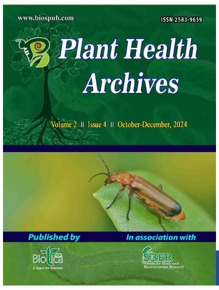

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Review Article

Microbial Pesticides in Pest Management

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Abstract

This review looks at how modern pest management strategies might use microbial pesticides as well as how they might reduce the negative consequences linked with conventional chemical pesticides. Comprising naturally occurring microorganisms, including bacteria, viruses, fungi, nematodes and protozoa, microbial pesticides offer a sustainable alternative to synthetic chemicals. Ranging from the development of particular toxins to host-targeted infections causing pest death, their modes of action provide an efficient and environment friendly pest management. This paper follows the historical development of microbial pesticide research and records its gradual incorporation into integrated pest management (IPM) systems. Presented in depth are the ways by which bacterial agents, especially *Bacillus thuringiensis*, disturb insect physiology by means of toxin-mediated effects. Viral agents are assessed in terms of host specificity and operational safety, especially baculoviruses. While the functions of nematodes and protozoa in the control of soil-dwelling pests are also discussed, fungal pathogens are investigated for their capacity to penetrate insect integuments and invade host tissues. The study also points out and addresses issues including field application uniformity, environmental sensitivity, mass manufacturing constraints and formulation stability. This paper, therefore, combines present research results to offer a thorough knowledge of practical use and microbial pesticide effectiveness and highlights the need of ongoing technical innovation in biopesticide development, hence opening the path for more integrated and sustainable pest management strategies supporting agricultural production and ecological balance.

Keywords: Bacterial pesticides, Fungal pesticides, Insect viruses, IPM integration, Nematodal pesticides, Protozoan pesticides

Introduction

Over the last few decades, global agricultural practices have shifted in pest management from a heavy dependence on chemical pesticides toward more sustainable alternatives. Uncontrolled use of synthetic chemicals not only harms the environment but also promotes the development of resistant insect populations that seriously threaten food security and ecosystem health (Edwards, 1990; Georgis, 1997).

Recent researches have validated the viability of microbial pesticides as sustainable alternatives for conventional agrochemicals. For example, Rajashekhar *et al.* (2021) discovered that in integrated pest management (IPM) initiatives, particularly in countries like India where biotic stress significantly reduces crop production, microbial pesticides, including *Bacillus thuringiensis*, entomopathogenic fungi and nematodes, showed favorable risk-benefit profiles. Shamsuddeen *et al.* (2024) revealed more, even if there are still challenges in public acceptability and regulatory approval, which these biopesticides may perform almost like chemical pesticides while significantly reducing environmental impacts.

Advances in application techniques and formulation have strengthened even more the part of microbial pesticides in sustainable farming. Ayilara *et al.* (2023) underlined

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that combining microbial, phyto- and nanobiopesticides enables targeted pest control with minimal environmental residues, hence supporting their application in contemporary agricultural systems. Simultaneously, Kambrekar *et al.* (2007) and Chaudhary *et al.* (2024) have noted that the efficacy and dependability of microbial pesticides are being significantly raised by improvements in formulation techniques and commercialization processes combined with improved quality control measures. These technological and regulatory advancements have spurred changes in testing procedures (Karaoğlan *et al.*, 2024) and paved the way for creative ideas like microbiome manipulation (Qadri *et al.*, 2020; Mawcha *et al.*, 2024) to further improve sustainable pest management strategies.

Aioub *et al.* (2021) also showed that combining entomopathogenic nematodes with sub-lethal insecticide dosages can efficiently manage pests including the cabbage white butterfly, therefore lowering chemical inputs and mitigating environmental risks. Complementary reviews by Samada and Tambunan (2020) and Hernández-Fernández *et al.* (2021) emphasized the benefits of biopesticides, especially their specificity, lower toxicity and dual role as biofertilizers and pest controllers, which collectively underscore the transforming potential of microbial pesticides in attaining long-term sustainability in agriculture. Microbial pesticides have therefore surfaced as a promising alternative given their inherent specificity, biodegradability and compatible with the integrated pest management (IPM) frameworks (Huber, 1998; Lacey *et al.*, 2001).

The current review looks at the evolution, mechanisms and applications of microbial pesticides, including bacterial, viral, fungal, nematodal and protozoan agents. Historically, these biological agents were limited to small-scale experimental trials; nevertheless, developments in biotechnology and microbial ecology have allowed their move to commercial applications. Microbial pesticides are being acknowledged not only for their effectiveness in pest control but also for their contribution to environmental sustainability and lowering human health risks (Carlton and Gawron-Burke, 1993; Moore, 1994). The subsequent section offers the basic concepts and historical developments in microbial pest management, which sets the reader for an in-depth examination of every microbial group and the problems related with their practical application. By underlining the transforming potential of microbial pesticides in modern agriculture, it underlines the need of continuous research and technical innovation.

Microbial Pesticides: An Overview

Comprising a wide range, microbial pesticides are the biocontrol agents made from living organisms or their metabolic by-products. Their key benefit is the capacity to target particular pest populations without harming helpful species, hence preserving ecological balance (Lacey and Goettel, 1995). Among the many microbial taxa included in these agents are bacteria, viruses, fungus, nematodes and protozoa. Every group shows different ways of acting from toxin generation to direct infection, which ultimately kills the target pests. Summarizing their modes of action, target pests, benefits and drawbacks, table 1 offers a comprehensive comparison of the major microbial pesticide groups.

Microbial pesticides have developed as a sustainable alternative to chemical pesticides worldwide owing to growing concerns of environmental sustainability, value chain regulations, as well as the capacity to scale up production technology in recent years. According to recent analyses in market development, microbial pesticides comprise a large majority of the biopesticides sector (over 55%) and are projected to be valued at USD 6.3 billion by 2033 (Figure 1), growing at a CAGR of approximately 7.3% (Anonymous, 2024b). Current process innovations, specifically fermentation and preparation technology increases continue to increase options of scale, while also preserving effectiveness of microbial pesticides to be part of modern integrated pest management (IPM) strategies worldwide (Verma *et al.*, 2024). In India, microbial pesticides account for only approximately 4-9% of the overall pesticide market; however, consumption data indicate that this market segment increased almost 40% from 2014-2015 to 2018-2019, demonstrating a change in preference for sustainable pest control options (Chakraborty *et al.*, 2023). Additionally, the Indian biopesticides market is forecast to increase from USD 82.2 million in 2024 to approximately USD 204.1 million by 2033, growing at a CAGR of 9.23%, directionally supported by favorable government policies, including the National Mission for Sustainable Agriculture and consumer demand for produce with little or no pesticide residue (Anonymous, 2023; Anonymous, 2024a).

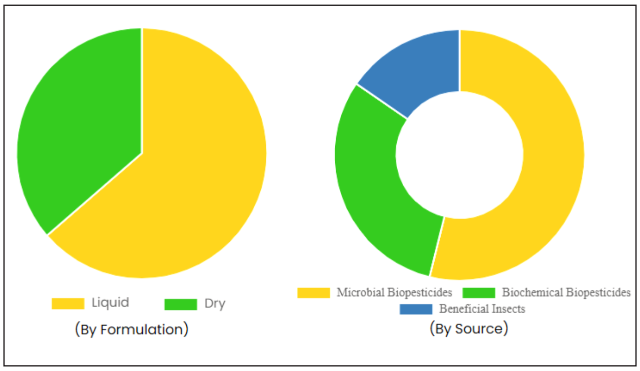

Figure 1: Indian biopesticides market 2024-2033 (Source: Anonymous, 2024a)

Apart from traditional methods of action, recent studies have more and more concentrated on creative formulation techniques to improve the effectiveness and field performance of microbial pesticides. Kariyanna *et al.* (2024) presented a thorough investigation of current encapsulation and adjuvant technologies revealing that under various environmental conditions these innovations significantly enhance stability and enable a controlled release of microbial active components. Complementing this perspective, Tiwari *et al.* (2024) underlined that the eco-friendly and inexpensive character of microbial biopesticides makes them a viable replacement for synthetic chemicals, particularly when

Table 1: Characteristics of microbial pesticides

Microbial Group	Mode of Action	Target Pests	Advantages	Limitations	Commercial Products	References
Bacteria (*e.g.*, *Bt*)	Cry toxins dissolve in the larval gut, bind to receptors and form pores that cause paralysis and death.	Mainly caterpillars (Lepidoptera); some flies and beetles.	Highly specific; safe for non-targets; can be engineered into crops.	Risk of resistance; UV sensitive; variable field efficacy.	Dipel®, XenTari®	Carlton and Gawron-Burke, 1993; Moore, 1994
Viruses (Baculoviruses)	Ingested occlusion bodies release virions that replicate in the host, leading to systemic infection and death.	Primarily Lepidoptera (*e.g.*, armyworms, codling moth, leafrollers).	Extremely specific; eco-friendly; organic compliant.	Slow kill; sensitive to UV; higher cost.	Helicovex®, Spodovir Plus®	Cherry *et al.*, 2000; Cunningham, 1998
Fungi (EPF, *e.g.*, *B. bassiana*, *M. anisopliae*)	Spores attach to the insect cuticle, germinate and penetrate to produce toxins that kill the pest.	A wide range, including concealed and soft-bodied insects.	Broad host range; residual activity; eco-friendly; fits IPM strategies.	Weather-dependent performance; slower kill rate.	Botanigard®, Mycotrol®, Met52®	Ferron, 1981; Langewald *et al.*, 1999
Nematodes (EPN, *e.g.*, *Steinernema, Heterorhabditis*)	Actively invade through natural openings and release bacteria that cause septicemia.	Soil-dwelling pests and hidden insect stages.	Rapid control; safe for non-targets; effective in soil.	Highly sensitive to temperature, moisture and UV; challenging to handle.	MeloCon WG®	Lacey and Goettel, 1995; Lacey *et al.*, 2001
Protozoa (Microsporidia)	Ingested spores germinate and establish chronic infections that reduce pest fitness and reproduction.	Mainly grasshoppers and select invertebrates.	Highly specific; minimal non-target effects; long-term suppression.	Slow acting; difficult to mass produce; limited availability.	Mycotal®	Bing and Lewis, 1991; Cherry *et al.*, 2000

modern formulation methods are applied to ensure high viability and continuous release of active components.

Moreover, contemporary research has broadened the spectrum of microbial pesticides beyond traditional bacterial and fungal agents. Gozel and Gozel (2016) emphasize the key importance of entomopathogenic nematodes (EPNs) in integrated pest management (IPM), stressing their compatibility with sustainable agriculture practices. Currently, microbial biopesticides make just approximately 5% of the market in India, as noted by Kiran Kumar *et al.* (2019); nonetheless, continuous developments in production technologies and formulation methodologies are rapidly increasing their possibilities. Described by Manochaya *et al.* (2022), further developments in *in-vivo* culturing methods for EPNs are set to increase mass-production yields and enable large-scale field applications, therefore encouraging the more general integration of microbial pesticides into efficient IPM approaches.

The formulation, production and field application of microbial pesticides have achieved significant advances in recent times. To increase the viability and efficacy of these agents under various environmental conditions, researchers have refined culture techniques, maximized fermentation processes and strengthened carrier systems (McCutchen *et al.*, 1991; Stewart *et al.*, 1991). Moreover, genetic engineering has been used to modify important microbial strains, hence increasing their persistence, specificity and insecticidal activity. Establishing policies that enable the safe registration and commercialization of these biopesticides has also much depended on regulatory agencies as the US Environmental Protection Agency (EPA) (Huber, 1998).

Rajashekhar *et al.* (2021) offered a thorough risk analysis of microbial pesticides, clarifying not only their efficacy in controlling insect pests but also the important quality control and production consistency issues. Though they now make a small part of the total pesticide market, their regular growth trajectory highlights the potential of significant market expansion. Improved production methods and stronger regulatory systems are suggested as key elements that could help their worldwide adoption in sustainable agriculture even further. Moreover, field performance optimization depends on formulation creativity. Thakur *et al.* (2020) critically examined the current developments in microbial biopesticide formulations that enhance stability, allow controlled release and prolong residual activity, qualities that allow these biopesticides to perform comparably or even exceed conventional chemical pesticides. Rodríguez *et al.* (2024) also showed that the use of OMIC technology produces a better knowledge of the genetic and metabolic systems supporting pesticide breakdown. Such knowledge helps to create next-generation biopesticides with better safety profiles and higher effectiveness.

The various types of microbial pesticides are thoroughly covered in this section. It investigates the basic biology of every microbial group, addresses their respective modes of action and highlights the challenges and innovations connected with their application. Understanding these elements will help scientists and researchers to more effectively include microbial pesticides into complete IPM strategies that address both current and emerging pest threats.

Bacterial Pesticides

The increasing focus on bacterial insecticides has been significantly influenced by a substantial body of research evidence supporting their effectiveness and safety. Among these, *Bacillus thuringiensis* (*Bt*) has become the most prominent bacterial agent used in pest management. A Gram-positive, soil-dwelling bacterium, *Bt* produces crystalline inclusions known as Cry proteins during its sporulation phase. Once consumed by vulnerable insect larvae, these proteins are activated in the alkaline environment of the larval midgut. Activated toxins cause pore formation in midgut epithelial cells by selective binding to receptor sites, hence causing cell lysis and ultimately insect death (Carlton and Gawron-Burke, 1993; Moore, 1994).

From the manufacture of Cry proteins to the final death of the insect larva, Figure 2 shows a comprehensive flowchart of the *Bt* mode of action.

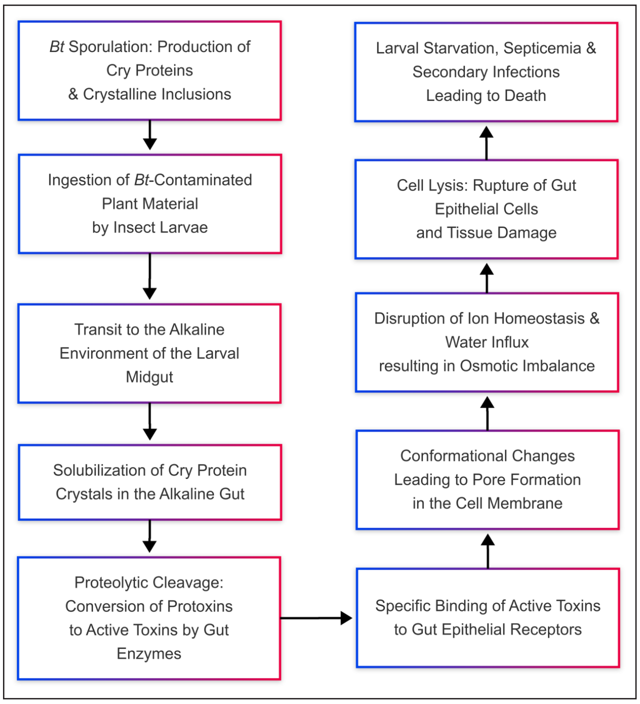

Figure 2: Detailed flowchart depicting the mode of action of *Bacillus thuringiensis* (*Bt*)

The efficacy of *Bt* is mostly attributed to the variety of Cry proteins it generates. Every variety shows a unique spectrum of activity that allows specifically control certain pest groups from Lepidoptera to Diptera and Coleoptera (Lane *et al.*, 1991). This selectivity not only reduces the probability of resistance development but also lowers the risk to non-target species. By offering constant in planta protection, integration of *Bt* into genetically modified (GM) crops has even more transformed pest control strategies. Ongoing research and the development of novel formulations are therefore required in spite of issues, such as target pest resistance evolution, toxin expression variability and Cry protein environmental degradation (McCutchen *et al.*, 1991).

Recent studies have concentrated on tackling issues such resistance development and toxin breakdown outside conventional ways of action. For example, Munnysha and Bunker (2024) showed that the co-application of *Bacillus thuringiensis* (*Bt*) with complementing microbial agents can have synergistic effects that reduce resistance while improving pest reduction performance. In the same vein, Tomar *et al.* (2024) provided a thorough survey of the biodiversity of entomopathogenic bacteria, describing the various toxin complexes these species generate, which emphasizes the need of genetic and metabolic variety among these bacterial strains in enhancing pest control results and fostering environmental sustainability, therefore supporting the more general incorporation of bacterial biopesticides into integrated pest management strategies.

Apart from *Bt*, other bacterial species include *Bacillus sphaericus* and *Bacillus suBtilis* have demonstrated as the promising biocontrol agents. Contributing to a broader spectrum of bacterial pesticides, these bacteria produce several bioactive compounds with insecticidal properties. Current studies emphasize identifying new bacterial strains, clarifying the molecular mechanisms behind their insecticidal action and enhancing formulation techniques to ensure constant field performance.

Insect Viruses

Insect viruses, particularly baculoviruses, have grown more crucial for microbiological pest control since they are very specific and harmless. Primarily classified as nuclear polyhedroviruses (NPVs) and granuloviruses (GVs), baculoviruses are characterized by their double-stranded circular DNA genomes. The insecticidal qualities of these viruses derive from their ability to generate occlusion bodies, protective protein matrices encircling viral particles. Target insects consume the occlusion bodies, which disintegrate in the midgut and release virions infecting host cells, hence causing systemic infection and death (Cherry *et al.*, 2000). Their small host range, which reduces harm to beneficial species and non-target organisms, makes baculoviruses particularly attractive for pest control. Moreover, the great degree of host specificity lessens environmental contamination. Several challenges, however, still limit the widespread application of baculoviral insecticides. Environmental variables like temperature changes, humidity and ultraviolet (UV) radiation greatly affect the persistence and infectivity of these viruses (Cunningham, 1998). To get around these limitations, scientists have created recombinant baculoviruses producing more insect-specific toxins, hence accelerating the death rate and extending the effectiveness under poor field conditions (Merryweather *et al.*, 1990).

Viral pesticides still provide major difficulties in quality control. Emphasizing that consistent field performance depends on standardized production methods, Kambrekar *et al.* (2007) undertook a thorough assessment of HaNPV sample quality. This study highlighted the need of thorough quality assurance policies in the commercial synthesis of microbial insecticides. At the same time, recent developments have focused on improving the stability and effectiveness of viral biopesticides. For example, recombinant DNA technologies have been used to optimize nucleopolyhedroviruses, hence increasing their virulence and environmental robustness (Kiran Kumar *et al.*, 2019). Such developments not only lower the needed application frequency but also minimize negative consequences on non-target species, hence supporting the incorporation of viral pesticides into current IPM systems.

Genetic engineering and molecular virology developments have further increased the potential applications of baculoviruses. Scientists are investigating methods to broaden the host range, enhance virulence and improve the stability of these biocontrol agents by manipulating the viral genomes. Integration of such technologies into pest control strategies is expected to significantly lower the reliance on chemical pesticides and thereby help in sustainable agricultural practices.

Fungal Pesticides

Entomopathogenic fungi represent a diverse and potent group of microbial insecticides. These organisms actively infect and eliminate insect hosts through a combination of mechanical penetration and enzymatic degradation of the insect cuticle. Notably, *Beauveria bassiana*, *Metarhizium anisopliae* and *Metarhizium flavoviride* have been extensively studied due to their broad host ranges and their demonstrated efficacy in controlling a wide variety of insect pests (Ferron, 1981).

These fungus start their infection cycle by having conidia (spores) attach to the insect cuticle (Figure 3). After attachment, the spores germinate and produce hyphae that release a cocktail of cuticle-degrading enzymes including chitinases, proteases and lipases. By means of this enzymatic action, the fungus may penetrate the protective barriers of the insect and infect the hemocoel where it multiplies, hence killing the host (Lane *et al.*, 1991). The effectiveness of fungal infections is significantly influenced by environmental factors including temperature, humidity and UV exposure, which has spurred intensive research on formulation improvements and adjuvant technologies (Langewald *et al.*, 1999).

Recent developments in formulation technique have produced improved fungal pesticide formulations more resistant to environmental challenges. The survival of fungal spores on crop surfaces, for example, has been improved by using moisture-retaining carriers and UV protectants. Furthermore, genetic engineering projects have produced fungal strains with higher virulence and faster kill rates, hence solving one of the main drawbacks linked with the somewhat slow action of fungal infections (Langewald *et al.*, 1999).

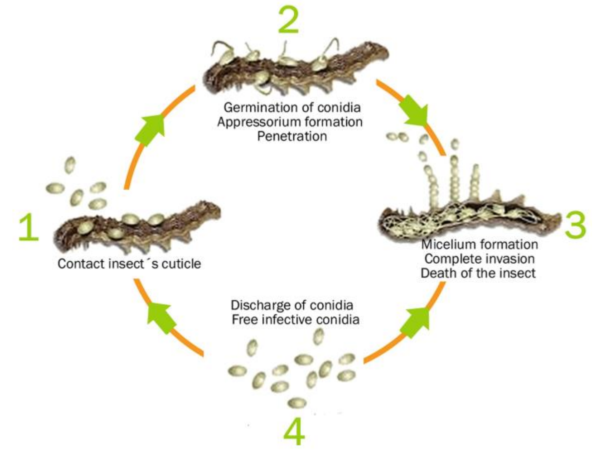

Figure 3: Mode of action of entomopathogenic fungus (Barra-Bucarei *et al.*, 2019)

Recent studies have focused on the optimization of fungal pesticide formulations to overcome natural environmental vulnerabilities. Innovations such as the use of UV-protectants and moisture-retaining carriers (Kariyanna *et al.*, 2024) have shown great promise in improving spore viability and field stability. At the same time, developments in formulation technology have significantly increased the operating performance of fungal biopesticides. Thakur *et al.* (2020) found that the combination of improved spore stabilization techniques and the inclusion of UV-protectant chemicals greatly increase field persistence and efficacy. Collectively, these advancements strongly advocate for the adoption of entomopathogenic fungi, including *Beauveria bassiana* and *Metarhizium anisopliae*, as dependable and environmentally sustainable alternatives to conventional chemical pesticides.

Beyond their direct role in pest control, entomopathogenic fungi also contribute to preserving beneficial insect populations and mitigating secondary pest outbreaks, thereby enhancing the overall health of agro-ecosystems. Research is planned to enhance the practical use of fungal biopesticide formulations optimized with advances in mass production techniques in diverse agricultural environments.

Nematodal Pesticides

Particularly for soil-dwelling pests where chemical control techniques sometimes fail, entomopathogenic nematodes (EPNs) have become acknowledged as the effective biological control agents. Though nematodes are multicellular organisms instead of microbes per se, their inclusion in microbial pesticide strategies is warranted by their fast infectivity and high lethality against target pests (Edwards, 1990).

The most commonly used EPNs belong to the genera *Steinernema* and *Heterorhabditis*. Respectively, these nematodes have a mutualistic relationship with symbiotic bacteria, *Xenorhabdus* spp. and *Photorhabdus* spp., which are absolutely essential for their insecticidal function. Infecting an insect host drives the nematodes to release their symbiotic bacteria into the hemocoel, where the bacteria rapidly proliferate and produce toxins, hence hastening the loss in host viability. Usually, the nematode and its bacterial symbiont working together kill the insect within 48 hours; hence EPNs are quite efficient for pest suppression (Lacey and Goettel, 1995).

Using EPNs in pest management has many benefits, including simple mass rearing under controlled conditions, low non-target impacts and compatibility with a broad spectrum of treatment techniques. Still, environmental factors have a great impact on the effectiveness of nematodal insecticides. Soil moisture, temperature and UV exposure are among the factors that can harm nematode survival and infectivity. Researchers have therefore concentrated on developing improved formulations that shield nematodes during storage and application and on investigating synergistic combinations with other biocontrol agents or reduced-risk insecticides (Lacey *et al.*, 2001).

Apart from the well-established mode of action, where entomopathogenic nematodes (EPNs) penetrate host insects *via* natural apertures and then release their mutualistic bacteria to create fast septicaemia, current research has substantially increased their practical applicability. Aioub *et al.* (2021), for instance, showed that combining EPNs with sub-lethal dosages of insecticides results in additive and occasionally synergistic effects on pest death, hence lowering total chemical use (Aioub *et al.*, 2021). Moreover, as described by Manochaya *et al.* (2022), developments in in vivo culturing methods have greatly improved the production yield and survivability of EPNs, hence ensuring more persistence under field settings. Kiran Kumar *et al.* (2019) also claimed that advancements in regional-specific formulations and fermentation technologies are effectively addressing quality control issues, hence increasing the market share of nematodal biopesticides in India (Kiran Kumar *et al.*, 2019). Furthermore, van der Linden *et al.* (2022) underlined that exact application techniques, including foliar treatments in controlled microclimates, can maximize the effectiveness of EPNs against foliar pests in ornamental plantings, therefore stressing the important impact of environmental conditions and application strategies on biopesticide performance (van der Linden *et al.*, 2022). These developments taken together highlight the need of improved production, formulation and application techniques to completely exploit the possibility of nematodal insecticides as a strong and sustainable part of integrated pest management.

Advancements in molecular biology and nematode ecology are also helping to clarify host-nematode relationships, which therefore helps to develop more robust and efficient nematode-based biopesticides. The maximization of EPN uses in various agricultural environments depends on this study, hence improving their role in sustainable pest control techniques.

Protozoan Pesticides

Though not as commonly used as bacterial, viral or fungal agents, entomopathogenic protozoa are a notable and emerging group of microbial insecticides. Because of their unique life cycles and host-specific infection mechanisms, *Microsporidia*, a genus of obligate intracellular parasites classed among protozoa, have been the focus of considerable research. Species in the genus *Nosema*, for instance, have been used to manage grasshopper populations by means of the pathogen's capacity to induce chronic infections that progressively reduce pest fitness (Cherry *et al.*, 2000).

Usually, the infection cycle of *Microsporidia* starts with an insect host consuming resilient spores. These spores germinate when they reach the midgut, hence producing infective sporoplasms that infiltrate host cells. Once within, the pathogen replicates and ultimately causes systemic infection and sublethal consequences that compromise the host's growth, feeding and reproductive capabilities. Though usually slower than bacterial or viral infections, protozoan diseases can have large long-term sublethal effects that significantly reduce pest populations over time (Bing and Lewis, 1991).

Both nematodal and protozoan insecticides' formulation stability and field efficacy have been significantly improved by recent developments in molecular biology and mass-production methods. Mawcha *et al.* (2024) showed how enhanced effectiveness of these agents in various agricultural environments results from optimal production protocols and improved formulation techniques. Though used less often than other microbial agents, protozoan insecticides have been shown by new studies to cause persistent infections that greatly lower pest fitness. Gradually, improved formulation techniques and scalable manufacturing processes are overcoming past constraints, so confirming protozoan pesticides as a feasible and complementary part of integrated pest control systems (Samada and Tambunan, 2020).

Reliable mass production and formulation techniques are one of the principal challenges associated with protozoan insecticides. Before these agents may be extensively used, important factors that have to be addressed are maintaining spore viability and ensuring effective delivery to target pest populations. Current studies are focused on optimizing culture conditions, clarifying the genetic basis of virulence and investigating novel application techniques that enhance the infectivity and persistence of microsporidian spores in the field.

Role of Microbial Pesticides in Integrated Pest Management (IPM)

The effective integration of microbial pesticides into integrated pest management (IPM) systems reflects a holistic approach to sustainable agriculture. IPM initiatives seek to attain efficient pest suppression by means of integrating microbiological agents with cultural practices, biological management and focused chemical applications, hence reducing environmental concerns. By providing focused pest control with minimum non-target impacts, microbial pesticides help to this approach and lower the overall dependence on broad-spectrum chemical pesticides (Lacey *et al.*, 2001). Table 2 provides a comparative analysis of the environmental impacts of microbial pesticides vs. conventional chemical pesticides. It compares the key parameters, such as residue persistence, non-target effects, degradation rates and overall ecological safety, emphasizing the superior environmental profile of microbial pesticides.

The successful implementation of microbial pesticides within IPM depends much on the synchronization of application timing with pest life cycles. *Bt* formulations, for instance, work best when administered during the larval feeding period; fungal and nematodal agents may require specific environmental conditions like high humidity and ideal soil moisture levels for peak efficacy. Improvements in precision agriculture, including remote sensing and real-time pest monitoring, have improved ability of practitioners to time and target microbial pesticide applications more precisely. The decision-making process for integrating microbial pesticides into a comprehensive IPM strategy is depicted in figure 4.

Table 2: Comparative analysis of environmental impacts between microbial and chemical pesticides

Feature	Microbial Pesticides	Chemical Pesticides
Environmental impact	Biodegradable, eco-friendly	Persistent, potential toxicity
Specificity to target pest	High specificity, minimal off-target	Broad-spectrum, affects non-targets
Cost	Higher initial cost, lower long-term	Lower initial cost, potential resistance
Environmental persistence	Short-term, degrades naturally	Long-lasting, accumulates in ecosystems
Regulatory status	Subject to bio-safety approval	Established regulatory framework
Economic viability	Cost-effective over time, sustainable	Immediate efficacy, but costly resistance management

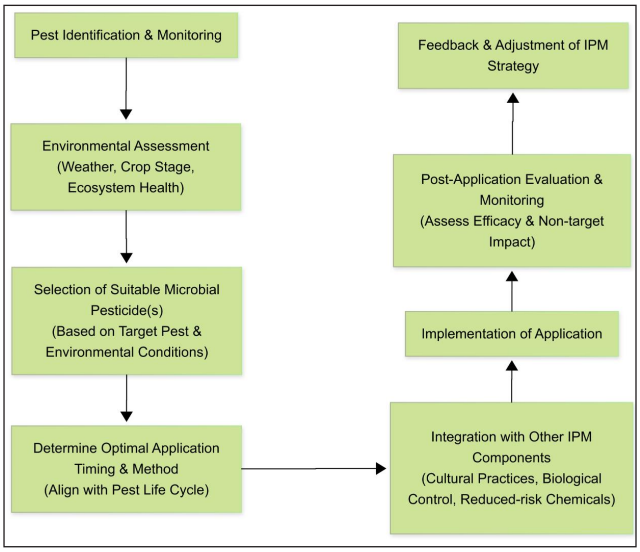

Figure 4: Flowchart showing the integration of microbial pesticides into an IPM approach

Furthermore, the combined use of several microbial agents or the combination of microbial and reduced-risk chemical pesticides has showed promise in attaining more comprehensive pest control. Such integrated approaches not only enhance pest control but also help to preserve beneficial insect populations and sustain soil health. Ongoing researches on the compatibility and synergistic interactions among different microbial pesticides could help to further refine IPM tactics, therefore guaranteeing that these biocontrol agents remain a viable and efficient component of modern pest management systems. From early *Bt* research to expected developments in next-generation biopesticides by 2024, figure 5 shows the timeline of microbial pesticide research and commercialization, hence underlining important turning points.

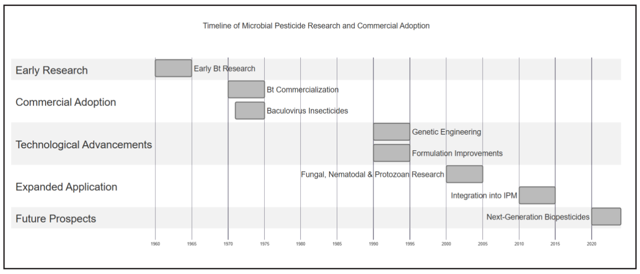

Figure 5: Timeline of microbial pesticide research and commercial adoption

Recent studies have highlighted the intentional use of microbial pesticides into integrated pest management (IPM) systems as a way to lower reliance on synthetic chemicals. For instance, Aioub *et al.* (2021) and van der Linden *et al.* (2022) have shown that such integration not only improves the general effectiveness of pest control but also reduces collateral effects on non-target species, hence helping to promote environmental sustainability. Moreover, studies show that microbial pesticides can be used to change pest microbiomes, hence affecting important physiological factors as nutrition, immunity, and behaviour. Examining these creative microbiome-based solutions, Qadri *et al.* (2020) proposed that including them into traditional IPM plans could produce more robust and sustainable pest control methods.

Equally crucial is the development of strong quality testing procedures and safety for microbial pesticides. Wend *et al.* (2024) have drawn attention to the difficulties natural in assessing microbial agents with traditional techniques used for chemical pesticides and support the creation of new testing approaches specifically suited to the particular qualities of live biopesticides. Aioub *et al.* (2021) have found that combining pesticides with entomopathogenic nematodes could have synergistic effects that decrease environmental toxicity and the probability of resistance formation. Given their unique biological characteristics compared to synthetic pesticides, Vermelho *et al.* (2024) underlined even more the requirement of regulatory frameworks and quality evaluation procedures especially created for microbial agents.

Conclusion

Ultimately, current pest management systems depend on microbial pesticides, which are dynamic and vital component. Their unique modes of action, high specificity and favourable environmental profiles provide significant advantages over traditional chemical pesticides. The integration of microbial agents into IPM systems is probably going to expand as agricultural practices shift toward sustainability. Future possibilities include the creation of next-generation biopesticides by means of genetic engineering, improve formulation technologies and upgraded delivery systems. These developments will allow environmentally balanced, efficient and more precise insect management. Overcoming current obstacles and completely exploiting the possibilities of microbial pesticides in protecting world food security and environmental health will depend on continued investment on ongoing researches and cooperation among industry, regulatory authorities and universities.

Sustainable agriculture seeks to promote the smart use of natural resources by means of a balance of technological soundness, economic viability, environmental safety and social acceptability. In reaction to growing worries about the detrimental effects of chemical pesticides on human health and the environment, research and development projects have become more concentrated on microbial insecticides. Employed under inundative or inoculative approaches for the biological control of insect pests in agricultural, forestry and horticultural environments, these biopesticides come from fungus, bacteria, viruses, protozoa and nematodes. High human safety, consistent pest control and renewable nature - these natural benefits make microbial pesticides as the appealing alternatives for integrated pest management. Advanced formulation technologies, strict quality control policies and new microbiome-based strategies are basically changing microbial pesticide research. To conclude, these developments not only increase the effectiveness of biopesticides but also support resilient and sustainable agricultural practices, which are vital for future pest control (Ayilara *et al.*, 2023; Qadri *et al.*, 2020).

The use of innovative OMIC technologies and genome-editing tools is anticipated to next improve the generation and performance of microbial insecticides. Recent studies by Thakur *et al.* (2020) and Rodríguez *et al.* (2024) have clarified the molecular mechanisms of pesticide degradation and resistance, hence guiding the creation of biopesticides that are more powerful and environmentally safe. Furthermore, the several functions of microbial agents not only as efficient pest controllers but also as major contributors to soil bioremediation (Vermelho *et al.*, 2024) highlight their great ecological advantages. These new ideas encourage the inclusion of microbial pesticides into holistic, sustainable pest management plans and offer a strong scientific basis for their increased application.

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