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Entomopathogenic Microorganisms as Eco-Friendly Tools for Insect Pest Management

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INTRODUCTION

Insect pests are one of the major constraints to sustainable agricultural production because they cause considerable losses in crop yield and quality. Insects damage crops by feeding on leaves, stems, roots, flowers, fruits and seeds, while some species also act as vectors of plant pathogens. Traditionally, synthetic chemical insecticides have been extensively used for the management of insect pests because of their rapid action and ease of application. However, indiscriminate and repeated use of chemical insecticides has resulted in several undesirable consequences, including development of insecticide resistance, resurgence of pest populations, secondary pest outbreaks, pesticide residues in food, contamination of soil and water, and adverse effects on beneficial insects and other non-target organisms. These limitations have increased the importance of environmentally safer and biologically based approaches to pest management. Among the different biological control options, entomopathogenic microorganisms have emerged as important and promising tools for sustainable insect pest management. Entomopathogenic microorganisms are naturally occurring or artificially selected microorganisms capable of infecting insects and causing disease, reduced growth, impaired reproduction or mortality. Important groups include entomopathogenic fungi, bacteria and viruses, while entomopathogenic nematodes and their bacterial symbionts are also widely used within microbial pest-management programmes. These microorganisms have different modes of infection and pathogenicity and can be integrated with other components of integrated pest management (IPM).

Entomopathogenic Microorganisms and Their Diversity

Entomopathogenic microorganisms occur naturally in agricultural ecosystems, forest soils, plant surfaces and insect populations. Their diversity provides opportunities for developing pest-specific biological control agents.

Important entomopathogenic fungi include *Beauveria bassiana*, *Metarhizium anisopliae*, *Lecanicillium* spp. and *Isaria fumosorosea*. Important bacterial pathogens include *Bacillus thuringiensis*, which is one of the most widely used microbial insecticides in agriculture. Among viruses, baculoviruses, particularly nucleopolyhedroviruses (NPVs) and granuloviruses (GVs), are important pathogens of many lepidopteran pests. Entomopathogenic nematodes belonging mainly to the genera *Steinernema* and *Heterorhabditis* are associated with symbiotic bacteria such as *Xenorhabdus* and *Photorhabdus*, respectively. Each group possesses distinct biological characteristics and mechanisms of infection, which determine its suitability against particular insect pests. The selection of an appropriate microorganism depends on the target pest, developmental stage, crop ecosystem, environmental conditions, formulation and method of application.

Entomopathogenic Fungi

Entomopathogenic fungi are among the most important microbial agents used for insect pest management. Unlike many bacterial and viral pathogens that generally require ingestion, entomopathogenic fungi can infect insects through the external cuticle. This characteristic makes them particularly useful against sucking pests such as aphids, whiteflies, thrips and certain scale insects. *Beauveria bassiana* is one of the most extensively studied entomopathogenic fungi and has been reported to infect a wide range of agricultural pests. Its conidia attach to the insect cuticle, germinate under favourable environmental conditions and produce germ tubes that penetrate the cuticle. During penetration, fungal enzymes such as proteases, chitinases and lipases contribute to degradation of cuticular components. Once inside the insect body, the fungus develops and multiplies within the haemocoel, producing hyphal bodies and various metabolites. The resulting infection interferes with normal physiological functions and eventually causes insect death. Under suitable humidity, the fungus may emerge from the dead insect and produce new conidia on the cadaver, which can contribute to further transmission.

Metarhizium anisopliae is another important entomopathogenic fungus with considerable potential against soil-dwelling insects, beetles, termites, grasshoppers and other pests. It follows a mechanism broadly similar to that of *Beauveria*, involving attachment, germination, cuticular penetration, internal proliferation and production of virulence-related metabolites. Species of *Lecanicillium* have also attracted considerable attention for the management of soft-bodied insects, particularly aphids, whiteflies and other sap-feeding pests. Entomopathogenic fungi are particularly valuable because insects do not necessarily have to consume the pathogen for infection to occur. However, their efficacy is strongly influenced by environmental conditions, especially relative humidity, temperature and ultraviolet radiation. High humidity often favours conidial germination and infection, whereas intense sunlight and dry conditions may reduce their persistence and efficacy.

Entomopathogenic Bacteria

Entomopathogenic bacteria are another important component of microbial pest management. Among them, *Bacillus thuringiensis* (Bt) is the most widely known and commercially successful bacterial insect pathogen. Bt is a Gram-positive, spore-forming bacterium that produces insecticidal crystal proteins during sporulation. These proteins include Cry and Cyt toxins, while vegetative insecticidal proteins (Vip) are produced during the vegetative growth phase by some strains. Different strains and toxins have activity against different insect groups. Bt products are particularly important for the management of lepidopteran larvae, although certain strains are active against coleopteran and dipteran pests.

The insecticidal activity of Bt generally begins when susceptible larvae ingest bacterial spores and toxin crystals while feeding on treated plant material. In the alkaline environment of the insect midgut, crystal proteins are solubilized and subsequently activated by digestive enzymes. The activated toxins bind to specific receptors on the midgut epithelial cells, resulting in disruption of the gut membrane and loss of cellular integrity. The affected larvae stop feeding, become lethargic and eventually die. Because Bt toxins have specific target ranges, they can be valuable in IPM programmes where conservation of natural enemies is important. However, the development of resistance to individual Bt toxins in some insect populations demonstrates the importance of toxin rotation, use of multiple modes of action and integration with other control tactics.

Entomopathogenic Viruses

Entomopathogenic viruses are highly specialized pathogens and have considerable potential for environmentally compatible insect management. Baculoviruses are the most important group of insect viruses used as biological control agents. They include nucleopolyhedroviruses and granuloviruses, which primarily infect larval stages of Lepidoptera. Nucleopolyhedroviruses have been developed against several economically important pests, including *Helicoverpa armigera* and *Spodoptera* species. HaNPV, or *Helicoverpa armigera* nucleopolyhedrovirus, is an important example used for the management of *H. armigera* in crops such as chickpea, cotton and tomato.

Baculovirus infection generally occurs when susceptible larvae consume virus-contaminated plant material. The virus reaches the midgut and initiates infection in susceptible cells. Viral replication subsequently occurs within host tissues, followed by systemic spread throughout the insect body. Infected larvae gradually lose their feeding activity and become weak before dying. Following death, viral occlusion bodies may be released into the environment and can contribute to secondary infection. The high host specificity of baculoviruses is an important advantage because it can minimize effects on many non-target organisms. However, this specificity can also limit their use when multiple unrelated pest species occur simultaneously. In addition, ultraviolet radiation can rapidly reduce virus persistence on plant surfaces, making application timing and formulation important considerations.

Entomopathogenic Nematodes and Their Symbiotic Bacteria

Entomopathogenic nematodes, although multicellular organisms, are commonly discussed within biological pest management because of their close association with insect-pathogenic bacteria. The most important genera are *Steinernema* and *Heterorhabditis*. *Steinernema* species are associated with *Xenorhabdus* bacteria, whereas *Heterorhabditis* species are associated mainly with *Photorhabdus*. Infective juvenile nematodes actively search for insect hosts in the soil and enter them through natural openings or, in some cases, by penetrating the cuticle. After entering the host, the nematodes release their symbiotic bacteria into the haemocoel. These bacteria multiply rapidly and produce toxins and other metabolites that kill the insect. The nematodes then feed on the bacterial biomass and insect tissues and reproduce within the cadaver.

Entomopathogenic nematodes are particularly useful against soil-dwelling insects and root-feeding larvae. They have been investigated against white grubs, cutworms, fungus gnat larvae and several other soil pests. Their ability to actively search for hosts distinguishes them from many other microbial agents. They can also be applied through irrigation systems in some cropping situations. Their effectiveness, however, depends on adequate soil moisture, temperature, nematode quality and successful contact with susceptible hosts.

Mode of Action of Entomopathogenic Microorganisms

Entomopathogenic microorganisms use diverse mechanisms to cause insect mortality. Fungal pathogens primarily penetrate the insect cuticle following attachment and germination of spores. Enzymatic degradation of the cuticle facilitates penetration, after which fungal growth inside the insect causes physiological disruption and death. Bacterial pathogens such as Bt primarily act through the insect midgut following ingestion. Viral pathogens such as baculoviruses replicate within susceptible insect cells and eventually cause systemic infection. Entomopathogenic nematodes deliver symbiotic bacteria into the insect haemocoel, where bacterial multiplication and toxin production result in rapid host mortality. Some microorganisms also produce secondary metabolites, enzymes and toxins that interfere with insect immunity, metabolism, feeding behaviour and physiological processes. This diversity of modes of action is valuable because it provides opportunities to combine microbial agents with other pest management tactics.

Major Entomopathogenic Microorganisms and Their Target Pests

Microbial group	Important examples	Major target insect groups/pests	Principal mode of action	Major advantage
Entomopathogenic fungi	*Beauveria bassiana*	Aphids, whiteflies, thrips, beetles, caterpillars	Cuticle attachment, germination, penetration and internal colonization	Useful against both chewing and sucking pests
Entomopathogenic fungi	*Metarhizium anisopliae*	Soil insects, beetles, termites, grasshoppers	Cuticular penetration and internal proliferation	Particularly useful against soil-associated pests
Entomopathogenic fungi	*Lecanicillium* spp.	Aphids, whiteflies, scales and other soft-bodied insects	Cuticle infection and fungal colonization	Potentially useful for sucking-pest management
Entomopathogenic bacteria	*Bacillus thuringiensis*	Lepidopteran larvae and selected coleopteran/dipteran pests	Ingestion of insecticidal proteins followed by midgut disruption	Specific and commercially established microbial insecticide
Entomopathogenic viruses	HaNPV and other baculoviruses	*Helicoverpa*, *Spodoptera* and other susceptible caterpillars	Viral replication and systemic infection	High host specificity
Entomopathogenic viruses	Granuloviruses	Selected lepidopteran larvae	Ingestion and viral multiplication	Specific biological control
Entomopathogenic nematodes	*Steinernema* spp.	Soil insects and root-feeding larvae	Host invasion and release of *Xenorhabdus* bacteria	Active host searching ability
Entomopathogenic nematodes	*Heterorhabditis* spp.	White grubs, cutworms and soil pests	Host penetration and release of *Photorhabdus* bacteria	Effective against several soil-dwelling insects

Environmental Factors Influencing Microbial Efficacy

Environmental conditions play a major role in determining the effectiveness of entomopathogenic microorganisms in agricultural ecosystems. Temperature influences spore germination, pathogen growth, viral replication and nematode activity. Each microbial species and strain has a particular temperature range within which infection is most effective. Relative humidity is especially important for entomopathogenic fungi because adequate moisture is generally necessary for conidial germination and successful penetration of the insect cuticle. Ultraviolet radiation is another major limiting factor because direct sunlight can reduce the persistence of fungal spores and viral occlusion bodies on plant surfaces. Rainfall can have contrasting effects: heavy rainfall may wash microbial agents from foliage, while moderate moisture can favour fungal infection. Therefore, environmental monitoring and appropriate timing of application are essential for obtaining consistent results.

Importance in Management of Sucking Pests

Sucking pests such as aphids, whiteflies, thrips and certain scale insects are major constraints in vegetable, pulse and horticultural crops. Their high reproductive potential, rapid population growth and ability to develop resistance to insecticides make their management difficult. Entomopathogenic fungi have considerable potential against these pests because they can infect insects through direct contact. *Beauveria bassiana* and *Lecanicillium* species have been investigated extensively for the management of sucking pests. Their integration with natural enemies, botanical pesticides, resistant varieties and selective insecticides can provide a more sustainable approach than repeated application of broad-spectrum insecticides. This is particularly relevant for pulse crops such as green gram, where aphids, whiteflies and other sucking pests may affect plant growth and productivity.

Importance in Management of Lepidopteran Pests

Lepidopteran caterpillars include several economically important pests such as *Helicoverpa armigera*, *Spodoptera litura*, *Plutella xylostella* and different fruit and shoot borers. Bt formulations and baculoviruses are important microbial tools for managing these pests. Their effectiveness is generally greatest when applied against young larval stages because older larvae may be less susceptible and can cause substantial crop damage before mortality occurs. Monitoring pest populations and applying microbial agents at the appropriate stage are therefore important for achieving satisfactory control. Entomopathogenic fungi may also contribute to caterpillar management and can provide an additional mode of action in integrated programmes.

Role in Integrated Pest Management

The greatest value of entomopathogenic microorganisms lies in their integration with other components of IPM. Rather than relying exclusively on microbial or chemical control, pest management should combine crop monitoring, cultural practices, host-plant resistance, biological control, microbial pesticides, pheromone-based monitoring, mechanical methods and selective insecticides. Microbial agents can reduce the frequency and quantity of chemical insecticide applications and may help conserve beneficial insects. For example, fungal pathogens can be integrated with parasitoids and predators when compatibility is carefully considered. Similarly, Bt and baculoviruses can be incorporated into programmes against caterpillar pests while avoiding unnecessary applications of broad-spectrum insecticides. Such integration can

improve sustainability and reduce selection pressure associated with repeated use of a single pest-control method.

Advantages of Entomopathogenic Microorganisms

Entomopathogenic microorganisms offer several ecological and agricultural advantages. Many are naturally occurring organisms and are biodegradable, thereby reducing long-term environmental contamination. Their specificity can reduce impacts on beneficial organisms when appropriate strains are selected. They can be incorporated into IPM programmes and can help reduce reliance on conventional insecticides. Microbial agents also provide different modes of action from many chemical insecticides, making them useful components of resistance-management strategies. Fungal pathogens are especially useful because they can infect insects through contact, while viral pathogens can provide highly specific control of selected pests. Entomopathogenic nematodes have the additional advantage of actively searching for insect hosts in soil. These characteristics make microbial agents important tools for developing sustainable and ecologically based pest management systems.

Limitations and Challenges

Despite their potential, microbial pesticides have several limitations. Their efficacy can be slower than that of many conventional insecticides, and this may influence farmer acceptance. Environmental sensitivity is another important limitation, particularly for fungal and viral pathogens. High temperature, low humidity, intense sunlight and rainfall can reduce field persistence and effectiveness. Some microbial products also have relatively demanding storage requirements, and poor storage conditions can reduce viability. Narrow host specificity, although environmentally advantageous, may limit their effectiveness when multiple pest species occur together. Production costs, formulation quality, availability of high-quality commercial products and farmer awareness are additional factors influencing adoption. Therefore, further research and extension efforts are required to improve the reliability and practical use of microbial pest-control agents.

Recent Advances and Future Prospects

Recent advances in molecular biology, genomics, biotechnology and formulation science are creating new opportunities for improving microbial pest management. Molecular characterization can help identify highly virulent strains and clarify mechanisms of host specificity and pathogenicity. Genomic studies are providing information about genes involved in toxin production, host recognition, immune evasion and environmental adaptation. Improved formulations are being developed to enhance microbial survival under field conditions. Microencapsulation and protective carriers may reduce the harmful effects of ultraviolet radiation and environmental stress. There is also increasing interest in the ability of some entomopathogenic fungi to colonize plants as endophytes, potentially providing additional protection against insect herbivores. Precision agriculture and digital pest monitoring may further improve microbial pesticide application by allowing treatments to be targeted according to pest density and crop conditions.

Artificial intelligence and machine-learning technologies may also contribute to microbial pest management by improving insect identification, pest-density estimation and application timing. Automated image recognition systems can potentially detect pest populations at an early stage, while weather-based models may help identify environmental conditions favourable for fungal infection or viral activity. Such technologies could improve the efficiency of microbial pesticide use and reduce unnecessary applications.

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CONCLUSION

Entomopathogenic microorganisms are important eco-friendly tools for managing insect pests and have considerable potential for sustainable crop protection. Entomopathogenic fungi such as *Beauveria bassiana*, *Metarhizium anisopliae* and *Lecanicillium* spp., bacterial pathogens such as *Bacillus thuringiensis*, baculoviruses and entomopathogenic nematodes provide diverse mechanisms for suppressing economically important insect pests. Their major benefits include biodegradability, compatibility with IPM, potential target specificity, reduced environmental contamination and the possibility of reducing dependence on conventional insecticides. Fungal pathogens are particularly promising for sucking pests, while Bt and baculoviruses are important tools for several lepidopteran pests. Entomopathogenic nematodes provide valuable options for soil-dwelling insects.