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Review Article

Biopesticides Production, Formulation and Applications: A Short Review

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ABSTRACT

Rising public concern over the environment and health risk of biochemical pesticides has accelerated the shift toward safer, more sustainable pest control methods. Biopesticides—source from microbes, plant extract, and natural biological compounds—offer an environmental alternative to synthetic compound. Their development involves selecting, cultivating, and processing biological agents to ensure both effectiveness and stability. Advanced formulation techniques improve performance, extend shelf life, and adapt application methods to various agricultural contexts, such as liquid suspensions, wettable powders, and granules. Effective use of biopesticides depends on factors like target pests, environmental conditions, and alignment with integrated pest management (IPM) approach. Despite hurdles such as short shelf life, regulatory task, and manufacturing costs, continuing progression in biotechnology and formulation are enhancing their viability. With continued investment in research, education, and helpful policies, biopesticides hold strong promise for reducing reliance on synthetic pesticides and promoting sustainable agriculture. This review examines the classification, production, and current status of biopesticides, with an attention on their role in Integrated Pest Management (IPM) and their adoption in India. The review highlights recent advancements, market trends, and regulatory frameworks shaping global and national biopesticide usage.

INTRODUCTION

Agriculture has long struggled with the destructive impact of pests such as fungi, weeds, and insects, leading to significant declines in crop yields. The introduction of chemical pesticides initially provided an effective solution to this challenge. However, excessive reliance on these chemicals and their uncontrolled use have raised environmental concerns, necessitating alternative approaches. Soil degradation and groundwater contamination have led to nutrient imbalances and reduced land productivity (Richmond 2015, Pérez-Lucas et al. 2019, Bisht and Singh Chauhan 2021). Additionally, pesticide residues sometimes compromise food safety

for consumers and create trade barriers for export crops. Therefore, adopting eco-friendly alternatives has become imperative (Avilara *et al.* 2023, Tadesse Mawcha *et al.* 2025)

Biopesticides are pest control agents derived from natural sources, offering an ecologically responsive methods to managing agricultural pests. They come from biological origins such as microbe (bacteria fungi, and viruses), herbal extracts, and naturally occurring biochemical compounds. Unlike synthetic pesticides, biopesticides are often highly specific to target pests, minimizing harm to beneficial organisms and ecosystems (Hezakiel *et al.* 2024, Karaoglan *et al.* 2024). They play a crucial role in combined

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pest management (IPM) by providing supportable and effective pest control solutions while reducing compounds residues in food and the environment. Among the most commonly used Pesticides are living organisms that exactly target pests. Biopesticides include different biological agents used for pest management, such as biofungicides, bioherbicides, and bioinsecticides. Common examples are *Trichoderma* as a biofungicide, *Phytophthora* in weed management, and *Bacillus thuringiensis* as an effective bioinsecticide. Plant-based compounds also play a crucial role in biopesticide development. Another important category is plant-incorporated protectants (PIPs), which are pesticidal substances synthesised by genetically engineered plants. These include inserted genes such as Bt toxins, protease inhibitors, lectins, and chitinase, enabling plants to produce their own defence compounds against insect pests (MacGregor, 2006; Gupta and Dikshit, 2010).

Biopesticides offer significant benefits to both agriculture and public health (Ayilara *et al.* 2023). Their increasing adoption is driven by several key advantages, including:

- **Environmentally Friendly** – Biopesticides are biodegradable and have minimal impact on soil, water, and air quality.
- **Target-Specific** – They selectively target pests while preserving useful insects, pollinators, and other non-target organisms.
- **Reduced Chemical Residues** – Since they degrade naturally, they leave little to no harmful residues in food and the environment.
- **Lower Risk of Resistance** – Unlike synthetic pesticides, biopesticides have diverse modes of action, reducing the likelihood of pest resistance.
- **Safe for Humans and Animals** – They pose lower toxicity risks to farmworkers, consumers, and wildlife compared to conventional pesticides.
- **Supports Sustainable Agriculture** – Biopesticides align with organic farming and IPM strategies, promoting long-term sustainability.
- **Enhances Soil Health** – Some biopesticides, such as microbial formulations, improve soil microbiota and contribute to soil fertility.
- **Regulatory Advantages** – Biopesticides often face fewer regulatory restrictions and faster approval processes than synthetic chemicals.
- **Effective in Low Doses** – Many biopesticides work efficiently even at lower application rates, reducing overall pesticide use.

Biopesticides are extremely compatible with other pest management practices and can be effectively combined with chemical pesticides, crop rotation, and biological control methods to improve overall pest control efficiency. Their integration into Integrated Pest Management (IPM) programs makes them an important component of sustainable agriculture by decreasing pest populations

while minimizing environmental risks. According to Kandpal (2014), biopesticides contribute significantly to long-term pest management strategies by supporting ecological balance and reducing dependency on synthetic chemicals. In recent years, the adoption of biopesticides has increased considerably as farmers and agricultural sectors increasingly prefer environmentally safe and sustainable approaches to crop protection (Kandpal, 2014) (Figure 1).

Classification of Biopesticides

Biopesticides are generally categorised into three major classes: microbial pesticides, plant-incorporated protectants (PIPs), and biochemical pesticides (Figure 2). Each category has unique feature and plays a crucial role in pest control by offering specific, environmentally friendly, and sustainable solutions for agricultural pest management.

Microbial Pesticides

Microbial pesticides are biological pest control agents obtained from microorganisms such as bacteria, fungi, viruses, and their metabolites. They are considered an effective and sustainable substitute for synthetic chemical pesticides in modern agriculture. These biopesticides work by targeting specific pests while causing legalizable harm to the environment and leaving very low toxic residues. Recent studies have shown that microbial biopesticides support the principles of climate-smart agriculture and contribute to sustainable agricultural development because of their eco-friendly nature and pest-specific action (Tadesse Mawcha *et al.*, 2025). However, their potential impact on non-target organisms remains an important concern, highlighting the need for proper evaluation and standardized testing protocols (Wend *et al.*, 2024). The increasing number of studies and

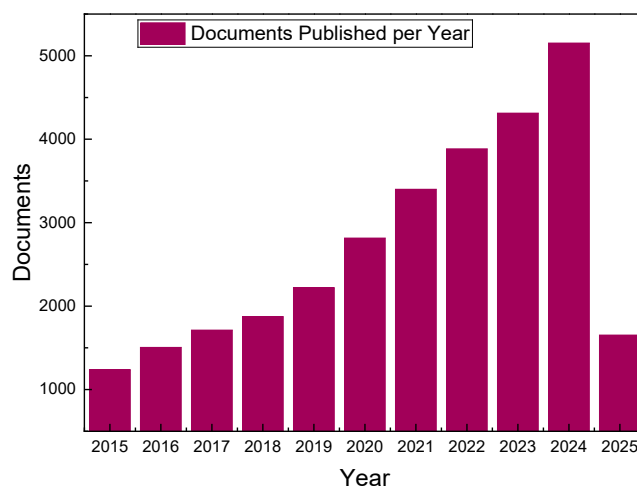


Figure 1: Number of documents published per year between 2015-14th Apr 2025 related to biopesticides. Data is generated from Scopus database with the keyword 'Biopesticides'



applications in recent years reflects the growing interest and adoption of microbial pesticides as an important tool for sustainable pest management (Sawangproh *et al.*, 2025). Innovative applications, such as the use of bioherbicides like Kichawi Kill in Kenya, demonstrate the practical benefits of microbial pesticides in controlling specific pests like witchweed, leading to substantial yield improvements for farmers (Netia and Holland 2024 Oct 30). Additionally, integrating biopesticides with microbe-pesticide interactions has been shown to enhance pest control efficacy while promoting soil health (Bhatt *et al.* 2023). As research advances, addressing challenges related to non-target effects and regulatory frameworks will be vital for the broader adoption of microbial pesticides in sustainable agriculture.

Plant-Incorporated Protectants (PIPs)

Plant-Incorporated Protectants (PIPs) are bioengineered pesticidal chemicals synthesized directly by plants through genetic modification, providing an internal defence system against insect pests and reducing dependence on conventional chemical pesticides. These protectants are developed by transferring resistance genes from naturally occurring organisms, particularly the bacterium *Bacillus thuringiensis* (Bt), into the plant genome. This genetic integration enables crops to synthesize insecticidal proteins that specifically target harmful pests while causing minimal effects on beneficial organisms and the surrounding environment (Sharma, 2023). The application of PIPs has expanded rapidly in important agricultural crops such as maize, cotton, and soybean, where they have demonstrated substantial improvements in pest management and yield enhancement (Li *et al.*, 2022). Recent developments in gene-editing technologies,

especially CRISPR-Cas9, have increased the precision of PIP development by allowing targeted modifications that improve resistance traits and minimize unintended effects (Zhang and Li, 2023). Moreover, PIPs play an important role in Integrated Pest Management (IPM) by lowering pesticide usage and supporting environmentally sustainable farming systems (Singh and Mazumdar, 2022). Despite these benefits, issues such as the development of pest resistance and possible impacts on non-target organisms remain important concerns, necessitating continuous biosafety and regulatory evaluations (Wang and Wang, 2023). Emerging approaches, including RNA interference (RNAi)-based PIPs, have shown promise in improving target specificity and delaying resistance development (Huang *et al.*, 2022). In addition, advances in synthetic biology are facilitating the creation of next-generation PIPs with greater effectiveness and ecological safety. Recent studies have also highlighted their contribution to lowering greenhouse gas emissions by reducing energy inputs associated with pesticide production and application (Kumar, 2023). Although ecological concerns persist, PIPs continue to be recognized as a valuable innovation for sustainable agriculture and improving global food security (Ronald, 2011). Future research is expected to focus on strengthening biosafety frameworks while optimizing the effectiveness of this technology (Kumar *et al.*, 2021).

Biochemical pesticides

Biochemical pesticides are naturally sourced pest control agents that provide an eco-friendly alternative to synthetic chemical pesticides. They comprise a wide range of substances such as insect pheromones, botanical extracts, and biologically active enzymes that interfere with

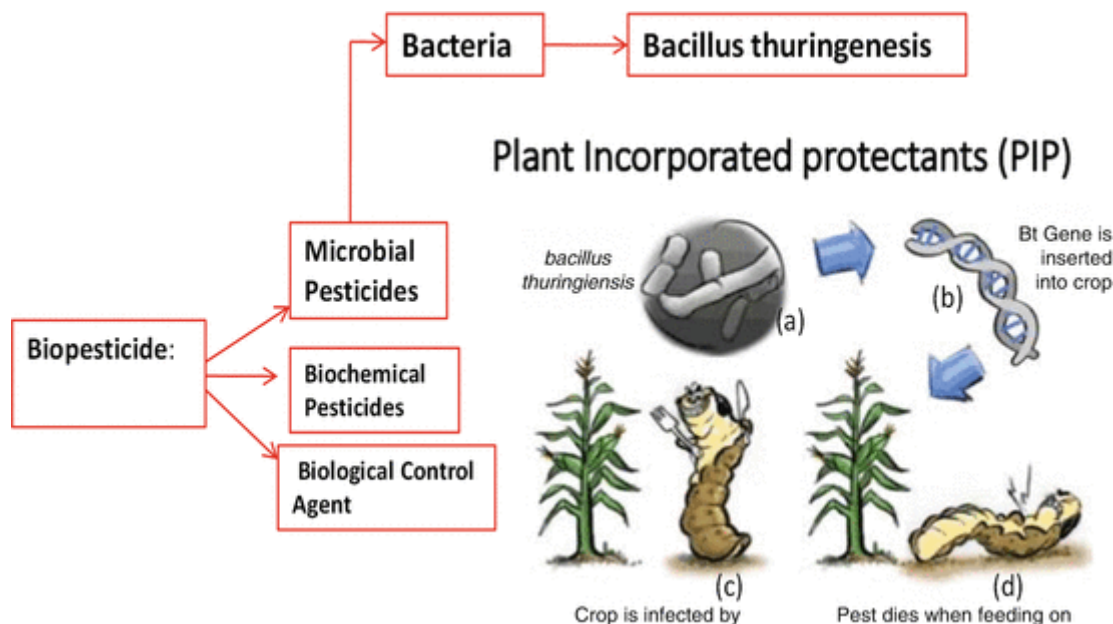


Figure 2: classification of biopesticides (<https://microbeonline.com/biopesticides>)

specific physiological or biochemical functions in pests, while generally posing low risk to useful organisms and the environment. Among these, insect pheromones have been widely recognized for their role in pest management, particularly for disrupting mating communication and reducing reproduction in insect populations, including moth species (El-Sayed, 2014; Rizvi *et al.*, 2021). Plant-based products such as neem-derived formulations and pyrethrins continue to attract significant attention due to their insecticidal, repellent, and growth-regulating properties, making them valuable components of Integrated Pest Management (IPM) programs (Pavela, 2016; Benelli *et al.*, 2017). Similarly, microbial-derived compounds like toxins from *Bacillus thuringiensis* have played a major role in reducing reliance on chemical insecticides, especially in crops such as cotton (Zhao *et al.*, 2003) (Figure 3). Recent advancements have also explored the application of nanotechnology to enhance the stability, delivery, and efficiency of plant-derived biopesticides (Chaud *et al.*, 2021). Evidence suggests that biochemical

pesticides can help slow the development of resistance in pest populations by targeting highly specific biological pathways. In addition, their use supports sustainable agricultural practices by reducing environmental pollution and conserving biodiversity. Enzyme-based biopesticides have further been investigated for controlling fungal pathogens through targeted biochemical reactions. However, despite their advantages, challenges such as large-scale production, formulation stability, and consistent field performance under varying environmental conditions remain significant concerns (Rizvi *et al.*, 2021). As global agriculture moves toward sustainability, biochemical pesticides are increasingly viewed as promising tools for reducing dependency on synthetic agrochemicals and strengthening food security (Gupta and Dikshit, 2010). Future progress will likely depend on integrated interdisciplinary research combining biochemistry, ecology, and technological innovation to optimize their practical application in pest management systems (Kumar *et al.*, 2021).

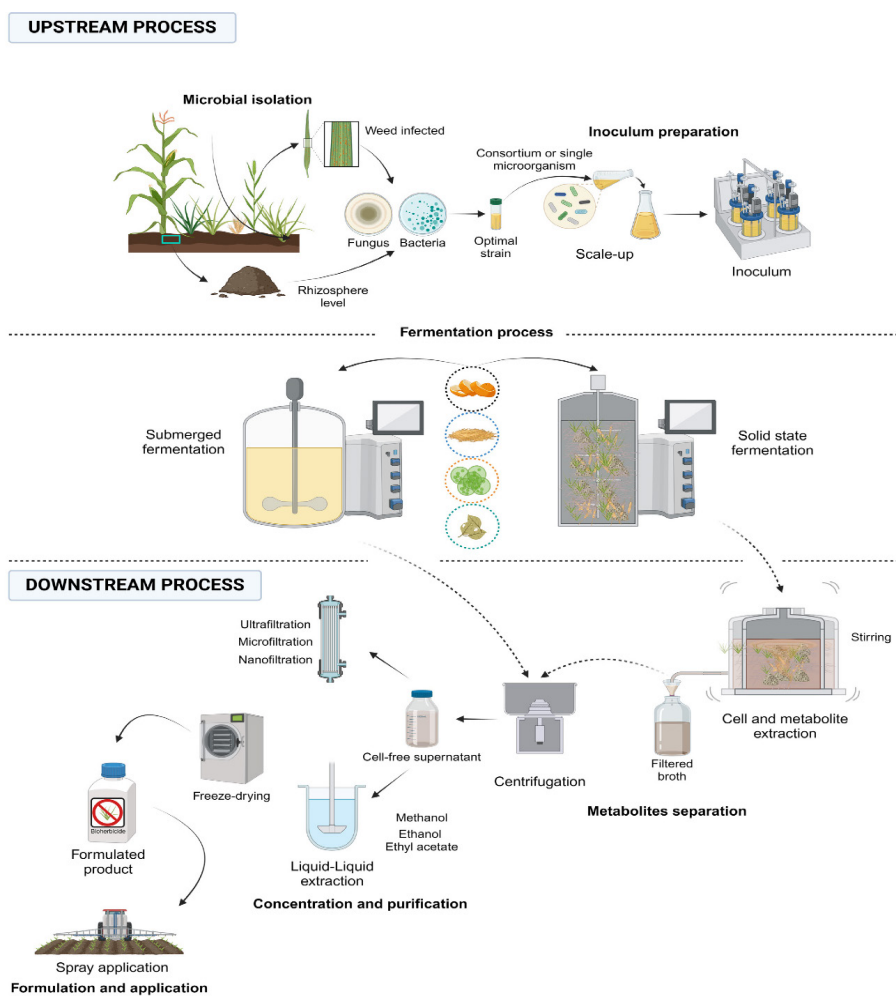


Figure 3: Illustration of the key stages involved in the production of biopesticides (https://www.mdpi.com/plants/plants-13-01996/article_deploy/html/images/plants-13-01996-g002.png)

Biopesticides Production and Market Growth

The production of biopesticides involves a series of well-defined stages that start with the identification of effective microbial strains such as bacteria, fungi, or viruses that possess pesticidal activity. These microorganisms are first isolated from natural sources and then thoroughly characterized to confirm their purity, identity, and biological effectiveness. After validation, the selected strains are mass-cultured under controlled conditions using either liquid-state fermentation (LSF) or solid-state fermentation (SSF), depending on the organism and production requirements. In LSF, microbes are grown in nutrient-enriched liquid media with continuous aeration and agitation to enhance biomass production, whereas SSF involves the developments of microorganisms on moist solid materials, which is particularly suitable for many fungal species.

Once fermentation is complete, the bioactive compounds or microbial cells are collected and processed into stable formulations. These formulations may be developed as wettable powders, granules, or liquid concentrates to facilitate easy application in the field. The final products are then subjected to rigorous quality assurance procedures, including bioefficacy testing and stability evaluation, to ensure their consistency, safety, and effectiveness. Overall, this production process provides environmentally friendly pest control solutions that reduce reliance on synthetic chemicals and support sustainable agricultural practices. Table 1 presents the main steps involved in microbial biopesticide production along with relevant examples.

Alongside advances in technology, the global biopesticide market has shown strong and steady growth in recent years (Figure 4). Microbial biopesticides, particularly widely used agents such as *Bacillus thuringiensis* (Bt), are increasingly preferred because of their precise pest-

targeting ability and minimal environmental impact. Biochemical biopesticides derived from plant-based sources such as neem and pyrethrum are also gaining importance because their effectiveness against a wide range of pests and their relatively low toxicity. In addition, biochemical approaches including pheromones and insect growth regulators are being progressively integrated into pest management programs, especially within integrated pest management (IPM) systems where they serve niche but important roles.

This growth trend is being driven by supportive regulatory frameworks, rising customer demand for organic and decrease free agricultural products, and increasing alertness of the harmful effects related with conventional synthetic pesticides. In the next section, the production methods of major categories of biopesticides will be discussed in relation to their specific applications.

Recent Innovations in Formulation Strategies of Biopesticides

Recent advances in formulation technologies have substantially increase the effectiveness, stability, and commercial applicability of biopesticides. These innovations are particularly important in overcoming inherent challenges such as short shelf-life, sensitivity to environmental conditions, and variable field performance (Gundreddy *et al.* 2024).

Microencapsulation

This technique involves enclosing active biopesticidal agents within microscopic capsules composed of polymers or biodegradable materials. It provides protection to sensitive microbial agents against UV radiation, desiccation, and temperature fluctuations, while also enabling controlled release and improved persistence under field conditions (Jalali *et al.* 2020; do Nascimento Junior *et al.* 2021).

Table 1: Production process of microbial biopesticides, including key steps and examples.

Step	Description	Example (Microbial Biopesticide)
Selection of Microorganism	A specific strain of bacteria, fungi, viruses, or protozoa is chosen based on its pest control properties.	<i>Bacillus thuringiensis</i> (Bt), <i>Beauveria bassiana</i> , <i>Metarhizium anisopliae</i>
Isolation & Culturing	The selected microorganism is isolated from nature or a culture collection and grown under controlled lab conditions.	Bt spores cultivated in nutrient-rich medium
Fermentation	Large-scale production in bioreactors or fermenters under optimal conditions (pH, temperature, aeration).	Bt grown in liquid fermentation medium
Harvesting	The microbial biomass is separated from the culture medium using filtration or centrifugation.	Separation of Bt spores and Cry proteins
Purification	The active microbial agent (spores, toxins, or cells) is purified and concentrated.	<i>Beauveria bassiana</i> conidia purified for use
Formulation	The microbial agent is processed into a usable form—powder, liquid, granules, or encapsulated formulations.	Wettable powder, emulsifiable concentrate
Quality Control	The final product is tested for efficacy, purity, stability, and non-toxicity.	Bioassays ensure proper potency
Packaging & Storage	The product is packaged with proper labelling and stored under recommended conditions to maintain viability.	Liquid Bt stored in cool, dry containers.

Nano-formulations

The application of nanotechnology in biopesticide development has improved bioavailability and targeted delivery to pest organisms (Kumar *et al.* 2019). Nanoemulsions, nanogels, and nanoparticles enhance adhesion to plant surfaces, increase residual activity, and improve penetration into target pests.

Wettable powders and water-dispersible granules

These dry formulations are designed for convenient storage, transportation, and easy mixing with water before application. They ensure uniform field distribution and improved handling safety.

Oil-based and emulsifiable concentrates

Oil-based formulations improve solubility and adhesion, particularly under high rainfall conditions or against pests with waxy cuticles. Emulsifiable concentrates allow active ingredients to disperse uniformly in water for effective application.

Gel and bead-based carriers

These advanced delivery systems provide controlled and sustained release of active agents over extended periods, making them especially useful for slow-acting microbial biopesticides (Garsmeur *et al.* 2018). They also create a protective microenvironment that enhances microbial survival.

Biopolymer carriers

Natural polymers such as alginate, chitosan, and starch are increasingly used as eco-friendly delivery matrices for biopesticides (Saberri Riseh *et al.* 2022). These systems can be engineered to respond to environmental triggers like pH and moisture, ensuring the release of active ingredients only under suitable conditions.

Production of *Bacillus thuringiensis* (Bt)

Bacillus thuringiensis (Bt) is a Gram-positive, spore-forming, rod-shaped bacterium widely familiar for producing insecticidal parasporal crystal proteins. It was first reported in 1901 by Japanese microbiologist Shigetane Ishiwatari during investigations of diseased silkworm larvae (*Bombyx mori*) (Karabörklü *et al.*, 2018). Later, in 1915, Ernst Berliner independently isolated the bacterium from infected Mediterranean flour moth larvae in a flour mill in Thuringia, which led to the naming of the species *Bacillus thuringiensis* (Valtierra-de-Luis *et al.*, 2020). Its first commercial biopesticide product, known as *Sporeine*, was introduced in France in 1938 (Roh *et al.*, 2007). Subsequent studies by N. B. Hannay demonstrated that the parasporal inclusions produced by Bt were proteinaceous crystals responsible for insect mortality (Hannay, 1967). At present, Bt-based formulations are among the most commonly utilized microbial biopesticides worldwide because of their eco-friendly nature, high specificity against insect pests,

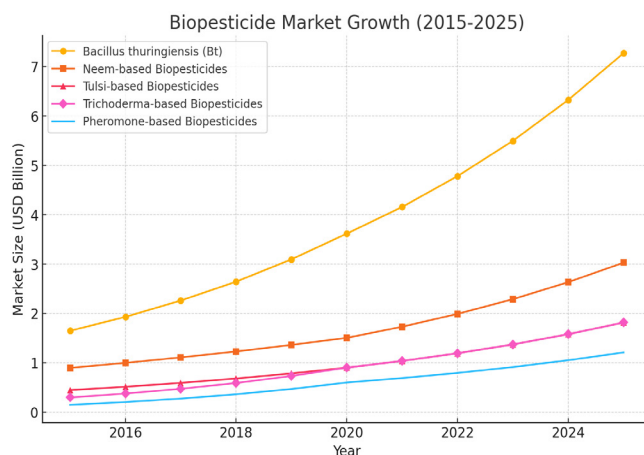


Figure 4: Market size of the different biopesticides in the last ten years between 2015-2025. (Source: Biopesticides Market, Report code AGI 2716, published in Jan 2025 MarketandMarkets(Biopesticides Market by Type (Bioinsecticides, Biofungicides, Bioinsecticides), Crop Type (Cereals & Grains, Oilseeds & Pulses), Formulation (Liquid and Dry), Source (Microbials, Biochemicals), Mode of Application, & Region - Global Forecast to 2029 2025) and Sci-Tech Today(D'Souza and Madrekar 2024).)

and reduced environmental contamination compared to synthetic pesticides (Li *et al.*, 2024). Their insecticidal function mostly depends on crystal (Cry) proteins, which are toxic to several insect groups including lepidopteran larvae, coleopterans, and dipterans. The synthesis of Bt biopesticides involves several sequential stages such as strain selection, fermentation, biomass recovery, purification, and formulation. Initially, an effective Bt strain is isolated and screened for its insecticidal activity against the target pest species. Since different strains possess distinct Cry toxins and host ranges, selecting a suitable strain is critical for maximizing efficacy (Bel *et al.*, 2020). After selection, the strain is cultured in a nutrient-enriched fermentation medium containing carbon sources (for example glucose or starch), nitrogen compounds, minerals, and essential growth factors. The inoculated medium is maintained under optimized conditions of temperature, pH, and aeration in fermenters to support bacterial multiplication and sporulation. During this stage, the bacterium produces both resistant endospores and insecticidal crystal proteins. Following a fermentation period of approximately 24–48 hours, the culture is processed for biomass recovery. The fermentation broth contains two biologically important components: dormant spores and Cry toxin crystals. These components are separated from the liquid medium through centrifugation or filtration methods. The collected biomass is further purified to concentrate the spores and crystal proteins, which represent the active ingredients of the final product. These purified materials are then converted into commercial formulations such as wettable powders, suspension concentrates, or granular preparations for

agricultural application. To improve storage stability and shelf life, the formulated product is often dried using techniques such as spray drying or freeze-drying (lyophilization). This step reduces moisture content and preserves the biological activity of the spores and toxins, ensuring effectiveness during long-term storage and field application.

Production of Neem-Based Biopesticides

Neem-based biopesticides are synthesised from the seeds and leaves of the neem tree, *Azadirachta indica*, which is widely valued for its insecticidal and medicinal properties. Among the deafferents bioactive chemical founds in neem, azadirachtin is considered the most important because of its ability to interfere with feeding, growth, molting, and reproduction of insect pests (Juma *et al.*, 2022). Owing to their biodegradable nature, low toxicity to non-target organisms, and compatibility with organic farming, neem-derived products have gained considerable importance in integrated pest management (IPM) systems.

The manufacturing of neem-based biopesticides begins with the collection of suitable raw materials. Mature neem seeds are generally preferred because they contain higher levels of azadirachtin compared to leaves. After collection, the seeds are cleaned to remove impurities and then dried under controlled situation to decrease moisture content, which helps prevent fungal or microbial spoilage.

Although neem leaves can also serve as a source of active compounds, their pesticidal efficiency is comparatively lower due to reduced azadirachtin content.

The next stage involves extraction of the active ingredients. Different extraction methods are used depending on the desired concentration and formulation:

Cold pressing

In this mechanical process, neem seeds are pressed to obtain neem oil containing azadirachtin and other biologically active substances. This technique is preferred because it preserves the natural pesticidal compounds effectively.

Solvent extraction

Organic solvents such as ethanol, methanol, or hexane are used to isolate azadirachtin and related compounds from neem seeds or leaves. This method generally provides a more concentrated extract than mechanical pressing.

Aqueous extraction

This traditional method involves soaking neem plant material in water to release bioactive compounds. Although economical and simple, the resulting extract is usually less concentrated and has lower pesticidal potency. After extraction, the crude neem extract is purified to improve its quality and enhance the concentration of

Table 2: Production of common plant-based biopesticides

Plant source	Active compounds	Extraction method	Formulation	Target pests	Application method
Neem (<i>Azadirachta indica</i>)	Azadirachtin, Nimbin, Salannin	Cold Pressing, Solvent Extraction	Oil, Emulsifiable Concentrate, Powder	Aphids, Whiteflies, Caterpillars, Locusts	Foliar Spray, Seed Treatment
Tulsi (<i>Ocimum sanctum</i>)	Eugenol, Camphor, Flavonoids	Steam Distillation, Solvent Extraction, Aqueous Extraction	Liquid Spray, Oil-Based Concentrate, Powder	Aphids, Mites, Caterpillars	Foliar Spray, Soil Application
Garlic (<i>Allium sativum</i>)	Allicin, Sulfur Compounds	Crushing & Water Extraction, Solvent Extraction	Liquid Spray, Emulsifiable Concentrate	Thrips, Mites, Beetles	Foliar Spray, Repellent Barrier
Chili Pepper (<i>Capsicum spp.</i>)	Capsaicin, Dihydrocapsaicin	Alcohol/Water Extraction, Grinding	Liquid Extract, Powder	Leafhoppers, Beetles, Caterpillars	Foliar Spray, Insect Repellent Coating
Pyrethrum (<i>Chrysanthemum cinerariifolium</i>)	Pyrethrins	Solvent Extraction	Powder, Emulsifiable Concentrate	Mosquitoes, Flies, Moths, Ants	Aerosol Spray, Fogging
Lemongrass (<i>Cymbopogon citratus</i>)	Citral, Geraniol, Limonene	Steam Distillation, Solvent Extraction	Essential Oil, Liquid Spray	Mosquitoes, Fleas, Aphids	Foliar Spray, Fumigation
Eucalyptus (<i>Eucalyptus spp.</i>)	Eucalyptol, Terpenoids	Steam Distillation	Essential Oil, Liquid Spray	Mosquitoes, Storage Pests	Fumigation, Foliar Spray
Tobacco (<i>Nicotiana tabacum</i>)	Nicotine, Anabasine	Solvent Extraction, Water Extraction	Liquid Spray	Aphids, Thrips, Caterpillars	Foliar Spray, Soil Drench
Marigold (<i>Tagetes spp.</i>)	Thiophenes, Limonene	Water Extraction, Solvent Extraction	Liquid Spray, Powder	Nematodes, Whiteflies	Soil Treatment, Foliar Spray

azadirachtin. Purification methods such as filtration, evaporation, and chromatographic separation are commonly employed to remove impurities and unwanted residues.

The purified extract is then processed into various formulations depending on agricultural requirements. Common neem-based biopesticide products include:

Neem oil sprays

Prepared by emulsifying neem oil with water and suitable surfactants for foliar application.

Neem seed cake

The residual solid material left after oil extraction, used as both a biofertilizer and a soil-applied pesticidal agent.

Neem extract concentrates

Highly refined extracts diluted to suitable concentrations for field application.

These formulations are widely used for controlling a broad range of insect pests while minimizing environmental pollution and preserving useful organisms, making neem one of the most effective botanical biopesticides in sustainable agriculture.

Table 2 tabulates the production methods, formulations, and applications in pest management of several plant based biopesticides. These natural alternatives offer an environmentally safe solution for sustainable agriculture.

Biopesticides production and consumption in India

India's wide agro-climatic diversity has encouraged the adoption of deferments biological control agents as part of sustainable agriculture practices. Among the most important biocontrol tools used in the country are *Bacillus thuringiensis* (Bt), baculoviruses, neem (*Azadirachta indica*), *Trichoderma harzianum*, *Trichoderma viride*, and *Trichogramma chilonis*. These agents provide environmentally safer replacements to chemical pesticides and support integrated pest management (IPM) and organic farming systems across the country. Among microbial biopesticides, *Bacillus thuringiensis* remains the most extensively utilized in India. It is mainly effective against destructive lepidopteran pests such as rice stem borers and the American bollworm (*Helicoverpa armigera*). The bacterium acts by releasing toxic proteins in the insect gut after ingestion, causing destruction of the midgut epithelium and eventually killing the pest. Commercial production and marketing of Bt-based pesticides in India have expanded steadily, with early reports indicating sales of nearly 70 tons by 1999 (Mishra *et al.*, 2020) (Figure-5). Baculoviruses, especially nucleo poly hedro viruses (NPVs), are another important class of viral biopesticides widely used in India. These viruses are highly effective against caterpillar pests such as *Helicoverpa armigera* and *Spodoptera litura*. Their production generally involves

mass multiplication in host larvae followed by formulation for field application (Kumar *et al.*, 2011; Grzywacz *et al.*, 2023). Because their host specificity and environment safety, they are commonly used in cotton, pulse, and vegetable cultivation. Large-scale acceptance has been supported by government biocontrol laboratories and private manufacturers, particularly in states such as Andhra Pradesh, Maharashtra, and Karnataka. Neem-derived biopesticides have a long history of use in Indian agriculture. Extracts from *Azadirachta indica* seeds and leaves have broad-spectrum pesticidal activity, mainly due to azadirachtin, which interferes with insect feeding, molting, and reproductive system. Neem formulations are commonly applied in rice, vegetable, and orchard crops. Both traditional and commercial neem derivatives, such as neem oil emulsions and azadirachtin concentrates, are widely available and registered under the Indian Insecticides Act.

Fungal biocontrol agents such as *Trichoderma harzianum* and *Trichoderma viride* have become important biofungicides in India (Mukherjee *et al.*, 2014; Meher *et al.*, 2020). These useful fungi reduce plant pathogens through mechanisms including mycoparasitism, nutrient competition, and induction of plant defence responses. They are frequently used as seed treatments, soil applications, and foliar sprays to manage diseases such as wilt, root rot, and damping-off in cereals, pulses, and horticultural crops. Their adoption has been actively promoted by agricultural universities, ICAR institutes, and state extension programs.

Egg parasitoids of the genus *Trichogramma*, particularly *Trichogramma chilonis* and *Trichogramma japonicum*, are also widely used in India as biological control agents. These minute wasps parasitize the eggs of lepidopteran pests, preventing larval emergence and crop damage. They are mass-produced and released in crops such as sugarcane, cotton, rice, and vegetables. Their use helps decrease chemical pesticide dependency and delays pest resistance. Institutions such as the Indian Council of Agricultural Research (ICAR) and state biological control centers have played an important role in distributing *Trichogramma* cards to farmers at subsidized rates.

Although biopesticides currently account for only a small proportion of India's pesticide market, their importance is increasing steadily. At present, they contribute around 4.2% of the total pesticide market, mainly due to limitations in research, production technology, and farmer awareness (Chakraborty *et al.*, 2023). However, growing interest in organic agriculture, export-oriented farming, and eco-friendly pest management is expected to boost the market significantly in the coming years. The Indian biopesticide industry is projected to expand rapidly, supported by policy initiatives and rising consumer demand for safer agricultural produce. At present, only a limited number of biopesticide products are officially



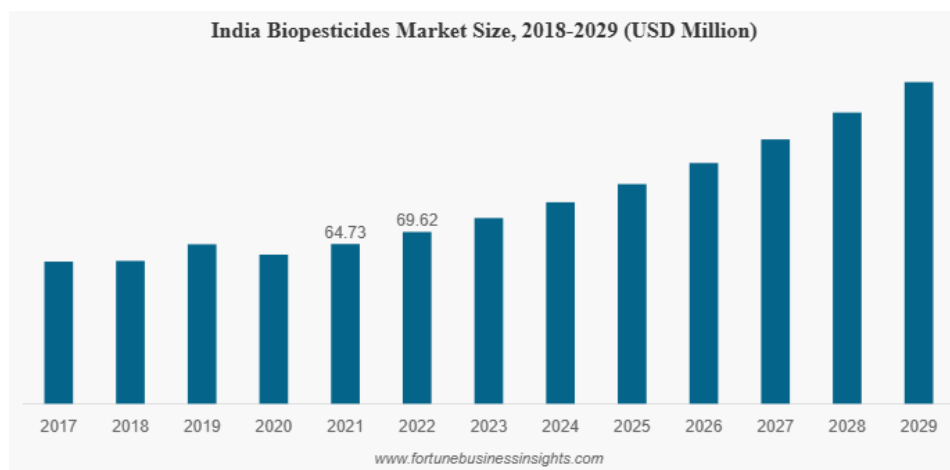


Figure 5: The projected growth of biopesticide market in India by 2029, driven by enhancing demand for organic products and sustainable crop protection strategies. (Source: <https://www.fortunebusinessinsights.com/india-biopesticides-market-106498>)

registered in India, including bacterial, fungal, viral, and botanical formulations (Kandpal, 2014). Commonly used examples include *Bacillus thuringiensis*, *Trichoderma viride*, *Metarhizium anisopliae*, *Beauveria bassiana*, nucleopolyhedrosis viruses, and neem-based products (Rao *et al.*, 2007). These biocontrol agents continue to play a crucial role in reducing pesticide residues, preserving biodiversity, and promoting sustainable crop production in India.

Although the future scenario of biopesticides in India are promising, their market share is still considerably smaller than that of conventional chemical pesticides. The growth of this sector continues to face several constraints, including inadequate industrial infrastructure, limited technological advancements, and policy-related barriers. Even so, government initiatives such as the National Policy for Farmers (2007) have encouraged the acceptance of biopesticides as part of sustainable agricultural practices. Over the last few decades, the consumption of biopesticides in India has indicates a substantial enhanced. Among botanical biopesticides, neem (*Azadirachta indica*) has remained one of the most widely used, with consumption increasing from 83 metric tons during 1994–1995 to 686 metric tons in 1999–2000. Similarly, the use of *Bacillus thuringiensis* (Bt) rose from 40 to 71 metric tons within the same period. Overall, biopesticide usage expanded dramatically from 123 metric tons in 1994–1995 to over 8,110 metric tons by 2011–2012, reflecting a significant rise in awareness and adoption (Sinha and Biswas, 2009). Further data from the Directorate of Plant Protection, Quarantine and Storage (PPQS) showed continued growth in recent years. Between 2014–2015 and 2018–2019, biopesticide consumption increased by nearly 40%, reaching 8,847 metric tons in 2019–2020 and 8,645 metric tons in 2020–2021. In contrast, the use of synthetic chemical pesticides decreases notably during the same

period, decreasing from 56,114 metric tons to 43,584 metric tons. This trend highlights a gradual shift toward safer and environmentally sustainable crop protection practices. India currently has around 410 biopesticide production units, of which nearly 130 are privately owned while about 280 are government-operated (Chakraborty *et al.*, 2023). Government-supported production facilities include 26 units under the Central Integrated Pest Management Centres, 31 units managed by the Indian Council of Agricultural Research and State Agricultural Universities (SAUs), and 22 units established with support from the Department of Biotechnology, along with several state-level biological control laboratories (Singhal, 2004). Since 2010, the Ministry of Agriculture and Farmers Welfare has provided support for around 32 Integrated Pest Management (IPM) centers and 35 commercial biopesticide production enterprises (Chetan *et al.*, 2019). In addition, state agriculture and horticulture departments in Gujarat, Uttar Pradesh, Karnataka, Tamil Nadu, Andhra Pradesh, and Kerala have established modern biocontrol laboratories to increase the growth and distribution of efficient biological control agents.

A significant share of India's biopesticide production arounds 70% is contributed by the public sector. Historically, the majority of biopesticide manufacturing units, including those producing botanical extracts, microbial agents, beneficial insects, and pheromone-based products, have been concentrated in southern India. However, recent expansion into northern parts of the country indicates a wider geographical spread of the industry (Singhal, 2004). The private sector also plays an important role in this increasing market. Major Indian biopesticide manufacturers include Biotech International Ltd., Ajay Biotech Ltd., Deep Farm Inputs Pvt. Ltd., Excel Crop Care Ltd., Kan Biosys Pvt. Ltd., and T. Stanes & Company Ltd., among others (Mishra *et al.*, 2020).

Biopesticides in Integrated Pest Management

The increasing spread of pest infestations across area, coupled with the globalization of agriculture, has made Integrated Pest Management (IPM) an important approach for minimizing pest outbreaks and delaying the development of pesticide resistance. In this context, biopesticides have emerged as valuable components of both IPM and bio-intensive pest management systems due to their environmentally safe nature and target-specific function. Their incorporation into organic and sustainable farming practices helps decrease dependence on synthetic pesticides while ensuring crop protection (Shishir *et al.*, 2015). Studies show that improving farmer awareness and documenting existing pest management practices are important for the wider adoption of these alternatives.

The primary objective of IPM is to maintain pest populations below economic threshold levels by combining biological, cultural, mechanical, and chemical control methods. This integrated strategy lowers the risk of resistance development by decreasing overreliance on chemical pesticides. For example, neem-based products and *Bacillus thuringiensis* formulations have shown considerable effectiveness against the legume pod borer *Maruca vitrata* in Thailand when used as part of an IPM strategy (Kumar *et al.*, 2014). These findings highlight the role of botanical and microbial pesticides in sustainable pest suppression. (World Vegetable Center)

Research under greenhouse conditions has also demonstrated that botanical pesticides, along with suitable conventional compounds, can improve the growth and productivity of crops such as tomato and bell pepper (George *et al.*, 2015). Similarly, invasive pests like the Guatemala potato tuber moth (*Tecia solanivora*), which has expanded rapidly in parts of South America, have prompted the development of innovative IPM programs. Such programs involve identifying entomopathogenic viruses through bioprospecting, selecting effective viral strains such as *Phthorimaea operculella* granulovirus, and formulating them into stable dust-based biopesticides using carriers and adjuvants for practical application (Carpio *et al.*, 2013; Samada and Tambunan, 2020). Sustainable pest management increasingly highlights the use of natural products and useful organisms, including predators and microbial agents, as alternatives to chemical pesticides. The effectiveness of IPM largely depends on the successful integration of biopesticides with biological control measures to achieve long-term pest suppression (Scudeler *et al.*, 2017). A notable example is *Pseudomonas fluorescens* strain Pf-CL145A, which has been applied as a biological control agent against dreissenid mussels, reducing the need for broad-spectrum chemical treatments in aquatic systems (Molloy *et al.*, 2013). Likewise, biopesticides have been recommended as safer alternatives for managing white grub infestations in teak nurseries (Meshram and Homkar, 2011). IPM can be implemented at multiple levels,

ranging from combining biological and chemical controls for specific pests to integrating pest management across entire farming systems. It also extends beyond field-level practices by considering socio-economic, cultural, and policy-related factors. Effective IPM therefore requires collaboration among farmers, researchers, industries, and regulatory authorities to build a holistic and sustainable pest management framework (Prokopy *et al.*, 1994).

A notable example of successful Integrated Pest Management (IPM) adoption can be observed in Brazil's soybean production system, where the use of insecticides has reportedly declined by nearly 50% through the inclusion of biological products based on viruses, bacteria, and fungi (Panizzi, 2013). This demonstrates the practical value of IPM as an effective and sustainable pest management strategy. Its growing acceptance among farmers, researchers, and policymakers is largely due to its economic viability and long-term environmental benefits. By incorporating renewable and eco-friendly approaches such as biological control and host plant resistance, IPM offers accessible pest management options, particularly for small and resource-limited farming communities (Thomas, 1999).

In addition to economic benefits, IPM contributes to environmental sustainability by decreasing greenhouse gas emissions related with the production and excessive application of synthetic pesticides. Biological control methods, in particular, have been recognized for their lower carbon footprint compared to conventional chemical-based pest management practices (Heimpel *et al.*, 2013). Among microbial biopesticides, *Bacillus thuringiensis* (Bt) remains one of the most widely utilized agents in IPM programs, especially in vegetable production systems in regions such as California and Mexico. Advances in Bt-based formulations and genetically engineered crops expressing Bt toxins have improved pest control efficiency by increasing residual activity, broadening target specificity, and enhancing overall effectiveness. However, inadequate farmer training, weak extension systems, and insufficient infrastructure may hinder IPM adoption, leading producers to rely solely on new biotechnological tools. Therefore, microbial pesticides and resistant crop varieties should be promoted as integral components of IPM rather than independent pest management solutions (Marrone, 1994).

Globally, pesticide consumption has reached around 3.5 billion kilograms annually, with an estimated market value of around US\$45 billion. The environmental and social costs linked to pesticide use are substantial, ranging between US\$4 and US\$19 per kilogram of active ingredient applied. In this regard, IPM offers a practical pathway for decreasing pesticide dependency. Evidence from 85 IPM initiatives conducted across 24 countries in Asia and Africa shows that ecological farming practices encouraged by IPM have significantly reduced pesticide applications, lowered



the incidence of resistance, and minimized risks related to human health and environmental contamination (Pretty and Bharucha, 2015; Jørs *et al.*, 2017). In Bangladesh, where population pressure on natural resources is high, decreasing the use of toxic agrochemicals through IPM is particularly important. Despite the presence of agricultural extension programs, only a limited number of the nation's 14.7 million farming households have adopted IPM methods. This low adoption rate highlights the need for stronger farmer education programs and better dissemination of information regarding the economic and ecological benefits of IPM (Harris *et al.*, 2013).

Overall, IPM represents a comprehensive and sustainable framework for pest management that integrates multiple control approaches while prioritizing environmental safety and human health. It supports both organic and conventional agriculture by encouraging the development and use of safer pest control products, including biopesticides and sustainable fungicides (Mascarin *et al.*, 2019). Replacing hazardous chemical pesticides with biological alternatives not only reduces ecological risks but also improves farm profitability. The economic effectiveness of IPM has been demonstrated in several cropping systems, including cauliflower cultivation during late winter, where it proved to be a practical and cost-efficient pest management strategy (Ahuja *et al.*, 2015).

Progress and Challenges in Biopesticide Adoption

The large-scale adoption of biopesticides comparatively low against synthetic chemical pesticides, mainly due to several practical and technical limitations. These include high production expenses, reduced shelf life, sensitivity to environmental conditions, and inconsistent field performance. However, improvements in formulation technologies have helped overcome some of these constraints by increasing product stability and extending biological activity (Gasic and Tanovic, 2013). Commercialization is also challenged by issues such as inadequate quality control, low farmer awareness, and relatively higher market prices, which restrict wider acceptance (Arthurs and Dara, 2019). Nevertheless, the global biopesticide sector continues to increase, with around 175 registered biopesticide types and around 700 active ingredient-based products currently available worldwide (Jiang and Wang, 2023). Among microbial biopesticides, *Bacillus thuringiensis* (Bt) remains the most extensively used and commercially successful. Bt is available in multiple forms, including microbial formulations, biochemical toxin-based products, and plant-incorporated protectants (PIPs). For more than thirty years, Bt has been widely applied for managing insect pests belonging to the orders Lepidoptera, Diptera, and Coleoptera (Kaur, 2000). At present, Bt products account for nearly 75% of total global biopesticide consumption, demonstrating their dominance in the

sector. Many biochemical biopesticides are based on purified insecticidal toxins isolated from Bt strains, reflecting their broad applicability and effectiveness (Palma *et al.*, 2014). Transgenic crops expressing Bt toxin genes have further strengthened pest management strategies by offering built-in resistance against major insect pests. However, the emergence of insect resistance to Bt formulations has become a growing concern, emphasizing the importance of diversifying pest control methods (Olson, 2015). To counter resistance, researchers have developed recombinant Bt strains with improved toxicity and expanded insecticidal spectra (Kaur, 2000). The future demand for Bt-based products is expected to rise further with the expansion of organic farming and the increasing preference for environmentally safer pest management options (Saiyad, 2017).

Botanical biopesticides also play a crucial role in sustainable pest management. *Azadirachtin*, a tetranortriterpenoid compound extracted from the seeds of *Azadirachta indica*, is one of the most effective plant-derived insecticides. It interferes with insect growth and metamorphosis, making it highly useful against a wide range of pests. Since neem seeds are predominantly available in arid and semi-arid regions, biotechnological methods have been explored to enhance azadirachtin production and ensure its commercial availability (Prakash and Srivastava, 2008). Similarly, vegetable oils have been identified as eco-friendly alternatives to synthetic insecticides because of their insecticidal and repellent properties (Rongai *et al.*, 2008). Certain species of *Senecio*, traditionally recognized for medicinal use, have also shown protective effects against crop pests when applied as powdered plant material or crude extracts (Portero *et al.*, 2012).

Oilseed by-products obtained after mechanical extraction represent another promising source of botanical biopesticides. These by-products are broadly classified into edible and non-edible oil cakes. While edible cakes are nutrient-rich and commonly used as livestock feed, non-edible oil cakes from plants such as *Jatropha curcas*, *Madhuca indica*, and *Pongamia pinnata* contain toxic compounds that make them unsuitable for animal use. These toxic residues, however, have demonstrated strong pesticidal activity, particularly against termites (Sharma *et al.*, 2013). Apart from direct pest control, beneficial microbial species also contribute significantly to sustainable agriculture. *Paenibacillus polymyxa* has gained attention as an eco-friendly alternative to chemical fertilizers due to its multifunctional properties, including phosphate solubilization, nitrogen fixation, plant growth hormone production, and lignocellulose degradation. In addition, certain strains possess antimicrobial activities that support plant health and productivity (Weselowski *et al.*, 2016). Other microbial agents also show strong biocontrol potential. *Photorhabdus luminescens*, a bacterial symbiont of entomopathogenic nematodes, produces

metabolites with antifungal activity and minimal environmental toxicity. One such metabolite, trans-cinnamic acid, has shown effectiveness against pecan scab disease (Bock *et al.*, 2014). Likewise, *Beauveria bassiana*, a naturally occurring soil fungus, acts as an entomopathogen by infecting and killing insect pests. Its biocontrol performance is influenced by factors such as soil pH and host insect physiology, making it a valuable component of integrated pest management systems (Padmavathi *et al.*, 2003).

Pathogen-based biopesticides have become a crucial component of modern pest management strategies, particularly for controlling serious pests such as *Varroa destructor*, a destructive ectoparasitic mite that threatens honeybee colonies and apiculture worldwide. Microbial pesticides based on bacteria, viruses, and fungi are increasingly recognized for their effectiveness and environmental safety. One of the earliest examples of microbial biopesticide commercialization was Japan's product *Matsukemin*, introduced in 1974, which combined cypovirus and *Bacillus thuringiensis* (Bt). Although microbial insecticides have gained global attention, their commercial use in Japan remains limited, accounting for less than 2% of the total market, with only about 25 products registered worldwide (Kunimi, 2007). In China, the development of viral biopesticides began during the 1960s and has expanded steadily over time. By 2014, the Ministry of Agriculture had approved 57 biopesticide products derived from 11 different insect viruses. Annual production reached nearly 1,600 tons, although this represented only a small fraction (around 0.2%) of the country's total insecticide production. This reflects the growing but still limited contribution of microbial pesticides in large-scale arthropod pest management (Lacey *et al.*, 2015). In addition to microbial agents, botanical pesticides have gained significant importance in global pest control programs. Plant-derived compounds such as pyrethroids, neem-based extracts, and essential oils from higher plants are widely used because of their insecticidal, antifungal, and antimicrobial properties. These natural products provide safer alternatives to synthetic chemicals while maintaining effective pest suppression (Dubey *et al.*, 2008). Similarly, fungal species have demonstrated strong biocontrol potential against plant pathogens and are increasingly being integrated into disease management programs (Rostami *et al.*, 2017). Biological approach have also been developed for the management of plant viral diseases, which commonly spread through mechanical injuries or insect vectors. One promising approach involves the development of genetically engineered virus-resistant crop varieties combined with appropriate agronomic practices. Such methods can significantly reduce crop losses and dependence on conventional pesticides. However, although many biopesticides are considered safer than synthetic

pesticides, some may still exhibit certain toxicological effects, which require further investigation and careful evaluation (Pengfei Leng, 2011). The future progress of biopesticides depends largely on systematic research, commercialization strategies, and strong regulatory frameworks. Advances in genetic engineering have opened new opportunities for pest management, but they also raise ecological, economic, and ethical concerns that must be addressed. Although Integrated Pest Management (IPM) has been adopted in several cropping systems, its full-scale implementation remains limited. Therefore, effective strategies are needed for selecting suitable biocontrol agents, evaluating their large-scale production feasibility, and maintaining consistent quality standards to improve farmer confidence and wider adoption (Koul *et al.*, 2013).

Prospects of Biopesticides

The increasing global emphasis on sustainable agriculture has highlighted biopesticides as important substitutes for synthetic chemical pesticides. Their capacity to protect crops while reducing harmful effects on ecosystems and human health makes them valuable tools in modern agricultural systems. Despite these advantages, several obstacles remain in their large-scale development, production, and practical application in the field. Future investigations should focus on optimizing manufacturing methods, improving formulation durability, and developing advanced delivery technologies to maximize their effectiveness. Strong cooperation between government agencies, private industries, and international organizations will be necessary to address production constraints, especially in developing countries where affordability and availability remain major challenges. Greater public investment and policy support from agrochemical industries can accelerate the commercialization and adoption of biopesticides. In addition, efficient regulatory systems are needed to ensure product quality while keeping these technologies affordable and accessible for small-scale farmers. At the same time, progress in biotechnology is expected to transform pest management practices. Emerging transgenic crops with features such as inducible expression systems, tissue-specific resistance, and pyramided genes provide more precise and durable pest control strategies (Moore *et al.* 2006). These developments can complement microbial biopesticides, particularly both conventional and improved strains of *Bacillus thuringiensis*, strengthening integrated pest management (IPM) approaches. Similarly, research on fungal herbicides has advanced considerably, with the discovery of new pathogenic strains capable of targeting a wider range of weed species. Such innovations are likely to increase the contribution of fungal-based weed management in sustainable crop production worldwide. Continuous progress in biological control research and technological innovation is improving the



consistency, effectiveness, and economic feasibility of biopesticides. Enhanced production technologies are also reducing manufacturing costs, making large-scale commercialization more practical. Market trends suggest strong future growth, particularly in the Bt-based biopesticide sector, along with expanding opportunities in biofungicides and bioherbicides. The development of IPM strategies centered on biopesticides is critical for reducing dependence on synthetic pesticides, delaying resistance development, and encouraging eco-friendly crop protection. Current research increasingly supports pest management systems that integrate biopesticides as a means of achieving sustainable agricultural productivity while protecting environmental and human health. Furthermore, improvements in fermentation technologies, liquid culture systems, and in vivo production methods can increase production efficiency, reduce costs, and enhance the availability of biopesticides for broader agricultural use.

Future pest management approaches are expected to further optimize the application of *Bacillus thuringiensis* (Bt) and its insecticidal crystal proteins, particularly with the growing adoption of transgenic crops. Recent developments in novel toxin identification, recombinant DNA technology, and proteomic studies are improving toxin delivery systems, enabling more precise targeting of insect pests. Likewise, baculoviruses have emerged as effective microbial pesticides in diverse agricultural systems. Their successful use in protecting more than two million hectares of soybean crops from velvet bean caterpillar infestations highlights their economic and practical value (Moscardi 1999). Future expansion of baculovirus-based biopesticides is likely to involve both naturally occurring strains and genetically modified variants designed to improve pesticidal performance. Advances in molecular diagnostics, in vitro propagation systems, and formulation technologies are expected to strengthen their field application. Rapid diagnostic tools will improve early detection and outbreak forecasting, while improved culture methods can lower production costs and reduce contamination risks. Furthermore, formulation enhancements will improve product stability and shelf life. Genetic engineering approaches, including the insertion of virulence genes from other pathogens, may also shorten pest mortality periods and enhance effectiveness.

Botanical pesticides continue to hold considerable importance in organic farming and environmentally sustainable agriculture, particularly in developing countries where they contribute significantly to crop protection and food security. The global rise in eco-conscious consumer preferences has accelerated the shift away from synthetic pesticides toward plant-derived alternatives. Natural phytochemicals are expected to become increasingly important in pest control strategies across both developed and developing

nations (Isman 2006). Organic farming systems further promote sustainability by improving soil organic carbon, minimizing nutrient leaching, reducing soil erosion, and supporting agroforestry-based land management practices. The use of compost, farmyard manure, and terracing also contributes to soil fertility and water conservation. Future studies should prioritize improving the efficiency, consistency, and scalability of currently available botanical pesticides rather than focusing solely on the discovery of new plant sources.

Among botanical pesticides, neem-based products derived from *Azadirachta indica* remain highly promising. However, broader commercialization requires continued research and biotechnological innovation. Standardized neem formulations with greater shelf stability are needed to replace crude extracts, which often degrade rapidly under environmental exposure. Improving ultraviolet tolerance and reducing the labor-intensive nature of neem processing will strengthen their market potential. Two major strategies for enhancing neem adoption include increasing its bioefficacy to widen its pest control spectrum and lower resistance development, and combining it with synergistic compounds such as Piperonyl butoxide to improve insecticidal activity (Schmutterer 1990). Post-harvest grain protection remains another crucial aspect of pest management, as inadequate storage protection can result in serious economic losses. Future pest management systems are increasingly expected to move from chemical-intensive methods toward integrated pest management (IPM) supported by computer-based decision-making tools. Bio-larvicides have also gained considerable attention because of their affordability, high efficacy, and prolonged activity against mosquito larvae, especially in breeding sites of *Anopheles* species. Advanced larval control strategies may include controlled-release formulations and toxin-encapsulated living delivery systems to maintain prolonged effectiveness. However, the environmental release of transgenic insecticidal organisms requires careful ecological monitoring and risk assessment. Overall, biological control methods alone are insufficient for long-term pest suppression and must be integrated with complementary approaches within comprehensive IPM frameworks. Strengthening farmer awareness, technical training, and sustainable pest management education through international cooperation will be essential. Active farmer participation in discussions regarding biological control technologies and addressing practical concerns will play a critical role in improving adoption and ensuring the long-term success of sustainable pest and vector management programs.

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AUTHOR CONTRIBUTIONS

JBT did conceptualization, methodology and writing original draft; VKP performed reviewing; SK supervised the study. All authors have read and agreed to the published version of the manuscript.

KEY MESSAGE

Biopesticides are gaining attention as eco-friendly alternatives to synthetic chemical pesticides, yet their broader adoption remains limited due to production, formulation, and efficacy challenges.

- The review synthesizes current advancements in microbial and botanical biopesticide development.
- It highlights recent innovations in formulation strategies—such as microencapsulation and nano-formulations—that enhance biopesticide stability, shelf-life, and field performance.
- The review identifies critical bottlenecks and regulatory hurdles in the commercialization of biopesticides, offering potential solutions to improve market adoption.
- Overall, this work underscores the promise of biopesticides in sustainable agriculture and integrated pest management, encouraging a shift toward safer and more resilient pest control strategies globally.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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