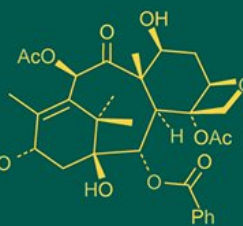
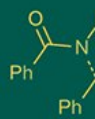


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Microbial biopesticides for sustainable crop protection: From biological potential to commercial reality

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Abstract

The excessive reliance on synthetic chemical pesticides over the past century has significantly enhanced crop productivity but has also triggered widespread ecological degradation, biodiversity loss, and human health concerns. In response, microbial biopesticides have emerged as a sustainable and eco-friendly alternative, offering specificity, environmental safety, and compatibility with Integrated Pest Management (IPM) systems. This review presents a comprehensive analysis of microbial biopesticides, including bacteria, fungi, viruses, and nematodes, and their entomopathogenic mechanisms. It discusses their formulation technologies, commercial product landscape, and application efficacy against key agricultural pests. Despite their promise, the adoption of microbial biopesticides in India remains limited due to quality control issues, short shelf life, production constraints, and a cumbersome regulatory framework. Highlighting India's case, the manuscript identifies systemic gaps in production, distribution, and farmer education, while underlining the challenges of unregistered or low-quality products in rural markets. The review concludes by outlining future opportunities for innovation, such as endophytic applications, post-harvest pest control, and regulatory reforms, to enhance the commercialisation and efficacy of microbial biopesticides. A collaborative approach involving research institutions, policymakers, industry, and farmers is essential to realise the full potential of microbial biopesticides in securing agricultural sustainability in the post-chemical era.

Keywords: Entomopathogenic, Formulation technologies, Endophytic fungi, Nucleopolyhedrovirus (NPV), Biopesticide regulation

1. Introduction

For decades, synthetic pesticides have been a cornerstone in modern agriculture for pest management and improved crop productivity (Anani *et al.*, 2020; Harun-Ur-Rashid and Imran, 2025) [35, 6]. These chemical pesticides are formulated using active ingredients and carriers like polymers to target specific pests (Rakhimol *et al.*, 2020) [62]. Their classification is often based on the pest type they control, ranging from herbicides (for weeds), fungicides (for fungi), insecticides, nematocides, and more (Anakwue, 2019; Garud *et al.*, 2024) [28, 5]. Alternatively, they can be grouped by their active compounds, such as organochlorines, diazinon, dichlorvos, diamides, and chlorpyrifos (Chau and Smith, 2018) [17].

While synthetic pesticides have contributed significantly to increased agricultural yields, their long-term impact on ecosystems is concerning (Khan *et al.*, 2023) [43]. They disrupt soil biodiversity, affect beneficial fauna like earthworms, and impair soil functions by reducing respiration and microbial activity (Pertile, 2020; Pelosi *et al.*, 2021) [58, 59]. Exposure to these chemicals has also been linked to reduced fertility, weakened immunity, and developmental issues in animals (Syromyatnikov *et al.*, 2020) [79]. Moreover, soil microorganisms responsible for crucial plant-growth activities, such as nitrogen fixation, siderophore production, and phytohormone synthesis, are negatively impacted (Kumar & Kumar, 2019) [47].

The environmental fate of these pesticides further exacerbates their risks. Pesticide drift, leaching, erosion, and improper disposal introduce these chemicals into unintended habitats

(Dubey *et al.*, 2024; Rashad *et al.*, 2025) [63, 22]. This not only harms non-target vegetation, diminishing their photosynthetic efficiency and reproductive success, but also contaminates aquatic ecosystems (Akhter *et al.*, 2024) [3]. The bioaccumulation and biomagnification of pesticide residues through food chains can lead to severe health conditions in animals and humans, including cancers, kidney dysfunction, and metabolic disorders (Jayaraj *et al.*, 2016; Sabarwal *et al.*, 2018; Manfo *et al.*, 2020) [37, 51, 70].

In response to these challenges, *biopesticides* have gained prominence as eco-friendly alternatives. Derived from natural sources, *biopesticides* are generally cost-effective, biodegradable, highly specific in action, and less harmful to the environment (Borges *et al.*, 2021; Soyel *et al.*, 2023; Fenibo *et al.*, 2025) [24, 76, 12]. The United States Environmental Protection Agency (EPA) defines *biopesticides* as a diverse group of pest control agents, which include naturally occurring substances (biochemical pesticides), beneficial microorganisms and their metabolic by-products (microbial pesticides), and genetically modified plant-based substances known as plant-incorporated protectants that are capable of managing pest populations (US EPA) [80]. Among these, microbial *biopesticides* are particularly important in augmentative biological control programs, where they are applied preventively to inhibit the establishment and spread of pests (Vero *et al.*, 2023; Rezaee Danesh *et al.*, 2025) [64, 83]. These microbial antagonists are typically produced on a large scale using industrial fermentation techniques and require multiple applications during a cropping season, as their populations generally persist in the environment for a limited duration often only partially or throughout a single growing season (Glare and O'Callaghan, 2019) [29].

These *biopesticides* act by disrupting pest cell membranes or inhibiting essential metabolic pathways. However, despite their advantages, several limitations hinder their widespread adoption. Their narrow host range, short shelf life, and limited

persistence in the environment can reduce their effectiveness in large-scale pest outbreaks (Kumar *et al.*, 2021) [46]. Interestingly, traits that make them environmentally favorable, such as specificity and rapid degradation, can become drawbacks when broader pest control or long-term suppression is desired.

Therefore, a nuanced assessment of both the strengths and limitations of *biopesticides* is crucial. There is an urgent need to enhance their formulation, improve their field efficacy, and integrate them effectively within holistic pest management strategies. This review underscores the comparative analysis of synthetic and microbial *biopesticides*, highlighting opportunities to refine microbial biopesticide technologies for sustainable integration into Integrated Pest Management (IPM) systems, aimed at reducing crop losses while preserving environmental health.

2. Entomopathogenic microorganisms

Microbial pesticides are substances derived from a variety of microorganisms such as bacteria, fungi, viruses, protozoa, and algae, and are utilized in pest management (Adeleke *et al.*, 2022a) [1]. These microorganisms produce toxic metabolites that effectively target and inhibit pest growth. The application of microbial pesticides in the environment is achieved using several techniques, including emulsion, electro-spraying systems, fluidized bed, spray drying, extrusion, lyophilization, spray cooling, and co-circulation methods (De Oliveira *et al.*, 2021) [21]. The primary groups of microorganisms used as *biopesticides* include bacterial genera like *Chromobacterium*, *Pseudomonas*, and *Yersinia*, fungal genera such as *Beauveria*, *Paecilomyces*, *Verticillium*, *Hirsutella*, *Metarhizium*, and *Lecanicillium*, as well as nematodes from the genera *Steinernema* and *Heterorhabditis* (Chang *et al.*, 2003; Kumar *et al.*, 2021; Adeleke *et al.*, 2022b) [2, 15, 46]. Details of major microbial *biopesticides*, their formulations, and target pests are presented in Table 1.

Table 1: Formulations and Target Pest Range of Important Microbial Biopesticides

Microorganism and Strain(s)	Formulation Type	Product Name(s)	Target Arthropod Pest(s)
<i>Beauveria bassiana</i> (various strains)	AS, SC, WP	ABTEC Beauveria, Avishi BB, Bassi-Care, BB Power, etc.	Aphids, beetles, thrips, white grubs, whiteflies, Lepidopteran pests
<i>B. brongniartii</i>	WP	Biogrubex	White grubs
<i>Metarhizium anisopliae</i> (various strains)	AS, SC, WP	Biomet, Thunder, Kalichakra, etc.	Aphids, beetles, plant hoppers, termites, cutworms, etc.
<i>Lecanicillium lecanii</i>	AS, WP	Bio-Catch, Vertisoft, Bioline, etc.	Aphids, mites, thrips, whiteflies, scale insects
<i>Hirsutella thompsonii</i>	AS, WP	Almite, Checkmite	Mites (especially eriophyid mites)
<i>Isaria fumosorosea</i>	AS, WP	Paecilomite, Mycomite, Priority	Aphids, thrips, jassids, whiteflies, mites
<i>Purpureocillium lilacinum</i>	WP	Bio-Nematon, Ecogreen, Bionemat	Plant pathogenic nematodes
<i>Pochonia chlamydosporia</i>	WP	Nematofree+, Pochonia	Root-knot nematodes
<i>Bacillus thuringiensis</i> var. <i>kurstaki</i>	AS, WP	Dipel, Biobit, Cezar, Caterpilin, etc.	Lepidopteran pests
<i>B. thuringiensis</i> subsp. <i>israelensis</i>	AS, WP, DG	Bacticide, Bacto Power-Bti	Mosquitoes, black flies, fungus gnats
<i>Lysinibacillus sphaericus</i>	WP	Sphericide	Mosquito larvae
<i>B. thuringiensis</i> subsp. <i>galleriae</i>	FC	Spicturin	DBM, Bollworms, Lepidopterans
<i>Bacillus firmus</i>	WP	BioNemaGon	Plant parasitic nematodes
NPV of <i>Helicoverpa armigera</i>	AS	HelioKill®, BioVirus-H	<i>Helicoverpa</i> species
NPV of <i>Spodoptera litura</i>	AS	Spodo-Cide, BioVirus-S	<i>Spodoptera litura</i> and <i>S. exigua</i>

(Ramanujam *et al.*, 2014) [18]

2.1 Bacteria

Bacterial species belonging to the family *Bacillaceae* have long been studied for their pathogenic interactions with invertebrates, particularly insects (Castagnola and Stock, 2014; Ruii, 2015) [67, 14]. Among these, *Bacillus thuringiensis* (Bt) is the most extensively researched and widely utilized entomopathogenic bacterium in commercial biopesticide

formulations. Its insecticidal effect stems primarily from the production of crystal proteins *Cry* and *Cyt* toxins during sporulation, which are associated with parasporal bodies. Additionally, other virulence factors and vegetative insecticidal proteins (*VIPs*) are produced during the active growth phase (Jurat-Fuentes *et al.*, 2012; Bari, 2026) [10, 38].

The effectiveness of Bt strains is closely linked to variations in the genetic sequences of these toxin genes, which determine

their specificity *and* affinity for insect midgut receptors. As a result, individual Bt strains tend to exhibit narrow host ranges due to their production of distinct insecticidal proteins (Pigott *and* Ellar, 2007) ^[60]. This specificity has driven ongoing research *and* commercial interest in identifying novel Bt strains *and* new insecticidal toxins. Once ingested, these toxins bind selectively to receptors in the insect midgut, initiating pore formation in epithelial membranes. This leads to compromised gut integrity, ultimately causing systemic infection (septicaemia) *and* insect death (Bravo *et al.*, 2007) ^[13]. A comparable mode of action is seen in *Lysinibacillus sphaericus* (previously known as *Bacillus sphaericus*), which targets mosquitoes *and* blackflies. It produces a combination of binary (*BinA and BinB*) *and* mosquitoicidal (*Mtx*) crystal proteins to achieve its lethal effect (Charles *et al.*, 2000) ^[16]. Toxins structurally similar to Bt Cry proteins have also been discovered in species of the genus *Paenibacillus*, adding to the diversity of entomopathogenic bacteria. Another notable member of *Bacillaceae* is *Brevibacillus laterosporus*, distinguished by its canoe-shaped parasporal body attached to a swollen sporangium. This bacterium has a broader spectrum of pesticidal activity, harboring a variety of virulence factors (Ruiu, 2013; Marche *et al.*, 2017; Marche *et al.*, 2018) ^[52, 53, 66]. Its potential role in integrated pest management strategies across diverse agroecosystems is gaining increasing attention (Ruiu *et al.*, 2011; Ruiu *et al.*, 2014) ^[69, 68].

Commercially, a wide array of bacterial-based biopesticide products are available globally, formulated using various species *and* strains. Notably, members of the class *Gammaproteobacteria* represent a diverse group that includes several entomopathogenic species. These comprise endosymbiotic bacteria such as *Photobacterium*, *Xenorhabdus*, *and Serratia*, commonly associated with entomopathogenic nematodes *and* known for their toxin-mediated insecticidal activity (Ffrench-Constant *&* Waterfield, 2006; Hurst *et al.*, 2000) ^[36, 26]. Additionally, non-spore-forming species such as *Yersinia entomophaga* *and Pseudomonas entomophila* have shown promise. *Y. entomophaga* produces a toxin complex (*Yen-Tc*) that includes both toxins *and* chitinases (Landsberg *et al.*, 2011) ^[49], while *P. entomophila* employs a toxin secretion system to exert its effects following ingestion (Vodovar *et al.*, 2006) ^[85]. The class *Betaproteobacteria* includes several promising candidates for biocontrol applications, owing to their insecticidal properties. A notable example is a recently identified strain of *Burkholderia rinjensis*, which has been developed into a commercial biopesticide (Hamrouni *et al.* 2025) ^[33]. This product is effective against a wide range of chewing *and* sucking insect pests as well as mites, functioning through both contact *and* ingestion routes (Cordova-Kreylos *et al.*, 2013) ^[20]. Its insecticidal activity is attributed to a suite of bioactive metabolites, *and* the formulation consists of heat-inactivated bacterial cells along with the residual fermentation medium. Another successful member of this class is a strain of *Chromobacterium subtsugae*, which produces a diverse array of metabolites exhibiting broad-spectrum insecticidal properties. This bacterium has demonstrated efficacy against multiple insect orders, including Lepidoptera, Hemiptera, Coleoptera, *and* Diptera, making it valuable for integrated pest management strategies (Martin *et al.*, 2007) ^[54]. In addition, the phylum *Actinobacteria* contributes several entomopathogenic species, particularly within the *Streptomyces* genus. These bacteria are known to produce a range of insecticidal compounds, such as macrocyclic lactones that target the peripheral nervous system of insects (Copping *&* Menn, 2000) ^[19]. Another prominent actinobacterial species, *Saccharopolyspora spinosa*, synthesizes highly effective

insecticidal compounds known as spinosyns. Both natural *and* semi-synthetic derivatives of these toxins have achieved considerable commercial success due to their broad-spectrum activity *and* favourable environmental profile (Kirst, 2010) ^[45].

2.2 Baculoviruses

Baculoviruses, members of the *Baculoviridae* family, are double-stranded DNA viruses known for their pathogenic interactions with invertebrates, particularly insects, *and* have garnered significant attention for their role in biological pest control (Clem *&* Passarelli, 2013; Haase *et al.*, 2015) ^[32, 18]. Their infectious nature is linked to the formation of occlusion bodies (OBs) proteinaceous structures within infected host cells that encapsulate the virus particles. Based on the shape *and* cellular location of these OBs, baculoviruses are categorized into two primary types: nucleopolyhedroviruses (NPVs), which form polyhedral OBs in the host cell nucleus, *and* granuloviruses (GVs), which produce granular OBs. In contrast, another group of insect-infecting viruses, the Cypoviruses (CPVs) from the *Reoviridae* family, generate polyhedral OBs in the cytoplasm *and* possess a double-stranded RNA genome (Rohrmann, 2011) ^[65].

Baculoviruses are typically ingested by insect larvae feeding on contaminated foliage. Once inside the insect midgut, the occlusion bodies dissolve in the alkaline environment, releasing occlusion-derived viruses (ODVs). These ODVs interact with the epithelial cells of the midgut via specific viral envelope proteins known as per os infectivity factors (PIFs). Upon successful infection of these cells, the virus undergoes a replication phase within the nucleus, producing budded viruses (BVs) that disseminate systemically throughout the insect host (Williams *et al.*, 2017) ^[86]. Eventually, the host succumbs to the infection, *and* its body liquefies, facilitating the release *and* environmental spread of new viral particles. Intriguingly, baculoviral infections can also modulate insect behavior *and* gene expression, further enhancing transmission *and* infection efficacy (Katsuma *et al.*, 2012) ^[39].

Due to their high specificity, baculoviruses are named by combining abbreviations of the host insect *and* virus, such as *LdMNPV* for *Lymantria dispar* multicapsid nucleopolyhedrovirus. Owing to their mode of action, these viruses are effective primarily against chewing insect pests, particularly lepidopteran larvae. However, practical use is somewhat constrained by environmental instability of baculovirus formulations *and* the high cost of mass production, which often requires propagation in live insect hosts. Consequently, their application is generally restricted to targeted, high-value or organic cropping systems (Sun, 2015; Harrison *&* Hoover, 2012) ^[34, 78].

2.3 Fungi

Entomopathogenic fungi encompass a wide array of genera *and* species that infect invertebrates with varying levels of host specificity. The infection process is typically initiated when fungal conidia or spores come into contact with the insect's cuticle. Upon attachment, germination is triggered under favourable environmental conditions, particularly optimal temperature *and* relative humidity. Penetration into the host is achieved through a synergistic action of mechanical pressure *and* the secretion of cuticle-degrading enzymes. Once inside, the fungal hyphae proliferate throughout the insect's body, colonising internal tissues *and* leading to the insect's death through a combination of physical damage *and* toxic metabolites released during vegetative growth (Vega *et al.*, 2012) ^[81].

During infection, many fungi also synthesise bioactive secondary metabolites that function either as virulence factors

or toxins, enhancing pathogenicity. Ultimately, the fungus breaches the host body and produces new conidia or spores externally, thereby facilitating dissemination in the environment. Among the various fungal phyla that include entomopathogens are Chytridiomycota, Zygomycota, Oomycota, Ascomycota, and Deuteromycota (Vega *et al.*, 2012) [81]. One of the most historically significant and widely utilized fungal biopesticides is *Beauveria bassiana*, which was first applied for insect microbial control as early as the late 1800s. Today, different *Beauveria* strains, including *B. bassiana* and *B. brongniartii*, are commercially formulated for targeting a range of insect pests (Zimmermann, 2007a) [87]. Recent findings also highlight their endophytic potential, wherein certain strains can colonize plant tissues and offer internal pest protection, adding a promising dimension to their use in integrated pest management (IPM) systems (McKinnon *et al.*, 2017) [55].

Another extensively studied and applied entomopathogenic fungus is *Metarhizium anisopliae*, known for its broad host range and the production of a suite of insecticidal toxins and virulence-associated enzymes (Zimmermann, 2007b; Schrank & Vainstein, 2010) [74, 87]. Other fungi used in commercial biopesticide formulations include *Verticillium lecanii* (Sugimoto *et al.*, 2003) [77], *Lecanicillium spp.* (Kim *et al.*, 2008) [44], *Hirsutella spp.* (Kaya & Koppenhöfer, 1996) [41]. Another extensively studied and applied entomopathogenic fungus is *Metarhizium anisopliae*, known for its broad host range and the production of a suite of insecticidal toxins and virulence-associated enzymes (Zimmermann, 2007b; Schrank & Vainstein, 2010) [74, 87]. Other fungi used in commercial biopesticide formulations include *Verticillium lecanii* (Sugimoto *et al.*, 2003) [77], *Lecanicillium spp.* (Kim *et al.*, 2008) [44], *Hirsutella spp.* (Kaya & Koppenhöfer, 1996) [41], *Paecilomyces*, and *Isaria spp.* (Zimmermann, 2008) [88]. These species often exert their effects through the production of insecticidal metabolites and have proven valuable in managing a wide range of agricultural pests.

In natural ecosystems, numerous other entomopathogenic fungi contribute to insect population regulation by naturally disseminating their spores and infecting susceptible hosts (Sawyer *et al.*, 1994) [73]. However, a major limitation of fungal-based biopesticides is their mode of action by direct contact, along with the necessity for specific environmental conditions for successful spore germination and infection (Vega *et al.*, 2012) [81]. To overcome these challenges, future

product development may focus on endophytic fungal strains capable of colonizing plant tissues and targeting pests internally (Vidal & Jaber, 2015) [84]. Furthermore, when deploying these fungi in the field, it is crucial to ensure the absence of residual fungicides used against plant pathogens, as they can negatively impact the viability and infectivity of entomopathogenic fungi.

2.4 Nematodes

Entomopathogenic nematodes (EPNs), primarily from the genera *Heterorhabditis* and *Steinernema*, function as obligate parasites of insects and have demonstrated substantial potential in biological control programs. Their efficacy is largely attributed to a symbiotic association with insect-pathogenic bacteria *Photobacterium* in the case of *Heterorhabditis*, and *Xenorhabdus* for *Steinernema* which play a pivotal role in the insect-killing process (Lewis & Clarke, 2012) [50].

These nematodes actively locate and penetrate their hosts through natural body openings such as the mouth, anus, or spiracles. Once inside the insect's hemocoel, the nematodes release their symbiotic bacteria, initiating a pathogenic cascade. The bacteria rapidly multiply, producing a range of toxins and virulence factors that compromise the host's immune system. Additionally, they release metabolites that modify the internal environment, making it conducive for nematode growth and reproduction (Poinar, 1990) [61]. A key feature of *Photobacterium* and *Xenorhabdus* species is their ability to produce a toxin complex (Tc), which comprises multiple subunits that exhibit potent insecticidal effects, even when ingested by the host (Ffrench-Constant *et al.*, 2007) [25]. The effectiveness of nematode-based control strategies is also influenced by the method of production. Over the years, both *in vivo* and *in vitro* techniques have been optimised to facilitate small- and large-scale nematode cultivation, ensuring consistency in yield and quality (Shapiro-Ilan *et al.*, 2012) [75]. The formulation quality of EPN-based products is critical, as it directly affects their field performance, shelf life, and infectivity. Numerous commercial biopesticide products formulated with different EPN species are available globally, each tailored to manage specific pest insects within targeted agricultural or ecological contexts. The major modes of action of microbial biopesticides against insect pests are illustrated in Figure 1.

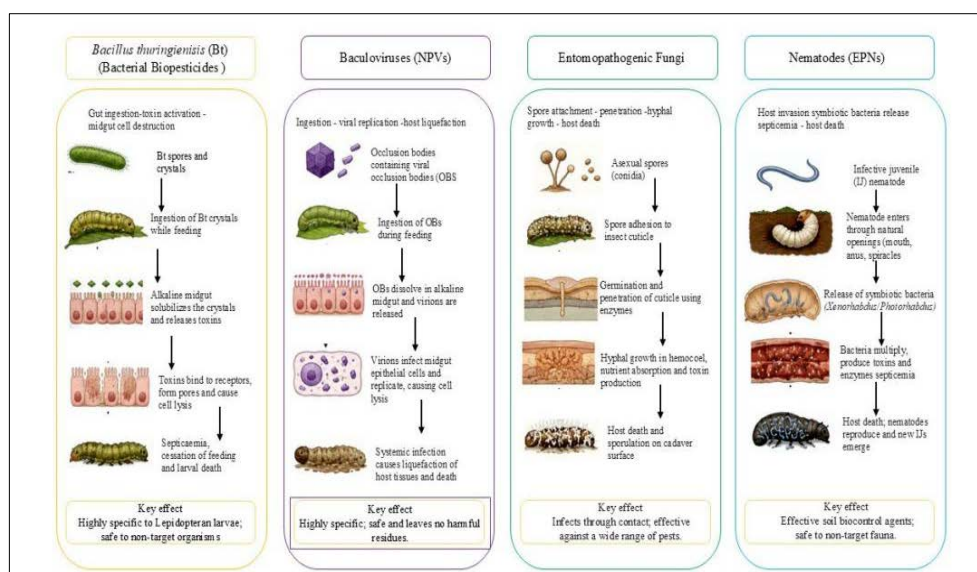


Fig 1: Modes of Action of Major Microbial Biopesticides Against Insect Pest

The figure illustrates the infection and pathogenic mechanisms of major microbial biopesticides, including *Bacillus thuringiensis*, baculoviruses, entomopathogenic fungi, and entomopathogenic nematodes. These agents suppress insect pests through diverse mechanisms such as toxin-mediated gut disruption, viral replication, cuticle penetration, and symbiotic bacterial release, ultimately leading to host mortality and pest population reduction.

3. Benefits of Microbial Biopesticides and Market Scenario

Microbial *biopesticides* derived from invertebrate-pathogenic microorganisms are widely acknowledged for their environmental safety *and* minimal impact on non-target organisms when compared to synthetic chemical pesticides. This is largely due to their highly specific mode of action, which typically restricts their activity to a particular pest species or a narrow range of targets (Kaya & Vega, 2012) ^[42, 81]. Furthermore, microbial *biopesticides* act through multiple biological pathways, making it harder for pests to develop resistance. This characteristic enhances their value in resistance management strategies, where they are often used in combination with or in rotation with conventional chemical pesticides (Musser *et al.*, 2006) ^[57].

While microbial products are commonly integrated into organic farming systems, where they can function effectively as standalone solutions, they are also favored for their short pre-harvest intervals *and* minimal residue concerns, which help in meeting food safety *and* export standards. The field performance of microbial *biopesticides* is strongly influenced by their formulation quality *and* application method. In recent years, the biopesticide industry has developed advanced formulation technologies aimed at improving critical aspects such as product adherence, dispersion, *and* spray drift behaviour, all of which contribute to greater efficacy on target pests (Satinder *et al.*, 2006) ^[72]. Driven by increased awareness about environmental sustainability *and* the adverse effects of conventional chemicals, the global biopesticide market has witnessed substantial growth (Lacey *et al.*, 2001; Glare *et al.*, 2012) ^[30, 48]. According to market analyses, the global value of this sector was projected to approach USD 7.7 billion by 2021,

with a strong compound annual growth rate (CAGR) of 14.1% over five years (BCC Research, *n.d.*) ^[11]. This upward trend reflects a broader global shift toward more sustainable agricultural practices, supported by regulatory frameworks that promote the development *and* use of eco-friendly pest control products. However, regulatory approval processes, though essential for ensuring human *and* environmental safety, continue to be a key bottleneck, potentially delaying the availability of innovative microbial solutions.

4. Constraints in the Growth of Microbial Biopesticides in India

Despite their ecological *and* safety advantages, microbial *biopesticides* have achieved limited commercial adoption in India due to several technical, infrastructural, *and* regulatory constraints. Poor product quality, including low microbial viability *and* inconsistent field performance, remains a major concern, compounded by inadequate large-scale production facilities *and* the circulation of counterfeit or unregistered products (Alam, 2000; Arora *et al.*, 2011; Gupta & Dikshit, 2010; Mishra *et al.*, 2014) ^[31, 4, 9, 56]. Studies by NBAIR reported that 50-70% of marketed formulations failed to meet CIBRC quality standards because of low propagule counts, excessive moisture, or microbial contamination (Ramanujam *et al.*, 2014) ^[8]. In addition, many products lack proper labeling *and* registration details, particularly in states such as Andhra Pradesh, Maharashtra, Karnataka, Tamil Nadu, Madhya Pradesh, *and* Gujarat (FICCI, 2015) ^[27]. Limited shelf life further restricts adoption, especially in rural areas lacking refrigeration facilities (Sadiq *et al.*, 2025) ^[71]. Liquid formulations are particularly prone to rapid degradation, while field efficacy is often reduced by slow action, UV sensitivity, *and* poor persistence under adverse environmental conditions (Mishra *et al.*, 2014; Aneja *et al.*, 2016) ^[7, 56]. Regulatory bottlenecks also remain significant, as lengthy *and* costly registration procedures can delay commercialization by more than five years (Venkatesan & Pattar, 2017) ^[82]. The major constraints affecting the commercialization *and* adoption of microbial *biopesticides* in India are summarized in Table 2

Table 2: Key Challenges Associated with the Production and Use of Microbial Biopesticides

Constraint	Description	Reference(s)
Poor Product Quality	Many products have low microbial count, excessive moisture, contaminants, and don't meet CIBRC standards.	Alam (2000) ^[4] ; Arora <i>et al.</i> (2011) ^[9] ; Mishra <i>et al.</i> (2015) ^[56]
Lack of Quality Control	50-70% of products failed to meet basic microbial quality standards in NBAIR tests.	Ramanujam <i>et al.</i> (2014) ^[8]
Unregistered or Fake Products	Many products lack registration numbers, proper labelling, or identifiable manufacturers. Problem especially prevalent in Andhra Pradesh, Maharashtra, Karnataka, Tamil Nadu, MP, and Gujarat.	FICCI (2015) ^[27]
Limited Shelf Life	Especially problematic in rural areas without access to refrigeration. Liquid formulations degrade faster than dry ones.	Mishra <i>et al.</i> (2014) ^[56] ; Ramanujam <i>et al.</i> (2014) ^[8]
Environmental Sensitivity	High UV radiation, poor water solubility, and lack of field persistence reduce efficacy.	Aneja <i>et al.</i> (2016) ^[7]
Slow Action	Biopesticides typically act slower than chemical pesticides, reducing farmer preference.	Aneja <i>et al.</i> (2016) ^[7]
Production Constraints	Limited large-scale production facilities restrict supply and accessibility.	Arora <i>et al.</i> (2011) ^[9] ; Gupta & Dikshit (2010) ^[31]
Stringent and Lengthy Registration	Delays between patenting and product registration can exceed 5 years, slowing commercialization.	Venkatesan & Pattar (2017) ^[82]

5. Future Prospects of Microbial Biopesticides in India

Despite existing constraints, the future of microbial *biopesticides* in India remains highly promising. Although the sector is still emerging, increasing efforts are focused on identifying efficient indigenous microbial strains *and* improving formulation technologies to enhance stability, shelf life, *and* cost-effectiveness. A largely underexplored opportunity lies in postharvest systems, particularly grain storage *and* silos, where microbial *biopesticides* could address pest infestations *and* pesticide residue concerns while expanding market potential. Wider adoption, however, depends on strengthening farmer awareness *and* technical capacity, especially in rural regions with limited access to formal agricultural education. Collaborative efforts among academic institutions, government agencies, *and* private stakeholders are therefore essential to improve knowledge regarding the safe *and* effective use of *biopesticides*. Initiatives such as Farmer Field Schools *and* the Diploma in Agricultural Extension Services for Input Dealers (DAESI) have already contributed to awareness generation *and* grassroots dissemination of Integrated Pest Management (IPM) practices. Demonstration-based success among progressive farmers *and* local opinion leaders may further accelerate acceptance of microbial technologies. Regulatory reforms are equally critical for sectoral growth. Current registration procedures remain complex *and* are often constrained by outdated toxicological requirements *and* cumbersome dossier protocols. Streamlining registration frameworks, strengthening quality control, *and* introducing microbial-specific intellectual property provisions would improve product accessibility *and* industry confidence. Harmonization of Indian regulations with internationally recognized FAO *and* WHO guidelines could further facilitate innovation, commercialization, *and* global competitiveness of microbial *biopesticides*.

6. Conclusion

Microbial *biopesticides* offer significant potential for sustainable agriculture by providing eco-friendly, target-specific alternatives to synthetic pesticides. Derived from bacteria, fungi, viruses, *and* nematodes, they are compatible with organic farming *and* Integrated Pest Management (IPM) programs while minimizing environmental *and* health risks. However, their large-scale adoption in India is constrained by inconsistent product quality, limited production infrastructure, short shelf life, variable field performance, *and* outdated regulatory frameworks. Advancing this sector requires the identification of locally adapted microbial strains, improved formulation technologies, stronger public-private partnerships, *and* enhanced farmer awareness through extension *and* demonstration programs. Streamlined regulatory systems aligned with international standards will further support innovation *and* commercialization. With coordinated efforts from researchers, policymakers, industry, *and* farming communities, microbial *biopesticides* can become integral to resilient *and* sustainable pest management strategies.

References

1. Adeleke BS, Ayilara MS, Akinola SA, Babalola OO. Biocontrol mechanisms of endophytic fungi. *Egyptian Journal of Biological Pest Control*. 2022;32:46.
2. Adeleke BS, Ayangbenro AS, Babalola OO. *In vitro* screening of sunflower associated endophytic bacteria with plant growth-promoting traits. *Frontiers in Sustainable Food Systems*. 2022;6:903114.
3. Akhter S, Naik VK, Naladi BJ, Rathore A, Yadav P, Lal D. The ecological impact of pesticides on non-target organisms in agricultural ecosystems. *Advances in Bioresearch*. 2024;15:322-334.
4. Alam G, Alam G. A study of biopesticides and biofertilisers in Haryana, India. London: International Institute for Environment and Development; 2000. p. 1-27.
5. Anakwue R. Cardiotoxicity of pesticides: are Africans at risk? *Cardiovascular Toxicology*. 2019;19(2):95-104.
6. Anani OA, Mishra RR, Mishra P, Enuneku AA, Anani GA, Adetunji CO. Effects of toxicant from pesticides on food security: current developments. In: *Innovations in food technology: current perspectives and future goals*. 2020. p. 313-321.
7. Aneja KR, Khan SA, Aneja A. Biopesticides an eco-friendly pest management approach in agriculture: status and prospects. *Kavaka*. 2016;47:145-154.
8. Ramanujam B, Rangeshwaran R, Sivakumar G, Mohan M, Yandigeri MS. Management of insect pests by microorganisms. *Proceedings of the Indian National Science Academy*. 2014;80(2):455-471.
9. Arora NK, Khare E, Maheshwari DK. Plant growth promoting rhizobacteria: constraints in bioformulation, commercialization, and future strategies. In: *Plant growth and health promoting bacteria*. 2011. p. 97-116.
10. Bari MA. Insecticidal activity of indigenous *Bacillus thuringiensis* strains against Tephritids fruit fly pests affecting fruits and vegetables [dissertation]. Dhaka: University of Dhaka; 2026.
11. BCC Research. Global Markets for Biopesticides (CHM029F). <https://www.bccresearch.com/pressroom/chm/market-forecasts:-modest-growth-for-synthetic-pesticides-big-growth-for-biopesticides>
12. Borges S, Alkassab AT, Collison E, Hinarejos S, Jones B, McVey E, *et al*. Overview of the testing and assessment of effects of microbial pesticides on bees: strengths, challenges and perspectives. *Apidologie*. 2021;52:1-22.
13. Bravo A, Gill SS, Soberon M. Mode of action of *Bacillus thuringiensis* Cry and Cyt toxins and their potential for insect control. *Toxicon*. 2007;49(4):423-435.
14. Castagnola A, Stock SP. Common virulence factors and tissue targets of entomopathogenic bacteria for biological control of Lepidopteran pests. *Insects*. 2014;5(1):139-166.
15. Chang JH, Choi JY, Jin BR, Roh JY, Olszewski JA, Seo SJ, *et al*. An improved baculovirus insecticide producing occlusion bodies that contain *Bacillus thuringiensis* insect toxin. *Journal of Invertebrate Pathology*. 2003;84(1):30-37.
16. Charles JF, Silva-Filha MH, Nielsen-LeRoux C. Mode of action of *Bacillus sphaericus* on mosquito larvae: incidence on resistance. In: Charles JF, Delecluse A, Nielsen-LeRoux C, editors. *Entomopathogenic bacteria: from laboratory to field application*. Dordrecht: Kluwer Academic Publishers; 2000. p. 237-252.
17. Chau AS, Smith AE. Organophosphorus pesticides. In: *Analysis of pesticides in water*. Boca Raton: CRC Press; 2018. p. 61-154.

18. Clem RJ, Passarelli AL. Baculoviruses: sophisticated pathogens of insects. *PLOS Pathogens*. 2013;9(11):e1003729.
19. Copping LG, Menn JJ. Biopesticides: a review of their action, applications and efficacy. *Pest Management Science*. 2000;56(8):651-676.
20. Cordova-Kreylos AL, Fernandez LE, Koivunen M, Yang A, Flor-Weiler L, Marrone PG. Isolation and characterization of *Burkholderia rinojensis* sp. nov., a non-*Burkholderia cepacia* complex soil bacterium with insecticidal and miticidal activities. *Applied and Environmental Microbiology*. 2013;79(23):7669-7678.
21. De Oliveira JL, Fraceto LF, Bravo A, Polanczyk RA. Encapsulation strategies for *Bacillus thuringiensis*: from now to the future. *Journal of Agricultural and Food Chemistry*. 2021;69(16):4564-4577.
22. Dubey DK, Agarwal S, Yadav MP, Goswami A, Ravat A. The study of the effects of improper hazardous waste disposal on ecosystems. *Indian Journal of Science and Research*. 2024;4(2):130-136.
23. FAO, WHO. FAO and WHO International Code of Conduct on Pesticide Management: guidelines for the registration of microbial, botanical and semiochemical pest control agents for plant protection and public health uses. Rome: FAO; 2017.
24. Fenibo EO, Matambo T. Biopesticides for sustainable agriculture: feasible options for adopting cost-effective strategies. *Frontiers in Sustainable Food Systems*. 2025;9:1657000.
25. Ffrench-Constant RH, Dowling A, Waterfield NR. Insecticidal toxins from *Photorhabdus* bacteria and their potential use in agriculture. *Toxicon*. 2007;49(4):436-451.
26. Ffrench-Constant R, Waterfield N. An ABC guide to the bacterial toxin complexes. *Advances in Applied Microbiology*. 2006;58:169-183.
27. Federation of Indian Chambers of Commerce and Industry. Indian agrochemical industry: imperatives of growth. New Delhi: FICCI; 2015.
28. Garud A, Pawar S, Patil MS, Kale SR, Patil S. A scientific review of pesticides: classification, toxicity, health effects, sustainability, and environmental impact. *Cureus*. 2024;16(8):e00000.
29. Glare TR, O'Callaghan M. Microbial biopesticides for control of invertebrates: progress from New Zealand. *Journal of Invertebrate Pathology*. 2019;165:82-88.
30. Glare T, Caradus J, Gelernter W, Jackson T, Keyhani N, Kohl J, *et al.* Have biopesticides come of age? *Trends in Biotechnology*. 2012;30(5):250-258.
31. Gupta S, Dikshit AK. Biopesticides: an ecofriendly approach for pest control. *Journal of Biopesticides*. 2010;3(Special Issue):186.
32. Haase S, Sciocco-Cap A, Romanowski V. Baculovirus insecticides in Latin America: historical overview, current status and future perspectives. *Viruses*. 2015;7(5):2230-2267.
33. Hamrouni R, Regus F, Farnet Da Silva AM, Orsiere T, Boudenne JL, Laffont-Schwob I, *et al.* Current status and future trends of microbial and nematode-based biopesticides for biocontrol of crop pathogens. *Critical Reviews in Biotechnology*. 2025;45(2):333-352.
34. Harrison R, Hoover K. Baculoviruses and other occluded insect viruses. In: Vega F, Kaya H, editors. *Insect pathology*. 2nd ed. Cambridge: Academic Press; 2012. p. 73-131.
35. Harun-Ur-Rashid M, Imran AB. Biomimetic and synthetic advances in natural pesticides: balancing efficiency and environmental safety. *Journal of Chemistry*. 2025;2025(1):1510186.
36. Hurst MR, Glare TR, Jackson TA, Ronson CW. Plasmid-located pathogenicity determinants of *Serratia entomophila*, the causal agent of amber disease of grass grub, show similarity to the insecticidal toxins of *Photorhabdus luminescens*. *Journal of Bacteriology*. 2000;182(18):5127-5138.
37. Jayaraj R, Megha P, Sreedev P. Organochlorine pesticides, their toxic effects on living organisms and their fate in the environment. *Interdisciplinary Toxicology*. 2016;9(3-4):90.
38. Jurat-Fuentes JL, Jackson TA. Bacterial entomopathogens. In: Vega F, Kaya H, editors. *Insect pathology*. 2nd ed. Cambridge: Academic Press; 2012. p. 265-349.
39. Katsuma S, Koyano Y, Kang W, Kokusho R, Kamita SG, Shimada T. The baculovirus uses a captured host phosphatase to induce enhanced locomotory activity in host caterpillars. *PLOS Pathogens*. 2012;8(3):e1002644.
40. Kaur K, Kaur P. Agricultural extension approaches to enhance the knowledge of farmers. *International Journal of Current Microbiology and Applied Sciences*. 2018;7(2):2367-2376.
41. Kaya HK, Koppenhöfer AM. Effects of microbial and other antagonistic organism and competition on entomopathogenic nematodes. *Biocontrol Science and Technology*. 1996;6(3):357-371.
42. Kaya HK, Vega FE. Scope and basic principles of insect pathology. In: Vega F, Kaya H, editors. *Insect pathology*. 2nd ed. Cambridge: Academic Press; 2012. p. 1-12.
43. Khan BA, Nadeem MA, Nawaz H, Amin MM, Abbasi GH, Nadeem M, *et al.* Pesticides: impacts on agriculture productivity, environment, and management strategies. In: *Emerging contaminants and plants: interactions, adaptations and remediation technologies*. Cham: Springer International Publishing; 2023. p. 109-134.
44. Kim JJ, Goettel MS, Gillespie DR. Evaluation of *Lecanicillium longisporum*, Vertalec, for simultaneous suppression of cotton aphid, *Aphis gossypii*, and cucumber powdery mildew, *Sphaerotheca fuliginea*, on potted cucumbers. *Biological Control*. 2008;45(3):404-409.
45. Kirst HA. The spinosyn family of insecticides: realizing the potential of natural products research. *Journal of Antibiotics*. 2010;63(3):101-111.
46. Kumar J, Ramlal A, Mallick D, Mishra V. An overview of some biopesticides and their importance in plant protection for commercial acceptance. *Plants*. 2021;10(6):1185.
47. Kumar V, Kumar P. Pesticides in agriculture and environment: impacts on human health. *Contaminants in Agriculture and Environment: Health Risks and Remediation*. 2019;1:76-95.
48. Lacey LA, Frutos R, Kaya HK, Vail P. Insect pathogens as biological control agents: do they have a future? *Biological Control*. 2001;21(3):230-248.

49. Landsberg MJ, Jones SA, Rothnagel R, Busby JN, Marshall SDG, Simpson RM, *et al.* 3D structure of the *Yersinia entomophaga* toxin complex and implications for insecticidal activity. *Proceedings of the National Academy of Sciences.* 2011;108(51):20544-20549.
50. Lewis EE, Clarke DJ. Nematode parasites and entomopathogens. In: Vega F, Kaya H, editors. *Insect pathology.* 2nd ed. Cambridge: Academic Press; 2012. p. 395-424.
51. Manfo FPT, Mboe SA, Nantia EA, Ngoula F, Telefo PB, Moundipa PF, *et al.* Evaluation of the effects of agro pesticides use on liver and kidney function in farmers from Buea, Cameroon. *Journal of Toxicology.* 2020;2020(1):2305764.
52. Marche MG, Camiolo S, Porceddu A, Ruiiu L. Survey of *Brevibacillus laterosporus* insecticidal protein genes and virulence factors. *Journal of Invertebrate Pathology.* 2018;155:38-43.
53. Marche MG, Mura ME, Falchi G, Ruiiu L. Spore surface proteins of *Brevibacillus laterosporus* are involved in insect pathogenesis. *Scientific Reports.* 2017;7:43805.
54. Martin PAW, Gundersen-Rindal D, Blackburn M, Buyer J. *Chromobacterium subtsugae* sp. nov., a betaproteobacterium toxic to Colorado potato beetle and other insect pests. *International Journal of Systematic and Evolutionary Microbiology.* 2007;57(5):993-999.
55. McKinnon AC, Saari S, Moran-Diez ME, Meyling NV, Raad M, Glare TR. *Beauveria bassiana* as an endophyte: a critical review on associated methodology and biocontrol potential. *BioControl.* 2017;62(1):1-17.
56. Mishra J, Tewari S, Singh S, Arora NK. Biopesticides: where we stand? In: *Plant microbes symbiosis: applied facets.* New Delhi: Springer India; 2014. p. 37-75.
57. Musser FR, Nyrop JP, Shelton AM. Integrating biological and chemical controls in decision making: European corn borer (Lepidoptera: Crambidae) control in sweet corn as an example. *Journal of Economic Entomology.* 2006;99(5):1538-1549.
58. Pelosi C, Bertrand C, Daniele G, Coeurdassier M, Benoit P, Nélieu S, *et al.* Residues of currently used pesticides in soils and earthworms: a silent threat? *Agriculture, Ecosystems & Environment.* 2021;305:107167.
59. Pertile M. Responses of soil microbial biomass and enzyme activity to herbicides imazethapyr and flumioxazin. *Scientific Reports.* 2020;10:7694.
60. Pigott CR, Ellar DJ. Role of receptors in *Bacillus thuringiensis* crystal toxin activity. *Microbiology and Molecular Biology Reviews.* 2007;71(2):255-281.
61. Poinar GO. Biology and taxonomy of Steinernematidae and Heterorhabditidae. In: Gaugler R, Kaya HK, editors. *Entomopathogenic nematodes in biological control.* Boca Raton: CRC Press; 1990. p. 23-62.
62. Rakhimol KR, Thomas S, Volova T, Jayachandran K, editors. *Controlled release of pesticides for sustainable agriculture.* Cham: Springer; 2020. 266 p.
63. Rashad S, El-Chaghaby GA, Abdul Moneem M. Pesticide runoff and its impact on water quality. In: *The interplay of pesticides and climate change: environmental dynamics and challenges.* Cham: Springer Nature Switzerland; 2025. p. 85-110.
64. Rezaee Danesh Y, Mulet JM, Porcel R. Bridging microbial biocontrol and phytochemical biopesticides: synergistic approaches for sustainable crop protection. *Plants.* 2025;14(22):3453.
65. Rohrmann GF. *Baculovirus molecular biology.* 2nd ed. Bethesda: National Library of Medicine, National Center for Biotechnology Information; 2011.
66. Ruiiu L. *Brevibacillus laterosporus*, a pathogen of invertebrates and a broad-spectrum antimicrobial species. *Insects.* 2013;4(3):476-492.
67. Ruiiu L. Insect pathogenic bacteria in integrated pest management. *Insects.* 2015;6(2):352-367.
68. Ruiiu L, Satta A, Floris I. Comparative applications of azadirachtin- and *Brevibacillus laterosporus*-based formulations for house fly management experiments in dairy farms. *Journal of Medical Entomology.* 2011;48(2):345-350.
69. Ruiiu L, Satta A, Floris I. Administration of *Brevibacillus laterosporus* spores as a poultry feed additive to inhibit house fly development in feces: a new eco-sustainable concept. *Poultry Science.* 2014;93(3):519-526.
70. Sabarwal A, Kumar K, Singh RP. Hazardous effects of chemical pesticides on human health: cancer and other associated disorders. *Environmental Toxicology and Pharmacology.* 2018;63:103-114.
71. Sadiq SM, Singh IP, Ahmad MM, Sani BS. Cold storage solutions to reduce post-harvest loss: start-ups for youth in the agricultural supply chain. *New Countryside.* 2025;4(2):37-44.
72. Satinder KB, Verma M, Tyagi RD, Valéro JR. Recent advances in downstream processing and formulations of *Bacillus thuringiensis*-based biopesticides. *Process Biochemistry.* 2006;41(2):323-342.
73. Sawyer AJ, Griggs MH, Wayne R. Dimensions, density, and settling velocity of entomophthoralean conidia: implications for aerial dissemination of spores. *Journal of Invertebrate Pathology.* 1994;63(1):43-55.
74. Schrank A, Vainstein MH. *Metarhizium anisopliae* enzymes and toxins. *Toxicon.* 2010;56(7):1267-1274.
75. Shapiro-Ilan DI, Han R, Dolinski C. Entomopathogenic nematode production and application technology. *Journal of Nematology.* 2012;44(2):206-217.
76. Soyel SA, Ruidas S, Roy P, Mondal S, Bhattacharyya S, Hazra DK. Biopesticides as eco-friendly substitutes to synthetic pesticides: an insight of present status and future prospects with improved bio-effectiveness, shelf-lives, and climate resilience. *International Journal.* 2023;2(2).
77. Sugimoto M, Koike M, Hiyama N, Nagao H. Genetic, morphological, and virulence characterization of the entomopathogenic fungus *Verticillium lecanii*. *Journal of Invertebrate Pathology.* 2003;82(3):176-187.
78. Sun X. History and current status of development and use of viral insecticides in China. *Viruses.* 2015;7(1):306-319.
79. Syromyatnikov MY, Isuwa MM, Savinkova OV, Derevshchikova MI, Popov VN. The effect of pesticides on the microbiome of animals. *Agriculture.* 2020;10(3):79.
80. United States Environmental Protection Agency. What are biopesticides? <https://www.epa.gov/ingredients-used-pesticide-products/what-are-biopesticides>

81. Vega FE, Meyling NV, Luangsa-ard JJ, Blackwell M. Fungal entomopathogens. In: Vega F, Kaya H, editors. Insect pathology. 2nd ed. Cambridge: Academic Press; 2012. p. 171-220.
82. Venkatesan T, Pattar S. Intellectual property guidelines and commercialization of biocontrol agents/biopesticides technologies. In: Training manual on identification, mass production and utilization of parasitoids, predators and entomopathogens for sustainable insect pest management. Bengaluru: ICAR-NBAIR; 2017. p. 115-126.
83. Vero S, Garmendia G, Allori E, Sanz JM, Gonda M, Alconada T, *et al.* Microbial biopesticides: diversity, scope, and mechanisms involved in plant disease control. *Diversity*. 2023;15(3):457.
84. Vidal S, Jaber LR. Entomopathogenic fungi as endophytes: plant-endophyte-herbivore interactions and prospects for use in biological control. *Current Science*. 2015;109(1):46-54.
85. Vodovar N, Vallenet D, Cruveiller S, Rouy Z, Barbe V, Acosta C, *et al.* Complete genome sequence of the entomopathogenic and metabolically versatile soil bacterium *Pseudomonas entomophila*. *Nature Biotechnology*. 2006;24(6):673-679.
86. Williams T, Virto C, Murillo R, Caballero P. Covert infection of insects by baculoviruses. *Frontiers in Microbiology*. 2017;8:1337.
87. Zimmermann G. Review on safety of the entomopathogenic fungi *Beauveria bassiana* and *Beauveria brongniartii*. *Biocontrol Science and Technology*. 2007;17(6):553-596.
88. Zimmermann G. The entomopathogenic fungi *Isaria farinosa* formerly *Paecilomyces farinosus* and the *Isaria fumosorosea* species complex formerly *Paecilomyces fumosoroseus*: biology, ecology and use in biological control. *Biocontrol Science and Technology*. 2008;18(9):865-901.