beneficial organisms through habitat management, careful pesticide selection, and appropriate release strategies enhances long-term pest regulation and ecosystem stability.

Companion planting, crop rotation, and other cultural practices further strengthen pest management by disrupting pest life cycles, reducing host plant attractiveness, and encouraging natural enemies. These preventive approaches reduce pest pressure before chemical interventions become necessary and contribute to healthier crops and soils.

Physical control methods, including barriers, trapping, and manual removal, offer additional non-chemical options that are especially valuable in early infestations and post-harvest protection. When combined with biological and cultural measures, they help minimize pesticide use while maintaining effective pest control.

The success of alternative pest control methods depends on understanding pest biology, careful monitoring, correct timing of applications, and suitable environmental conditions. Biopesticides are most effective when used proactively, applied according to label instructions, and integrated with other IPM strategies rather than used as standalone solutions.

In conclusion, alternative pest control methods represent a viable, environmentally responsible, and economically sustainable approach to modern agriculture. By adopting IPM-based strategies and increasing awareness of biopesticides and non-chemical controls, farmers can protect crop productivity, safeguard ecosystems, and contribute to safer food production for consumers.

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