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# A Review on Biorational Formulations and Their Role in Pest Control

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***Abstract***— *The primary problem confronting global agriculture today is to satisfy the escalating food requirements of a burgeoning population while managing evolving patterns of insect pest infestations and environmental circumstances. Insects are the most diverse assemblage of organisms on Earth, with numerous species offering significant ecological and economic advantages to humanity. However, certain insect species impose considerable harm on crops by feeding directly and by transmission of viral and other diseases to plants and humans indirectly. These harmful insects are commonly referred to as insect pests. The widespread application of synthetic chemical pesticides has elicited societal concern due to their detrimental impacts on human health, non-target species, and the ecosystem. Given these conditions, there is a growing necessity to implement biologically derived insecticides as safer as well as sustainable options. In this context, biorational pesticides have gained considerable attention in recent years. Being primarily of natural origin, these pesticides exert minimal negative impacts on the environment while providing effective control of insect pests. Insect pests continue to pose serious threats to agricultural productivity, food security, and public health worldwide. Biorational formulations have emerged as promising alternatives to conventional pesticides by utilizing naturally occurring compounds and ecological principles to manage pest populations effectively. The present review comprises the recent knowledge on biorational formulations and their applications in insect pest management. It also examines various strategies for the formulation and deployment of biorational products within integrated pest management (IPM) programs, highlighting their potential to promote sustainable, environmentally friendly, and effective pest control practices.*

***Keywords*— *Biopesticides, Microbial pesticides, Insect pest management, Semiochemicals.***

## I. INTRODUCTION

Pests are organisms that damage or interfere with desirable plants in agricultural fields, orchards, forests, and landscapes. A pest may be defined as any organism whose population exceeds the economic injury level and adversely affects human welfare, convenience, health, or profit (Pedigo and Rice, 2014). Numerous insect pests and diseases threaten economically important agricultural, horticultural, and ornamental crops, leading to substantial yield and quality losses worldwide (Oerke, 2006).

Pest control denotes the regulation or management of organisms deemed pests due to their detrimental impacts on human well-being, environmental health, or the economy. It is an essential component of crop protection and hygiene management aimed at minimizing pest-related losses (Dent and Binks, 2020). Although many pests can be harmful when present in homes, commercial establishments, or food-processing areas, it is important to recognize their ecological roles within food webs and ecosystems. Therefore, pest populations are often managed and controlled rather than completely eradicated (Kogan, 1998).

The widespread application of chemical pesticides has greatly enhanced crop protection; however, it has also resulted in soil, water, food, and environmental contamination (Pimentel and Burgess, 2014). While modern agricultural practices have enhanced productivity, they have also generated long-term concerns such as soil degradation, disruption of nutrient cycling, reduced biodiversity, and detrimental impacts on human health (Aktar et al., 2009; Nicolopoulou-Stamati et al., 2016). As a result, there is growing interest in sustainable and eco-friendly pest management strategies.

Traditional pest management methods, including the use of locally available natural resources, traps, field sanitation, ploughing, crop rotation, conventional plant breeding, and natural repellents and deterrents, have long been employed to suppress pest populations (Pretty and Bharucha, 2015). Although these methods remain valuable, pesticide application continues to be one of the most extensively used approaches for monitoring insect pests and disease vectors.

In recent years, biorational formulations have surfaced as viable alternatives to traditional synthetic pesticides. Biorational formulations are pest control agents originating from natural sources or engineered to replicate naturally occurring compounds (Ware and Whitacre, 2004). These formulations are crucial for controlling insect pests while reducing environmental pollution and safeguarding human health (Isman, 2006). Their development has provided a practical means of achieving effective pest control while promoting ecological sustainability.

Insects continue to pose significant challenges to agriculture, forestry, and public health sectors. Biorational formulations offer an effective alternative for insect management, and many of these products have demonstrated favorable profiles in terms of environmental safety, selectivity, and reduced toxicity to non-target organisms (Copping and Menn, 2000; Isman and Grieneisen, 2014). Consequently, they have emerged as crucial elements of Integrated Pest Management (IPM) systems (Kogan, 1998).

The term "biorational pesticides" was introduced to describe natural or synthetic substances that are effective against target pests while causing minimal harm to natural enemies and other beneficial organisms (Hara, 2000; Shi, 2000). Biorational pesticides include a diverse range of products such as microbial pesticides, botanicals, insect growth regulators, semiochemicals, and other biologically based pest management tools (Marrone, 2019).

This review explores the role of biorational formulations in the control of insect pests across agriculture, forestry, and public health sectors. Particular emphasis is placed on microbial pesticides, semiochemicals, and other biorational approaches, highlighting their efficacy, advantages, limitations, and integration into sustainable pest management programs. The review aims to provide insights into current developments and identify future research directions for environmentally sound pest control strategies.

## II. TRADITIONAL METHODS USED FOR PEST CONTROL

Traditional pest control methods have been employed for centuries to regulate pest populations and reduce their adverse effects on agriculture, public health, and sanitation. These approaches primarily rely on cultural, mechanical, biological, and ecological practices that are environmentally friendly and sustainable (Dent and Binks, 2020; Pretty and Bharucha, 2015).

### 2.1 Traps

Traps are among the oldest and most widely used mechanical methods of pest control. They are designed to capture or kill pests and are available in various forms, including snap traps, glue traps, pitfall traps, pheromone traps, and live traps. Trapping is considered a safe, non-toxic, and environmentally sound method for monitoring and managing pest populations. Rodents, insects, and other nuisance pests can be effectively controlled using commercially available traps in households, storage facilities, and agricultural systems (Pedigo and Rice, 2014).

### 2.2 Sanitation

Sanitation practices play a vital role in pest prevention by eliminating breeding sites, food sources, water sources, and shelter that support pest survival and reproduction. Proper disposal of waste, removal of crop residues, maintenance of clean storage facilities, and elimination of standing water significantly reduce pest infestations. Sanitation is an essential component of Integrated Pest Management (IPM) programs and is widely recognized as an effective preventive strategy (Kogan, 1998; Dent and Binks, 2020).

### 2.3 Ploughing and Tillage

Ploughing is one of the oldest agricultural practices used for pest management. It involves preparing the soil for cultivation by turning and loosening the soil layers. This process exposes soil-dwelling insects, pupae, eggs, and weed propagules to adverse environmental conditions and natural enemies, thereby reducing their survival. Deep summer ploughing has been reported to suppress several insect pests and weeds by disrupting their life cycles and destroying overwintering stages (Singh and Singh, 2019).

### 2.4 Crop Rotation

Crop rotation is a cultural pest management practice that involves growing different crops sequentially on the same field. By alternating susceptible and non-susceptible crops, the life cycles of pests and pathogens are disrupted, reducing their population buildup and preventing recurrent infestations. Crop rotation also improves soil fertility and biodiversity, making it an important component of sustainable agricultural systems (Altieri and Nicholls, 2004; Pretty and Bharucha, 2015).

### 2.5 Biological Control Agents

Biological control entails employing natural adversaries, including predators, parasitoids, and diseases, to mitigate pest populations. Predatory insects, parasitic wasps, entomopathogenic fungi, bacteria, and viruses can efficiently manage pest populations while minimizing detrimental effects on non-target organisms and the environment. Biological control is regarded as one of the most environmentally sustainable methods for pest management and is extensively integrated into Integrated Pest Management (IPM) programs (van Lenteren, 2012; Heimpel and Mills, 2017).

### 2.6 Traditional Plant Breeding

Traditional plant breeding has been employed for an extended period to create crop types with improved resistance or tolerance to insect pests and illnesses. Selective breeding integrates desired characteristics, such as insect resistance, disease resistance, and stress tolerance, into crop plants. Host plant resistance reduces pest damage and dependence on chemical pesticides, contributing to sustainable crop production (Smith, 2005).

### 2.7 Natural Repellents and Deterrents

Natural plant-derived substances have traditionally been used to repel or deter pests from feeding, oviposition, or colonization. Products derived from neem (*Azadirachta indica*), garlic (*Allium sativum*), chilli pepper (*Capsicum* spp.), and other botanicals possess insecticidal, antifeedant, repellent, and growth-regulating properties. These natural products are biodegradable, relatively safe to non-target organisms, and compatible with environmentally sustainable pest management practices (Isman, 2006; Pavela, 2016).

Conventional pest management techniques remain integral to sustainable agriculture. Their incorporation with contemporary biological and biorational methods can improve pest control while mitigating environmental effects and decreasing dependence on synthetic pesticides (Kogan, 1998; Pretty and Bharucha, 2015).

## III. MICROBIAL FORMULATIONS PRACTICED IN PEST CONTROL PROGRAMMES

### 3.1 Microbial Pesticides

Microbial pesticides are biopesticides in which the active ingredient is a microorganism, including bacteria, viruses, fungi, or protozoa (Rosell et al., 2008). These pesticides may consist of naturally occurring or genetically modified microorganisms that are capable of suppressing pest populations (Vongati et al., 2022). Microbial pesticides are formulated using living or inactivated strains of microorganisms that directly or indirectly affect the survival, growth, development, or reproduction of target pests (Addesso et al., 2022).

Microbial pesticides are efficacious against a diverse array of insect pests and other harmful organisms through the production of toxic metabolites, infection processes, or other biological mechanisms that inhibit pest growth and development. Although microbial pesticides can target diverse pest groups, each active ingredient is generally highly specific to a particular pest or closely related group of pests (Kumar et al., 2019). For example, certain fungal species are used for weed management, whereas others are effective against specific insect pests.

Among microbial pesticides, the most extensively utilized are strains and subspecies of the entomopathogenic bacterium *Bacillus thuringiensis* (Bt). This bacterium produces crystalline proteins (Cry toxins) that are toxic to specific insect groups. Different Bt strains synthesize distinct combinations of these proteins, which bind to receptors in the larval midgut, causing gut disruption and ultimately leading to the death of susceptible insect larvae (Leahy et al., 2014). Some Bt strains are particularly effective against lepidopteran larvae (moths and butterflies), whereas others target dipteran larvae such as mosquitoes and flies (Rosell et al., 2008).

Microbial pesticides are generally considered environmentally safe and have minimal adverse effects on producers, consumers, and non-target organisms associated with agricultural ecosystems (Guven et al., 2020). Owing to their biological origin, target specificity, low toxicity to humans, and reduced environmental impact, microbial pesticides have gained considerable attention and popularity as sustainable substitutes to conventional synthetic pesticides in modern pest management programs (Fishel, 2005).

### 3.2 Bacteria

Entomopathogenic bacteria are prokaryotic, unicellular microorganisms that vary in size from less than 1 µm to several micrometers. Based on their morphology, rigid-walled bacteria may occur as spiral, rod-shaped, or coccoid forms, whereas pleomorphic bacteria lack a definite shape due to the absence of a rigid cell wall (Manda et al., 2020). These bacteria are significant in biological pest management due to their capacity to infect and eliminate insect hosts.

Among the entomopathogenic bacteria, *Bacillus thuringiensis* (Bt) is the most widely used and commercially successful microbial pesticide. Different formulations of *B. thuringiensis* contain insecticidal toxins that are effective against various insect orders. Bt is particularly pathogenic to the larval stages of several insect pests, especially lepidopteran species, causing mortality following ingestion of the bacterial toxins. The bacterium produces crystalline endotoxins (Cry proteins) during sporulation, which, upon ingestion by susceptible insects, bind to specific receptors in the larval midgut. This interaction disrupts the gut epithelium, resulting in paralysis or lysis of the digestive tract, cessation of feeding, and eventual death of the insect through starvation and septicemia (Shivakumara et al., 2021).

Several insecticidal products have been developed using different subspecies of *Bacillus thuringiensis*, each targeting specific groups of insect pests. Due to their high efficacy, ease of mass production, simple handling, storage stability, affordability, target specificity, and safety to humans and the environment, Bt-based formulations have become essential components of Integrated Pest Management (IPM) programs (Shivakumara et al., 2021). Some important entomopathogenic bacteria used in pest management are listed in Table 1.

**TABLE 1**
**IMPORTANT ENTOMOPATHOGENIC BACTERIA USED IN INSECT PEST MANAGEMENT**

| Entomopathogenic Bacteria | Target Pests | Reference(s) |
|---|---|---|
| *Bacillus thuringiensis* | Lepidoptera, Coleoptera, Diptera | Himeno (1999); Saberi et al. (2020); Tanada and Kaya (1993) |
| *Arthrobacter gandavensis* | Coleoptera: Elateridae | Danismazoglu et al. (2012) |
| *Bacillus thuringiensis* subspecies *kurstaki* | Lepidoptera | van Frankenhuyzen (2009); Jurat-Fuentes and Jackson (2012); Nawaz et al. (2016); Manda et al. (2020) |
| *Bacillus thuringiensis* subspecies *aizawai* | Lepidoptera | Nawaz et al. (2016); Mashtoly et al. (2011); Manda et al. (2020) |
| *Bacillus thuringiensis* subspecies *japonensis* | Coleoptera: Scarabaeidae | Mashtoly et al. (2010); Nawaz et al. (2016); Manda et al. (2020) |
| *Paenibacillus popilliae* | Coleoptera: Scarabaeidae, *Popillia japonica* | Koppenhofer et al. (2012); Nawaz et al. (2016); Manda et al. (2020) |
| *Bacillus thuringiensis* subspecies *israelensis* | Diptera | Lee et al. (2021); Manda et al. (2020) |
| *Bacillus thuringiensis* subspecies *tenebrionis* | Coleoptera | Manda et al. (2020) |
| *Bacillus lentimorbus* | Diptera, Coleoptera: Scarabaeidae | Falqueto et al. (2021); Manda et al. (2020); Dutky (1940) |
| *Bacillus sphaericus* | Diptera | Manda et al. (2020); Falqueto et al. (2021); Yap (2013) |
| *Bacillus popilliae* | Coleoptera: Scarabaeidae | Himeno (1999); Falqueto et al. (2021); Manda et al. (2020); Dutky (1940) |
| *Bacillus moritai* | Diptera, Hymenoptera | Himeno (1999); Aizawa and Fujiyoshi (1968) |
| *Bacillus brevis* | Diptera | Balaraman et al. (1979) |
| *Bacillus laterosporus* | Diptera | Favret and Yousten (1985) |
| *Bacillus megaterium* | Lepidoptera: Crambidae, Lepidoptera: Noctuidae | Lynch et al. (1976); Sevim et al. (2010) |

## 3.3 Fungi

Entomopathogenic fungi constitute a category of fungi that infect and exterminate insect hosts. These fungi have emerged as excellent biological control agents for insect pest management, as they may significantly reduce pest populations with low adverse effects on non-target organisms and the environment (Kumar et al., 2019). In contrast to numerous other microbial control agents, entomopathogenic fungi can infect multiple developmental stages of insects, encompassing eggs, larvae, pupae, and adults.

The pathogenicity of these fungi is due to their capacity to generate several toxins and extracellular enzymes, including chitinases, proteases, and lipases, which aid in penetrating the insect cuticle and subsequently colonizing host tissues (Shivakumara et al., 2021). Under optimal environmental conditions, asexual spores (conidia) scattered within the habitat of the insect host trigger fungal infection. Upon contact with the insect cuticle, the spores attach to the surface, germinate, and infiltrate the integument by mechanical pressure and enzymatic destruction.

Upon penetrating the insect's body cavity (haemocoel), the fungal hyphae multiply throughout the haemolymph and tissues of the host. As the mycelium proliferates and disseminates within the insect's body, essential physiological functions are impaired, ultimately resulting in the demise of the host insect. Subsequent to the host's death, the fungus may proliferate from the carcass and generate new spores, thus promoting transmission to additional vulnerable insects (Copping and Menn, 2000). Table 2 enumerates some significant entomopathogenic fungi utilized in biological pest management.

**TABLE 2**
**IMPORTANT ENTOMOPATHOGENIC FUNGI USED IN INSECT PEST MANAGEMENT**

| Fungi | Target Pests and Insects | Reference(s) |
|---|---|---|
| *Aschersonia aleyrodis* | Hemiptera | Lacey et al. (2011); McCoy et al. (2009); Nawaz et al. (2016) |
| *Beauveria brongniartii* | Coleoptera (Scarabaeidae) | Nawaz et al. (2016); Townsend et al. (2010) |
| *Conidiobolus thromboides* | Hemiptera, Thysanoptera | Hajek et al. (2012); Nawaz et al. (2016) |
| *Beauveria bassiana* | Coleoptera, Hemiptera | Himeno (1999); McGuire and Northfield (2020) |
| *Lecanicillium longisporum* | Hemiptera | Down et al. (2009); Kim et al. (2009); Nawaz et al. (2016) |
| *Hirsutella thompsonii* | Mites | Himeno (1999) |
| *Metarhizium anisopliae* | Coleoptera, Diptera, Hemiptera, Isoptera, Lepidoptera | Lacey et al. (2011); Jaronski and Jackson (2012); Nawaz et al. (2016); Himeno (1999) |
| *Verticillium lecanii* | Hemiptera | Himeno (1999) |
| *Nomuraea rileyi* | Lepidoptera | Thakre et al. (2011); Himeno (1999); Nawaz et al. (2016) |
| *Isaria fumosorosea* | Termites, grasshoppers, caterpillars, beetles | Gautam (2020) |
| *Paecilomyces fumosoroseus* | Insects and mealybugs | Abbas (2020) |
| *Lagenidium giganteum* | Mosquito species | Kaczmarek and Bogus (2021) |

## 3.4 Viruses

Entomopathogenic viruses are obligate intracellular pathogens that infect and reproduce exclusively within susceptible insect hosts. These viruses cause disease in insects and play an important role in the biological control of insect pests. Infection generally occurs when susceptible insects ingest viral occlusion bodies present on plant surfaces or in the environment. Following ingestion, the virus infects host cells, replicates within tissues, and spreads throughout the insect body, ultimately resulting in host mortality (Moscardi, 1999; Szewczyk et al., 2011).

Among the entomopathogenic viruses, baculoviruses (BVs) are the most widely used viral biopesticides. Baculoviruses are highly host-specific pathogens and are primarily employed for the management of lepidopteran insect pests. They are classified into two major groups: Nuclear Polyhedrosis Viruses (NPVs) and Granuloviruses (GVs) (Szewczyk et al., 2011). These viruses generate proteinaceous occlusion bodies that facilitate transmission among susceptible insect populations and safeguard virions from deleterious environmental conditions (Rohrmann, 2019).

Baculoviruses replicate within host tissues and are responsible for both systemic infection and cell-to-cell spread within the insect body upon infection. This results in extensive tissue destruction and the eventual mortality of the host insect (Kapoor and Sharma, 2020). This results in a decrease in pest population density and crop injury as infected larvae frequently cease feeding, become sluggish, and ultimately perish (Moscardi, 1999). Baculoviruses are regarded as valuable biological control agents for sustainable pest management due to their high host specificity, environmental safety, biodegradability, and compatibility with Integrated Pest Management (IPM) programs (Lacey et al., 2015; Szewczyk et al., 2011). Table 3 contains a list of several significant entomopathogenic viruses that are employed in the management of insect pests.

**TABLE 3**
**IMPORTANT ENTOMOPATHOGENIC VIRUSES USED IN INSECT PEST MANAGEMENT**

| Entomopathogenic Viruses | Target Pests | Reference(s) |
|---|---|---|
| Corn earworm NPV (HezeSNPV) | *Helicoverpa zea*, *Heliothis virescens* | Rowley et al. (2011) |
| Alfalfa looper NPV (AucaMNPV) | Noctuidae | Yang et al. (2012) |
| Nuclear Polyhedrosis Virus (NPV) | Butterflies and Moths (Lepidoptera) | Himeno (1999); Harish et al. (2021) |
| Granulosis Virus | Butterflies (Lepidoptera) | Himeno (1999) |
| Diamondback moth GV | *Plutella xylostella* | Yang et al. (2012) |
| Cotton bollworm NPV (HearNPV) | *Helicoverpa armigera* | Rowley et al. (2011); Hauxwell et al. (2010); Rabindra and Grzywacz (2010); Yang et al. (2012) |
| Velvetbean caterpillar NPV (AngeMNPV) | *Anticarsia gemmatalis* | Moscardi et al. (2011); Panazzi (2013) |
| Non-occluded Baculovirus | Beetles | Himeno (1999) |
| Cytoplasmic Polyhedrosis Virus (CPV) | Moths | Himeno (1999) |
| Imported cabbageworm GV (PiraGV) | *Artogeia (Pieris) rapae* | Singh et al. (2019) |
| Potato tuber moth GV (PhopGV) | *Phthorimaea operculella* | Singh et al. (2019) |
| Tea moth NPV (BuzuNPV) | *Buzura suppressaria* | Yang et al. (2012) |
| *Atalantia guillauminii*, *Eucalyptus procera* | Tenebrionid pests | Idris et al. (2022) |

### 3.5 Protozoa

Protozoa are microscopic, unicellular eukaryotic organisms that act as important biological control agents against several insect pests. Entomopathogenic protozoa are generally host-specific and slow-acting pathogens that exhibit complex biological interactions with their insect hosts. Unlike many bacterial and viral pathogens, protozoan infections often result in chronic diseases that reduce insect survival, reproduction, feeding activity, and overall fitness rather than causing rapid mortality (Lacey and Goettel, 1995).

The infective stage of most entomopathogenic protozoa is the resistant spore, particularly in microsporidian species. These spores are ingested by susceptible insects and germinate within the host, initiating infection and subsequent pathogen development (Kapoor and Sharma, 2020). Once established, the protozoan multiplies within host tissues, disrupting normal physiological functions and contributing to long-term suppression of pest populations.

The genus *Nosema* is home to some of the most extensively investigated and employed protozoan pathogens in biological pest management. *Nosema* species have exhibited significant potential for pest suppression and infect a diverse array of insect hosts (Ahmed et al., 2022). The sole commercially available microsporidian pathogen among the diverse species is *Nosema locustae*, which is marketed under a variety of trade names (e.g., Nolo Bait, Semaspore) for the control of grasshoppers and crickets. It is a valuable element of biological control programs due to its capacity to induce chronic infections and disseminate within insect populations (Shivakumara et al., 2021). Some important entomopathogenic protozoa used in insect pest management are listed in Table 4.

**TABLE 4**
**IMPORTANT ENTOMOPATHOGENIC PROTOZOA USED IN INSECT PEST MANAGEMENT**

| Protozoa | Target Pests | Reference(s) |
|---|---|---|
| *Nosema locustae* | Grasshoppers, European corn borer caterpillars, Mormon crickets | Himeno (1999); Zhang and Lecoq (2021); Solter et al. (2012) |
| *Nosema pyrausta* | European corn borer (*Ostrinia nubilalis*) | Kachhawa (2017); Gassman and Clifton (2017) |
| *Vairimorpha necatrix* | Armyworm (Noctuidae) | Solter et al. (2012) |

### 3.6 Nematodes

Entomopathogenic nematodes (EPNs) are among the most promising and commercially successful biocontrol agents currently available in the biopesticide market. They are extensively employed in plant protection programs to control a wide variety of insect invaders (Ahmed et al., 2022). Entomopathogenic nematodes are non-segmented, soft-bodied roundworms that parasitize insects either obligately or facultatively. These nematodes are considered safe for humans, exhibit relatively high host specificity, and can be applied using conventional pesticide application equipment (Ilan et al., 2006).

The most significant entomopathogenic nematodes utilized in biological pest management are found in the families Steinernematidae and Heterorhabditidae. The potential of species from the genera *Steinernema* and *Heterorhabditis* to manage insect pests, including those associated with stored cereals and soil habitats, has been considerable. In *Steinernema*, these nematodes maintain a mutualistic association with symbiotic bacteria, specifically *Xenorhabdus* spp., and *Photorhabdus* spp. found in *Heterorhabditis*. The nematode-bacterium complexes collectively exert effective control over parasites from the Coleoptera, Diptera, and Lepidoptera orders (Boemare et al., 1993).

Entomopathogenic nematodes are particularly valuable in situations where chemical pesticides are ineffective, such as against soil-dwelling insects, pests inhabiting galleries or concealed habitats, or populations that have developed resistance to conventional insecticides. Consequently, species of *Steinernema* and *Heterorhabditis* have become important tools in integrated pest management programs (Ehlers, 2001).

The infective juvenile stage actively searches out and enters the insect host through natural body openings, such as the mouth, anus, and spiracles. The nematodes release their symbiotic bacteria when they enter the haemocoel. These bacteria rapidly proliferate in the insect haemolymph and produce toxins and other virulence factors that cause septicemia and the death of the host insect (Manda et al., 2020). The nematodes reproduce within the cadaver and eventually emerge to seek new hosts, after which the infected insects typically expire within 24–48 hours. Among the commercially important entomopathogenic nematodes, *Steinernema feltiae*, *S. scapterisci*, *S. riobrave*, *S. carpocapsae*, and *Heterorhabditis heliothidis* are extensively employed in agricultural systems to regulate insect infestations through biological means (Shivakumara et al., 2021). Table 5 presents selected entomopathogenic nematodes commonly used in insect pest management.

**TABLE 5**
**IMPORTANT ENTOMOPATHOGENIC NEMATODES USED IN INSECT PEST MANAGEMENT**

| Nematodes | Target Pests | Reference(s) |
|---|---|---|
| *Heterorhabditis taysearae* | *Bactrocera dorsalis* | Godjo et al. (2018) |
| *Steinernema riobrave* | Armyworm | Gozel and Gozel (2021) |
| *Steinernema bicornutum* | Leafminers | Abbas (2022) |
| *Steinernema carpocapsae* | Armyworms, caterpillars, clearwing borers, shore flies, weevils | El-Ashry and El-Marzoky (2018) |
| *Steinernema feltiae* | Various insect pests | Ehlers (2001) |
| *Heterorhabditis bacteriophora* | Coleoptera, Lepidoptera | Boemare et al. (1993) |

## IV. SEMIOCHEMICALS

Semiochemicals are chemical substances or blends of compounds that mediate communication between organisms by eliciting specific physiological or behavioral changes in individuals of the same or different species. These signaling molecules play a crucial role in regulating insect behavior and are involved primarily in insect–insect and plant–insect interactions (Abd El-Ghany, 2019). Because of their ability to modify pest behavior, semiochemicals have become important tools in environmentally sustainable pest management programs (Howse et al., 1998).

Semiochemicals can be utilized in insect pest management through several strategies, including: (a) monitoring, (b) mating disruption, (c) mass trapping, (d) attract-and-kill, and (e) push–pull systems. These approaches exploit the natural behavioral responses of insects to chemical cues, thereby reducing pest populations and minimizing crop damage without relying heavily on conventional insecticides (Witzgall et al., 2010).

Based on the organisms involved in the communication process, semiochemicals are broadly classified into two categories. Intraspecific semiochemicals, which are commonly referred to as pheromones, are included in the first category. These compounds facilitate communication among members of the same species. These consist of mating pheromones, aggregation pheromones, alarm pheromones, trail pheromones, and host-marking pheromones. The second category consists of interspecific semiochemicals, collectively referred to as allelochemicals, which mediate interactions between different species. Allelochemicals include allomones, kairomones, synomones, and other signaling compounds that influence ecological interactions among insects, plants, and natural enemies (Howse et al., 1998; Abd El-Ghany, 2019).

Semiochemicals offer several advantages for insect pest management. They are naturally occurring compounds, highly species-specific, environmentally benign, and exhibit minimal persistence in nature. Moreover, they pose negligible risks to humans, beneficial insects, and other non-target organisms. Due to these characteristics, semiochemicals are considered valuable components of Integrated Pest Management (IPM) programs and provide significant potential for the sustainable control of a wide range of insect pests using ecologically sound and environmentally safe approaches (Ramalakshmi et al., 2020; Witzgall et al., 2010).

The increasing adoption of semiochemical-based technologies reflects their effectiveness in reducing pesticide use while maintaining pest populations below economic threshold levels. Consequently, semiochemicals have emerged as an important category of biorational pest management tools for modern sustainable agriculture (Howse et al., 1998; Abd El-Ghany, 2019).

### 4.1 Monitoring

Monitoring is one of the most important applications of semiochemicals in insect pest management. Semiochemical traps baited with pheromones or kairomones are widely used because they are simple, cost-effective, and efficient tools for detecting and tracking insect pest populations. Currently, kairomones, sex pheromones, and aggregation pheromones are extensively employed to monitor insect activity and population dynamics in agricultural and forest ecosystems. Among kairomone-based monitoring systems, one of the most successful applications has been in the management of the spruce bark beetle, *Dendroctonus micans*. Kairomone-baited traps have been effectively used to monitor the biological control agent *Rhizophagus grandis*, a specialized predator of *D. micans* populations (Hosking et al., 2003).

Pheromone traps provide a simple, reliable, and highly sensitive method for the detection and monitoring of various insect species, even at low population densities (Trematerra, 2012). Sex pheromones are generally released by females to attract males of the same species for mating purposes. In contrast, aggregation pheromones are commonly produced by males and attract individuals of both sexes, resulting in aggregation at feeding, mating, or breeding sites (Abd El-Ghany, 2019). Semiochemical-based monitoring systems have also been successfully applied to economically important crop pests. For example, populations of the whitefly *Bemisia tabaci* and the tomato leaf miner *Tuta absoluta* have been effectively monitored using sticky traps and water traps, respectively (Abdel-Razek et al., 2017; El-Ghany et al., 2018). Such monitoring techniques provide valuable information on pest occurrence, abundance, and seasonal activity, thereby facilitating timely implementation of appropriate pest management strategies. Overall, semiochemical-based monitoring serves as an essential component of Integrated Pest Management (IPM) programs by enabling early pest detection and informed decision-making while minimizing reliance on chemical pesticides.

### 4.2 Mass Trapping

Mass trapping is an important semiochemical-based pest management strategy that aims to capture a substantial proportion of a pest population before mating, oviposition, or feeding occurs, thereby preventing or reducing crop damage. This approach relies on the use of pheromone- or attractant-baited traps to reduce pest populations below damaging levels. In lepidopteran pests, mass trapping is most effective when males are captured before mating, particularly in species where females mate only once during their lifetime. In coleopteran pests, aggregation pheromone-based trapping targets both males and females, thereby reducing population densities before oviposition occurs or feeding damage is inflicted on crops (Ramalakshmi et al., 2020).

Mass trapping is considered a density-dependent pest management technique that removes a significant number of individuals from the pest population, resulting in reduced mating success and suppression of population growth. Depending on the target species and trapping system, either males, females, or both sexes may be removed from the population, thereby disrupting reproductive processes and limiting pest establishment (Abd El-Ghany, 2019).

As a mechanical pest management approach, mass trapping is generally implemented following pest monitoring and surveillance programs. It is particularly effective when pest populations are relatively low and can be maintained below economic threshold levels through continuous trapping efforts (Knipling, 1979; El-Sayed et al., 2006). The success of this strategy depends on factors such as trap density, lure attractiveness, pest biology, and population dynamics.

In recent years, mass trapping has proven to be an effective management tactic for several economically important insect pests. One notable example is its successful application in the management of the Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae), where pheromone-based trapping systems have contributed to reducing pest populations and associated crop damage (Piñero and Dudenhoeffer, 2018). Mass trapping serves as an eco-friendly and species-targeted pest management strategy that may be efficiently integrated into Integrated Pest Management (IPM) programs to diminish dependence on traditional chemical pesticides.

### 4.3 Mating Disruption

Mating disruption is a pest management approach that employs species-specific sex pheromones to disrupt the mating behavior of insect pests. This technique involves the release of large quantities of synthetic pheromones into the pest habitat, creating an environment saturated with chemical signals that prevent males from locating females for mating. As a result, successful mating is reduced, leading to a decline in pest populations in subsequent generations (Ramalakshmi et al., 2020).

Artificial pheromones or parapheromones used in mating disruption do not necessarily prevent mating completely; however, they significantly reduce mating success and may decrease female fecundity by approximately 50%. Female insects generally have a limited period during which they can mate and reproduce. Therefore, delays in mating can negatively affect their reproductive fitness and may impair their ability to locate suitable oviposition sites (Rochat et al., 1991).

Several mechanisms have been proposed to explain the effectiveness of mating disruption:

a) **Competitive attraction (false trail following):** Males are attracted to artificial semiochemical sources instead of females, causing them to follow false odor trails and reducing the likelihood of successful mate location.

b) **Male confusion (camouflage):** High concentrations of pheromones in the environment create a confusing chemical background that disrupts male orientation and causes random flight behavior, thereby preventing males from locating females.

c) **Sensory desensitization:** Continuous exposure to elevated concentrations of semiochemicals may result in adaptation of the male antennal receptor system or habituation of the central nervous system. This neurophysiological response reduces the insect's ability to perceive and respond to pheromone signals (Mafra-Neto et al., 2014; Barclay and Judd, 1995).

d) **Disguise (male emigration before mating):** Excessive pheromone concentrations may induce males to leave the treated area, reducing their availability for mating with virgin females and consequently lowering reproductive success (Mafra-Neto et al., 2014; Barclay and Judd, 1995).

Mating disruption has been widely adopted as an effective management strategy for numerous lepidopteran pests. In addition to sex pheromones, heterospecific semiochemical compounds such as anti-aggregation pheromones and heterospecific synomones have been employed to disrupt aggregation behavior in certain insect species, resulting in reductions in pest population densities (Abd El-Ghany, 2019).

Sex pheromone-based mating disruption has been successfully incorporated into pest management programs for a variety of economically important insect pests, particularly lepidopteran species attacking fruit, vegetable, and forest crops. The technique is recognized as an environmentally friendly and species-specific approach that reduces reliance on conventional chemical insecticides while supporting sustainable Integrated Pest Management (IPM) programs (Welter et al., 2005; Cork and Basu, 1996).

### 4.4 Attract-and-Kill

The attract-and-kill strategy is a modification of mass trapping in which target insects are attracted to a semiochemical source and subsequently exposed to a toxicant, resulting in their death rather than physical capture. This approach combines the specificity of semiochemicals with the efficacy of insecticidal agents, thereby reducing pest populations while minimizing the amount of pesticide released into the environment. Attract-and-kill formulations have been developed for the management of various insect pests, including flies, moths, and beetles. One of the most successful examples of this strategy is the control of the olive fruit fly, *Bactrocera oleae*, in Greece (Ramalakshmi et al., 2020).

The attract-and-kill approach exploits semiochemicals such as pheromones, kairomones, or food attractants to manipulate insect behavior. By attracting insects to a localized source containing a toxicant, this technique disrupts essential activities such as mating, feeding, aggregation, or host location, ultimately leading to suppression of pest populations. Consequently, attract-and-kill systems provide an effective means of simultaneously attracting and eliminating target pests while reducing non-target impacts and pesticide exposure.

This strategy has been successfully employed against insect pests associated with both stored products and field crops. Research on attract-and-kill technologies has been conducted at different scales, ranging from long-term management of established pest populations to eradication programs targeting invasive species. Examples include the management of Egyptian cotton leafworm, biting flies, codling moth, apple maggot, and bark beetles, as well as eradication efforts directed against invasive tephritid fruit flies and boll weevils (Phillips, 1997; Prokopy et al., 2000; Stelinski and Liburd, 2001; El-Sayed et al., 2009).

Due to its species specificity, reduced pesticide requirements, and compatibility with Integrated Pest Management (IPM) programs, the attract-and-kill strategy represents a promising and environmentally compatible approach for sustainable insect pest control. Continued advances in semiochemical technology and delivery systems are expected to further enhance the effectiveness and applicability of this pest management tactic (Phillips, 1997; Prokopy et al., 2000; Stelinski and Liburd, 2001; El-Sayed et al., 2009).

### 4.5 Push–Pull Strategy

Push–pull pest management is a semiochemical strategy that uses both repellent and attractant cues to influence the behavior of insect pests and their natural predators (Pickett et al., 2014). This concept has developed into an effective and sustainable pest management method that utilizes insect behavioral reactions to chemical signals for crop protection.

The push–pull system involves the simultaneous use of repellents or deterrents (push factors) within the main crop to drive pests away, and attractants (pull factors) placed outside or around the crop to lure pests toward trap crops, trapping devices, or other control measures. By combining these complementary mechanisms, the strategy reduces pest pressure on the main crop while enhancing targeted, environmentally friendly pest suppression. The effectiveness of the push–pull approach has been demonstrated in several cropping systems, including the management of fall armyworm, *Spodoptera frugiperda*, in maize fields (Komala et al., 2021).

The fundamental principles of the push–pull strategy are to maximize pest control efficacy, sustainability, and crop productivity while minimizing environmental impacts and dependence on chemical pesticides. This approach relies primarily on ecological interactions and behavioral manipulation rather than direct toxicity, making it compatible with Integrated Pest Management (IPM) programs and sustainable agricultural practices.

As an emerging pest management technology, the push–pull strategy utilizes non-toxic components to suppress pest populations and reduce pesticide inputs. In addition to minimizing environmental contamination, the approach contributes to the conservation of beneficial organisms and promotes ecological balance within agroecosystems. Consequently, push–pull technology has gained considerable attention as an innovative and environmentally sound method for insect pest management (Agelopoulos et al., 1999).

Overall, the push–pull strategy represents a promising semiochemical-based tool for sustainable pest suppression, offering effective pest control while reducing reliance on conventional chemical insecticides (Pickett et al., 2014; Agelopoulos et al., 1999).

## V. FUTURE PROSPECTS

The worldwide biopesticide market is projected to expand significantly owing to the rising demand for eco-friendly and sustainable agricultural protection products. Increasing apprehensions about pesticide residues, environmental contamination, and the emergence of resistance have expedited the utilization of biopesticides as substitutes for traditional chemical pesticides.

Future advancement of biopesticides will depend on continued research, effective collaboration among researchers, industry, and farmers, and supportive government policies promoting eco-friendly pest management. Training programs and awareness campaigns are essential to enhance farmers' understanding and proper utilization of biopesticides.

Further studies on the ecology, efficacy, formulation, and field performance of biopesticides are needed to improve their reliability and large-scale adoption. In addition, investment from public institutions, private sectors, and agrochemical industries will be crucial for developing cost-effective and high-quality products. Biopesticides provide numerous benefits, such as target specificity, environmental safety, compatibility with Integrated Pest Management (IPM) strategies, and sustained agricultural protection. Therefore, strengthening research, regulatory frameworks, product availability, and farmer education will be essential for maximizing their contribution to sustainable agriculture and global food security.

## VI. CONCLUSION

Biopesticides have emerged as sustainable and eco-friendly substitutes for traditional synthetic pesticides in the management of insect pests. Biopesticides, originating from natural substances, microbes, or their metabolites, successfully manage pests by several processes, such as interfering with insect development, metabolism, feeding, and reproduction. Their target specificity, biodegradability, and diminished toxicity to non-target organisms render them essential elements of Integrated Pest Management (IPM) programs.

In contrast to synthetic pesticides, frequently linked to environmental pollution, insect resistance, bioaccumulation, and detrimental impacts on human and animal health, biopesticides provide a safer and more sustainable method for crop protection. The increasing demand for organic food and environmentally responsible agricultural practices has further accelerated the adoption of biopesticide-based technologies.

Microbial pesticides, semiochemicals, entomopathogenic organisms, and other biorational formulations have demonstrated significant potential for managing a wide range of agricultural pests while minimizing ecological impacts. However, broader adoption of biopesticides requires continued research and development to improve their efficacy, formulation stability, field performance, and cost-effectiveness. Strengthening regulatory support, farmer awareness, and commercialization strategies will also be essential for maximizing their utilization. Biopesticides serve as a promising instrument for sustainable agriculture and food security, providing effective pest management while safeguarding environmental integrity and human health.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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