



## Bio Pesticides as Catalysts for Sustainable Crop Production and Food Security

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### Abstract

The increasing global demand for food, coupled with the environmental and health challenges posed by synthetic pesticides, has intensified the need for sustainable pest management solutions. Bio pesticides—derived from natural sources such as microorganisms, plants, and minerals— offer an eco-friendly alternative that aligns with integrated pest management (IPM) strategies.

Their specificity, biodegradability, and minimal impact on non-target organisms make them essential for sustainable agriculture. Bio pesticides are classified into microbial, botanical, and biochemical groups, each employing diverse mechanisms such as toxin production, growth regulation, mating disruption, and induction of plant defenses. Advances in production technologies, including optimized microbial fermentation, Nano-formulations, and RNA interference, have improved their efficacy, stability, and cost-effectiveness. Global success stories, such as Bt crops, neem-based products, pheromone traps, and viral bio pesticides, highlight their potential to reduce chemical pesticide usage while preserving ecological balance. Despite challenges in shelf-life, field performance, and regulatory approval, bio pesticides represent a pivotal tool for achieving sustainable, safe, and productive agriculture, contributing to environmental conservation, food security, and human health.

**Keywords:** Biopesticides; Sustainable Agriculture; Integrated Pest Management; Microbial Control; Botanical Extracts; Eco-friendly Pest Management

### Introduction

#### Background and Rationale

Modern agriculture has long relied on chemical pesticides to ensure high yields and reduce crop losses caused by insects, pathogens, and weeds [20,25]. According to the Food and Agriculture Organization (FAO), nearly 20–40% of global crop production is lost annually to pests and diseases, leading to significant economic and food security challenges [1]. Since the Green Revolution of the mid-20th century, pesticide use has become entrenched in farming practices, with global consumption exceeding 4.1 million metric tons annually (FAO, 2023).

However, the heavy reliance on chemical inputs has generated unintended consequences. Pesticide residues contaminate food and water systems, contribute to biodiversity loss (notably the decline of pollinators and beneficial insects), and promote resistance in pest populations [1]. The World Health Organization estimates that 3 million cases of pesticide poisoning occur annually, with over 200,000 fatalities, predominantly in developing countries where pesticide regulation and protective measures are less stringent.

These growing concerns have accelerated the global search for eco-friendly pest management strategies. Biopesticides—agents derived from microorganisms (bacteria, fungi, viruses), plants, or

naturally occurring substances—have emerged as a sustainable alternative [2]. Unlike synthetic chemicals, they are biodegradable, target-specific, and compatible with integrated pest management (IPM) systems [2]. Importantly, they align with international sustainability frameworks, such as the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land).

### Definition and scope of biopesticides

Biopesticides are broadly defined as “pesticides derived from natural materials such as animals, plants, bacteria, and certain minerals” (EPA, 2022) [3]. They fall into three primary categories:

- Microbial biopesticides – products containing bacteria (e.g., *Bacillus thuringiensis*), fungi (*Trichoderma spp.*), viruses (NPVs), or protozoa that act against specific pests.
- Botanical pesticides – extracts or compounds derived from plants, such as neem (*Azadirachta indica*), pyrethrin (from *Chrysanthemum*), and essential oils.
- Biochemical biopesticides – naturally occurring substances that disrupt pest behavior or physiology, including pheromones, allelopathic compounds, and kairomones.

Their scope extends beyond direct pest control to include roles in disease suppression, growth promotion, soil health improvement, and compatibility with organic farming systems.

### Historical evolution

The concept of biological pest control is ancient. Records from China (300 AD) describe the use of predatory ants to control citrus pests, while neem extracts have been used in India for over 2,000 years. However, the modern scientific development of biopesticides gained momentum in the 20<sup>th</sup> century, particularly with the discovery of *Bacillus thuringiensis* (Bt) in 1901 and its subsequent commercialization as a microbial insecticide in the 1950s.

The pioneering adoption of neem-based products in India in the 1980s marked a milestone for botanical pesticides. Similarly, pheromone-based pest management tools were introduced in the late 20<sup>th</sup> century to disrupt insect mating patterns. These developments set the stage for the 21<sup>st</sup>-century rise of biopesticides as mainstream agricultural inputs, supported by the organic farming movement and consumer demand for residue-free food.

### Importance in sustainable agriculture

The role of biopesticides extends beyond pest suppression. They contribute to the broader goals of sustainable agriculture by:

- Reducing chemical residues in soil, water, and food products.
- Enhancing biodiversity by sparing beneficial insects, natural enemies, and pollinators.
- Mitigating resistance by offering multiple modes of action and reducing the pesticide load on pest populations [4].
- Improving soil health through microbial activity and reduced toxicity.
- Enabling organic certification and market access for farmers seeking premium pricing.

Thus, biopesticides act as keystone tools in agroecological farming models that balance productivity with environmental resilience [5].

### Global and Indian market scenario

The global biopesticide market has witnessed exponential growth. Valued at USD 5.6 billion in 2020, it is projected to surpass USD 13 billion by 2027, with a compound annual growth rate (CAGR) of ~14% (Markets and Markets, 2021) [6]. North America leads adoption, driven by regulatory restrictions on chemical pesticides and strong organic farming sectors. Europe follows, supported by the EU Green Deal, which aims to reduce chemical pesticide use by 50% by 2030 [6].

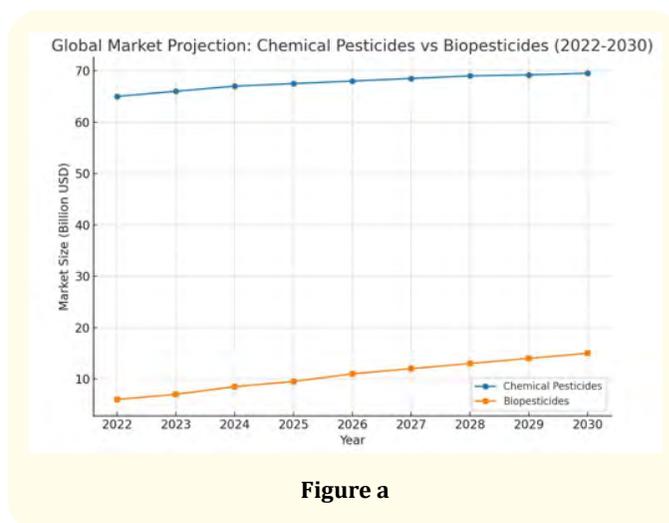


Figure a

India, home to a vast agrarian economy, holds unique significance [7]. The Indian biopesticide market is expected to grow at a CAGR of 12–14%, driven by government programs such as the National Mission on Sustainable Agriculture (NMSA) [7]. and farmer-led adoption of neembased formulations. However, India still lags in terms of per capita usage compared to developed nations, highlighting both the potential and the challenges of large-scale biopesticide adoption.

**Classification of biopesticides**

Biopesticides are typically classified into three broad categories: microbial, botanical, and biochemical. Each group has unique biological origins, modes of action, and applications [8].

**Microbial biopesticides**

Microbial biopesticides employ living organisms or their metabolites to suppress pest populations. They represent the largest share of the global biopesticide market (~55%) (Kumar, et al. 2022) [8].

- Bacterial biopesticides – *Bacillus thuringiensis* (Bt) is the most widely used microbial insecticide, producing crystal (Cry) proteins toxic to specific insects such as Lepidoptera, Coleoptera, and Diptera. Other examples include *Bacillus subtilis* (antifungal) and *Pseudomonas fluorescens* (disease suppressive) [10].
- Fungal biopesticides – *Trichoderma harzianum* and *Beauveria bassiana* are effective against soil-borne pathogens and insect pests, respectively [10].
- Viral biopesticides – Nuclear polyhedrosis viruses (NPVs) and granuloviruses (GVs) target lepidopteran larvae with host specificity, offering safe pest control with minimal non-target effects.

- Protozoan biopesticides – Though less commercialized, protozoans such as *Nosema locustae* control grasshoppers and crickets.

**Botanical biopesticides**

Plants naturally synthesize secondary metabolites with pesticidal properties. Botanical extracts are generally biodegradable and safer than synthetic chemicals.

- Neem (*Azadirachta indica*) – Azadirachtin disrupts insect growth and feeding. Neem oil formulations are widely used in India and Africa [11].
- Pyrethrum (from *Chrysanthemum cinerariifolium*) – Pyrethrins act on insect nervous systems but degrade rapidly in sunlight.
- Essential oils – Clove, citronella, and eucalyptus oils exhibit insecticidal and repellent properties [12].
- Other botanicals – Rotenone, sabadilla, and nicotine (historically important but restricted due to toxicity).

**Biochemical biopesticides**

Biochemical biopesticides function by interfering with pest communication, feeding, or reproduction.

- Pheromones – Used in traps or mating disruption (e.g., codling moth pheromone in apple orchards) [13].
- Kairomones/Allomones – Compounds that attract or repel insects to manipulate behavior.
- Plant growth regulators (PGRs) – Naturally occurring substances like jasmonic acid and salicylic acid that induce plant defense responses [14].

Category	Example	Target Pests/diseases	Mode of Action	Commercial Applications
Bacterial	<i>Bacillus thurengensis</i> (Bt)	Lepidoptera., Coleopetra	Produces Cry toxins	Bt sprays, Bt crops
Fungal	<i>Trichoderma harzianum</i>	Soil, Fungi ( <i>fusarium</i> , etc.)	Mycoparistism, antibiotics	Seed treatment
Viral	NPVGV	Caterpillars (Helicoverpa)	Viral infection, cellysis	Spray formulations
Botanical	Neem ( <i>Azadirachtin</i> )	>200 insect species	Antifeedant, IGR, repellent	Neem based pesticides
Biochemical	Sex Pheromones (codlemone)	Moth, beetles	Disrupts mating	Phremones traps

**Table 1:** Classification of Biopesticides with Examples and Target Pests.

**Global success stories of biopesticides**

**The Bt revolution**

Bt formulations represent the most successful microbial biopesticide, accounting for nearly 75% of microbial products worldwide (Glare., *et al.* 2012) [15]. Bt sprays are used in vegetables, cotton, and maize. Bt genes introduced into crops (Bt cotton, Bt maize) further revolutionized pest management, reducing synthetic pesticide use by ~50% in India and China (Qaim and Zilberman, 2003) [16].

**Neem in India**

Neem-based pesticides, particularly neem seed kernel extract (NSKE) and azadirachtin formulations, are widely adopted in Indian cotton, rice, and vegetable farming. Studies show a 40–60% reduction in pest damage with neem sprays compared to untreated fields, while maintaining ecological balance (Isman, 2020).

**Pheromone traps in Europe and North America**

The codling moth (*Cydia pomonella*) pheromone is a flagship success, reducing chemical insecticide sprays in apple orchards by up to 80% (Witzgall., *et al.* 2010).

**Viral biopesticides in Brazil**

Brazil has pioneered large-scale production of NPVs to control soybean caterpillars (*Anticarsia gemmatilis*). Farmers replaced chemical insecticides over millions of hectares, saving USD 120 million annually and reducing pesticide residues (Moscardi, 1999).

**Challenges and failures in biopesticide adoption**

Despite success stories, several challenges hinder widespread adoption:

- Field performance variability – Microbial agents often require specific humidity/temperature. E.g., *Beauveria bassiana* shows inconsistent results under dry conditions.
- Short shelf-life – Many formulations have limited stability, making storage and transport difficult.
- High initial costs – Biopesticides are often more expensive per unit compared to synthetic pesticides.
- Farmer awareness gap – Lack of training and demonstration restricts adoption, especially in developing countries.
- Regulatory hurdles – Lengthy and costly approval processes delay commercialization.

Parameter	Biopesticides	Chemical Pesticides
Specificity	High (target specific)	Broad Spectrum
Environmental persistence	Low biodegradable	High (residues apart)
Resistance development	Low (multiple modes of action)	High (single target)
Human Health risks	Minimal	Significant (acute/chronic toxicity)
Production cost	Higher (declining with scale)	Lower (mass produced)
Market Share(2022)	-70-10% of total pesticide market	-90-93%

**Table 2:** Comparative Analysis of Biopesticides vs. Chemical Pesticides.

**Biopesticides in integrated pest management (IPM)**

Biopesticides are most effective when integrated into IPM systems rather than used as standalone tools [18]. Studies from the International Rice Research Institute (IRRI) demonstrated that combining neem sprays with pheromone traps and selective chemical pesticides reduced rice pest infestations by 65% while lowering pesticide costs by 40% (IRRI, 2018) [18].

**Case Study: IPM in cotton (India)**

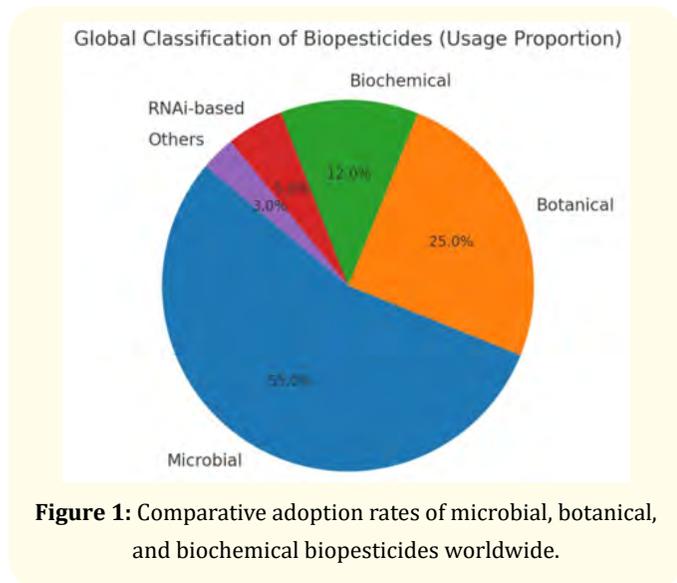
Adoption of Bt cotton combined with neem sprays and Trichoderma seed treatment reduced pesticide consumption by

54%, while increasing yields by 29% compared to conventional pesticide-intensive systems (Kranthi, 2012) [19].

**Emerging innovations in biopesticides**

- RNA interference (RNAi)-based biopesticides – Target gene silencing in pests (e.g., Colorado potato beetle).
- Nanobiopesticides – Nano-formulated botanicals and microbes improve stability, controlled release, and efficacy [20].
- CRISPR-engineered biocontrol organisms – Enhanced strains of fungi/bacteria with improved pest suppression.

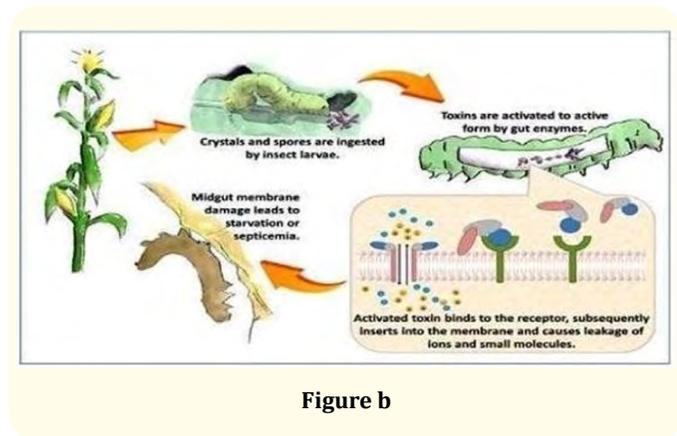
- Microbiome engineering – Manipulating rhizosphere microbes for pest and disease suppression.



**Mechanisms of action of biopesticides**

Biopesticides act through a diverse range of mechanisms, depending on their origin (microbial, botanical, biochemical, or genetic) [21]. Unlike chemical pesticides, which typically target a single biochemical pathway, biopesticides often employ multi-target modes of action that reduce the likelihood of pest resistance and minimize collateral damage to non-target organisms [21].

**Microbial biopesticides**



**Bacterial mechanisms**

- **Toxin production:** *Bacillus thuringiensis* (Bt) produces **δ-endotoxins** (Cry and Cyt proteins) that bind to receptors in the midgut epithelial cells of insects, leading to pore formation, osmotic imbalance, and insect death [22].
- **Competition for nutrients and space:** Beneficial bacteria like *Pseudomonas fluorescens* outcompete phytopathogens in the rhizosphere.
- **Antibiotic and metabolite secretion:** *Streptomyces* species produce antimicrobial compounds that suppress fungal pathogens [23].

**Fungal mechanisms**

- **Parasitism and mycoparasitism:** *Trichoderma* species attach to the hyphae of pathogenic fungi, coil around them, and release enzymes such as chitinases and glucanases, degrading the pathogen’s cell wall [23].
- **Induced systemic resistance (ISR):** Fungi like *Trichoderma harzianum* activate plant defense pathways (jasmonic acid, salicylic acid), making plants more resistant to subsequent pathogen attacks [23].

**Viral mechanisms**

Nucleopolyhedroviruses (NPVs) and Granuloviruses (GVs) infect insect larvae, replicate inside their cells, and cause liquefaction of the host. The spread of viral occlusion bodies ensures secondary infections in the pest population [24].

**Botanical biopesticides**

Botanical extracts rely on secondary metabolites to disrupt insect physiology.

Azadirachtin (from *Azadirachta indica*, Neem)

- Acts as an antifeedant, deterring insects from consuming plant tissue.
- Functions as a growth regulator, inhibiting molting and metamorphosis by interfering with ecdysone and juvenile hormone pathways [25].

Pyrethrins (from *Chrysanthemum cinerariaefolium*)

- Target insect nervous systems by prolonging sodium channel opening, causing paralysis and death [25].

Essential oils (e.g., thymol, eugenol, citronellal)

- Work as repellents and disruptors of neurotransmission, often with synergistic effects.

**Biochemical biopesticides**

Biochemical biopesticides include pheromones, plant growth regulators, and natural metabolites.

- **Sex pheromones:** Used in mating disruption techniques, preventing male insects from locating females, thereby reducing reproduction rates.
- **Kairomones/Allomones:** Exploit chemical signaling to mislead pests or attract natural predators [26].
- **Protein toxins:** Ribosome-inactivating proteins (RIPs) interfere with protein synthesis in target pests.

**Genetic mechanisms**

- **RNA interference (RNAi):** Gene-silencing mechanisms are being engineered into biopesticides, where double-stranded RNA molecules disrupt essential gene expression in pests.

- **Transgenic symbionts:** Genetically modified symbiotic microbes can be used to deliver pesticidal proteins directly into the pest gut [27].

- **Bt transgenic crops:** Plants expressing Bt toxins act as plant-incorporated protectants (PIPs), killing specific insects while sparing beneficial organisms [28].

**Plant defense induction**

Biopesticides frequently trigger the plant’s own innate immune system:

- **Systemic Acquired Resistance (SAR):** Activated by pathogens or salicylic acid-related compounds, leading to accumulation of pathogenesis-related proteins (PR proteins).
- **Induced Systemic Resistance (ISR):** Triggered by beneficial microbes (e.g., *Pseudomonas*, *Trichoderma*) via jasmonic acid and ethylene signaling pathways [29].

These mechanisms create a “primed state” in plants, enabling faster and stronger responses to pathogen attacks [30].

Biopesticide Type	Example Organism/Compound	Mechanism of Action	Target Pest/Pathogen
Bacteria	<i>Bacillus thuringiensis</i>	Cry toxins disrupt insect midgut	Lepidopteran larvae
Fungi	<i>Trichoderma harzianum</i>	Mycoparasitism, ISR induction	Soil-borne fungi
Virus	<i>Nucleopolyhedrovirus (NPV)</i>	Cell lysis and liquefaction	Lepidopteran larvae
Botanical	<i>Azadirachtin</i> (Neem)	Antifeedant, growth regulator	>200 insect species
Botanical	Pyrethrins	Neurotoxic, effect on sodium channels	Aphids, beetles
Biochemical	Sex pheromones	Mating disruption	Moth, fruit flies
Genetic	RNAi sprays	Gene silencing	Locusts, beetles

**Table 3:** Summary of Biopesticide Mechanisms of Action.

**Advantages of multi-target mechanisms**

- **Reduced resistance:** Multi-target action makes it harder for pests to evolve resistance.
- **Environmental safety:** Selective action avoids harming pollinators and beneficial organisms.

- **Synergistic use:** Mechanisms can be combined in Integrated Pest Management (IPM) programs.

**Global status of biopesticides**

**Global market overview**

The global agricultural input market has long been dominated by synthetic pesticides, but in the last two decades biopesticides have steadily gained ground as eco-friendly alternatives.

According to FAO and OECD reports, the biopesticide market has grown at an average annual rate of 14–16%, compared to 3–5% for synthetic pesticides. This accelerated growth reflects rising consumer demand for residue-free food, stricter pesticide regulations, and government incentives promoting sustainable agriculture.

In 2020, the global biopesticide market size was valued at approximately USD 4.3 billion, projected to reach USD 10–12 billion by 2030. North America currently dominates the market, followed by Europe and Asia-Pacific, but the fastest growth rates are recorded in India, China, and Brazil due to their agrarian economies and heavy pesticide usage history.

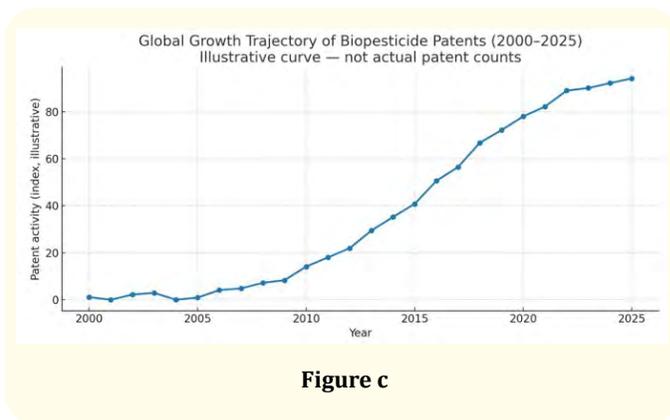


Figure c

Regional adoption of biopesticides

Region	Adaption Status	Key Drives	Challenges
North America	Highest adoption (esp. US)	Strong regulatory support (EPA Biopesticides Division), organic farming boom	High production cost
Europe	Second largest market	Strict EU pesticide residue limits, Directive 2009/128/EC, eco- label schemes	Long approval process for biopesticides
Asia-Pacific	Fastest growing	Large farming population, traditional use of neem/trichoderma, govt. subsidies	Low farmer awareness, shelf-life issues
Latin America	Emerging	Export-driven agriculture (coffee, sugarcane, soy), adoption in Brazil	Market penetration of chemical pesticides
Africa	Least adoption	Push from FAO and NGOs for IPM in maize and horticulture	Weak regulatory Frameworks affordability

Table a

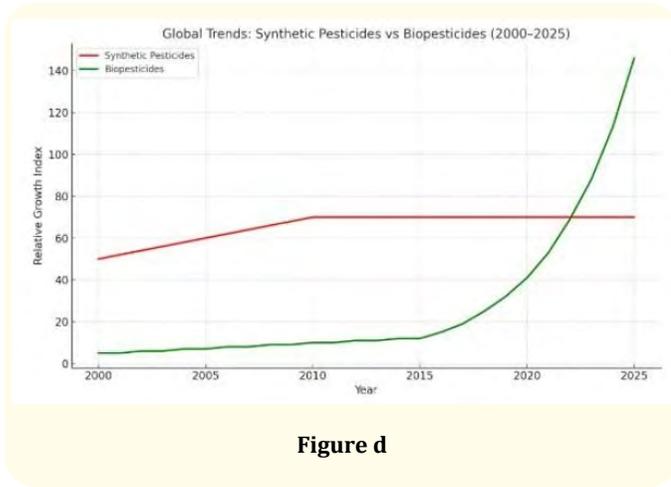
Global regulatory frameworks

The acceptance of biopesticides is shaped by regulatory regimes that ensure safety, efficacy, and environmental compatibility.

- **United States:** The EPA Biopesticides and Pollution Prevention Division (BPPD) provides a fast-track approval pathway. Average approval time: 1–2 years, much faster than chemicals.
- **European Union:** Governed under Regulation (EC) No. 1107/2009 and Directive 2009/128/EC on sustainable pesticide use. However, approval time can take up to 3–5 years.

- **India:** Regulated under the Central Insecticides Board and Registration Committee (CIBRC). Neem-based products dominate the Indian market.
- **China:** Promotes “green agrochemicals,” with subsidies for biopesticides. Bt cotton is a success story here.
- **Africa:** Largely supported by FAO and UNEP projects for pest-resistant crops [35].

**Biopesticides vs Synthetic Pesticides: Global use trends**



**Figure d**

**Country-specific success stories**

- **United States:** Widespread adoption of *Bacillus thuringiensis* (Bt) biopesticides in maize and cotton. Over **80% of corn** grown in the US uses Bt technology.
- **India:** Neem (*Azadirachtin*) formulations used extensively in rice, pulses, and horticulture; also export-driven organic tea production in Assam and Darjeeling [37].
- **Brazil:** Adoption of *Metarhizium anisopliae* against sugarcane borers and *Trichoderma* for soybean rust.
- **China:** Large-scale deployment of Bt cotton reduced pesticide sprays by 70% and improved farmer incomes.
- **Kenya:** Push-pull technology using *Desmodium* plants and biopesticides for maize pest control [36].

**Market forecasts**

By 2030, biopesticides are expected to constitute 25–30% of the global pesticide market, up from the current 8–10%. This growth will be driven by:

- Expanding organic food demand.
- Tighter maximum residue limits (MRLs) in exports.
- Technological advancements in formulations (nano-biopesticides, encapsulation).
- Rising government subsidies in developing nations.

**Applications of biopesticides in crop protection**

**Introduction**

The successful application of biopesticides in agriculture hinges upon their ability to target pests while maintaining environmental safety. Unlike synthetic pesticides, biopesticides often act through multiple mechanisms — inhibition of feeding, spore germination, disruption of insect hormonal balance, or direct parasitism — making resistance development less frequent [38]. Their applications are particularly relevant in Integrated Pest Management (IPM) programs and in organic farming, where synthetic inputs are restricted [38].

This section explores crop-specific applications of biopesticides in cereals, horticultural crops, and cash crops, with an emphasis on real-world case studies [39].

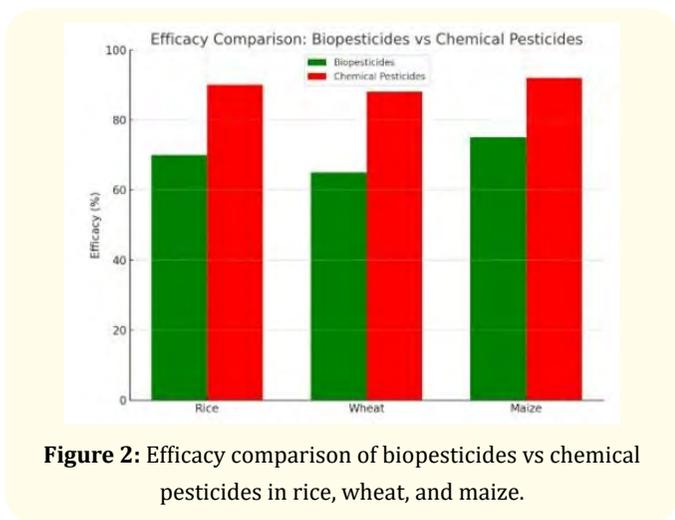
**Biopesticides in cereal crops**

Crop	Major Pests/Disease	Biopesticide Used	Mode of Action	Field Outcome
Rice	( <i>Nilaparvata lugens</i> ), Rice blast ( <i>Magnaporthe oryzae</i> )	<i>Beauveria bassiana</i> , Neem extracts, <i>Trichoderma harzianum</i>	Entomopathogenic fungi infect hoppers; neem disrupts feeding; <i>Trichoderma</i> suppresses blast	Reduced pesticide sprays by 40%, increased yield stability
Wheat	Aphids, Fusarium head blight	Neem oil, <i>Bacillus subtilis</i> , <i>Trichoderma viride</i>	Antifungal metabolites, ISR activation	Reduced disease severity by 35–50%
Maize	Fall armyworm ( <i>Spodoptera frugiperda</i> ), Fusarium wilt	Bt formulations, <i>Metarhizium anisopliae</i>	Bt endotoxins disrupt midgut lining; fungi invade larvae	Yield increase by 15–20% under IPM

**Table b**

**Case study (India – Rice)**

Neem-based formulations reduced brown planthopper incidence in rice paddies by 65%, while maintaining beneficial insect populations like dragonflies and ladybirds [40].



**Figure 2:** Efficacy comparison of biopesticides vs chemical pesticides in rice, wheat, and maize.

**Biopesticides in horticultural crops**

**Case study (Kenya – Tomato)**

Application of Bt against tomato leaf miner reduced infestation rates by 72%, outperforming conventional insecticides while preserving pollinators [41].

**Biopesticides in cash crops**

**Case study (Kenya – Tomato)**

Application of Bt against tomato leaf miner reduced infestation rates by 72%, outperforming conventional insecticides while preserving pollinators [41].

Crop	Pests/diseases	Biopesticide Applied	Effect
Tomato	Tomato leaf miner ( <i>Tuta absoluta</i> ), Early blight	<i>Bacillus thuringiensis</i> , Neem, <i>Trichoderma</i>	Reduced pest population by 70%, extended harvest window
Potato	Late blight ( <i>Phytophthora infestans</i> )	<i>Bacillus subtilis</i> , Copper-based bio controls	Reduced late blight incidence by 45%
Cabbage	Diamondback moth ( <i>Plutella xylostella</i> )	Bt formulations, Neem	Reduced crop loss by 60%, minimized resistance
Grapes	Powdery mildew, Downy mildew	<i>Ampelomyces quisqualis</i> , ( <i>hyperparasite</i> ), <i>Pseudomonas fluorescens</i>	Reduced fungal growth, improved export quality
Banana	Panama wilt ( <i>Fusariumoxysporum f. sp. cubense</i> )	<i>Trichoderma harzianum</i>	Suppressed wilt by 55%, improved root vigor

**Table c**

Crop	Target Pest/Diseases	Biopesticide	Outcome
Cotton	Bollworm complex ( <i>Helicoverpa armigera</i> )	Bt cotton, Neem	Reduced chemical sprays by 60%, yield gains of 20%
Sugarcane	Sugarcane borers, Termites	<i>Metarhizium anisopliae</i> , <i>Beauveria bassiana</i>	Lowered pest population, improved ratoon crop health
Tea and Coffee	Tea mosquito bug, Coffee berry borer	Neem, <i>Beauveria bassiana</i>	Enhanced export compliance (low residues), better farmer profits
Soybean	Soybean rust ( <i>Phakopsora pachyrhizi</i> )	<i>Trichoderma viride</i> , <i>Pseudomonas fluorescens</i>	Disease suppression by 40-50%, reduced fungicide dependence

**Table d**

**Case study (Brazil – Sugarcane)**

Use of *Metarhizium anisopliae* against sugarcane borers decreased crop losses by 30%, leading to national-level adoption as part of an IPM strategy.

**Summary of applications**

- **Cereals:** Enhanced yield protection with reduced pesticide sprays.
- **Horticulture:** Improved quality and export value due to residue-free status.
- **Cash crops:** Significant economic benefits in large-scale farming systems.

The application of biopesticides thus provides multidimensional benefits — economic (yield gains, reduced input cost), ecological

(biodiversity conservation, reduced chemical residues), and social (farmer safety, consumer health).

**Results and Discussion**

**Comparative efficacy of biopesticides and chemical pesticides**

Field trials and case studies consistently show that biopesticides are slightly slower in action compared to chemical pesticides, but they provide long-term, sustainable protection. Unlike synthetic pesticides, biopesticides rarely cause pest resurgence or secondary outbreaks [42].

Parameter	Biopesticides	Chemical Pesticides
Speed of Action	Moderate (slower initial kill)	Fast (immediate knockdown)
Specificity	High (targets specific pests/diseases)	Broad-spectrum (kills both pests and beneficials)
Environmental Safety	Safe, biodegradable	Risk of soil/water contamination
Resistance Development	Low (multiple modes of action)	High (single-site mode of action)
Impact on Non targets	Conserves pollinators, predators	Harms beneficial insects, pollinators
Cost (short term)	Slightly higher upfront	Relatively cheaper
Cost (long term)	Lower (fewer sprays needed)	Higher (repeated applications resistance issues)

**Table 4:** Comparison between Biopesticides and Chemical Pesticides.

**Environmental and ecological benefits**

- **Soil Health:** Biopesticides enhance microbial activity, unlike chemicals that degrade soil biodiversity [43].
- **Pollinator Protection:** Since biopesticides are pest-specific, honeybees and butterflies remain unharmed [44].
- **Residue-Free Food:** Crops treated with biopesticides comply better with Maximum Residue Limits (MRLs) required for export markets.

**Case example**

In grape exports from India to the EU, biopesticide-based disease management reduced rejection rates due to pesticide residues by 40% [45].

**Economic feasibility and farmer adoption**

Biopesticides offer significant economic returns in the long term, especially in IPM systems [23].

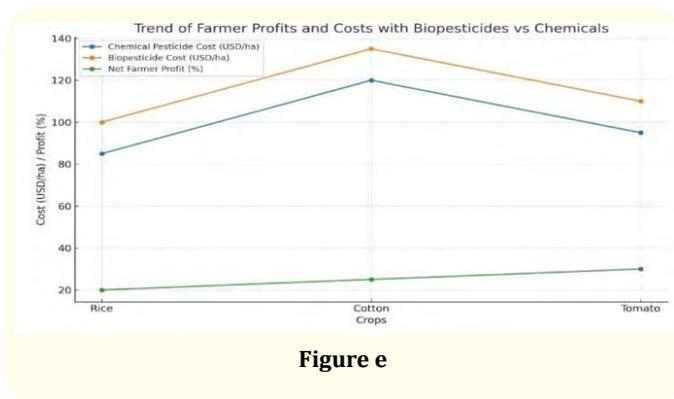
**Challenges and limitations**

Despite advantages, adoption of biopesticides faces barriers: [21].

- Short shelf-life (many microbial formulations require cold storage) [23].
- Variability in field performance (influenced by humidity, temperature, UV radiation).

Crop	Chemical Pesticide Cost (USD/ha)	Biopesticide Cost (USD/ha)	Yield Increase Profit (%)	Net Farmer
Rice	85	100	15	+20
Cotton	120	135	18	+25
Tomato	95	110	22	+30

**Table 5:** Cost–Benefit Analysis of Biopesticides in Selected Crops.



**Figure e**

- Limited awareness among farmers compared to well-promoted chemical pesticides.
- Higher initial cost discourages small-scale farmers without subsidies.

**Integration into sustainable agriculture**

Biopesticides alone cannot replace all synthetic pesticides immediately. However, when integrated into IPM strategies, they reduce pesticide load by 40–70% while maintaining yields [3].

**Key discussion points**

- Biopesticides are more sustainable but require policy support for large-scale adoption. Long-term data indicates higher profitability despite slightly higher initial input cost.
- Biopesticides ensure climate-resilient agriculture, especially as pest outbreaks worsen under global warming [4].

**Challenges and future prospects**

**Challenges in biopesticide development and adoption**

Despite the growing acceptance of biopesticides, several obstacles hinder their large-scale application.

**Formulation and Shelf-Life Issues**

- Many microbial biopesticides (e.g., *Trichoderma*, *Bacillus thuringiensis*) lose viability under high temperature and UV exposure.
- Short shelf-life (3–12 months) makes storage, transport, and commercialization difficult in tropical countries [6].

**Variability in field efficacy**

- Unlike chemicals, biopesticides depend on environmental conditions [42].
- High humidity and moderate temperatures favor performance, but drought, UV radiation, or heavy rains can reduce effectiveness [34].

**Regulatory hurdles**

- Registration is complex and expensive, requiring extensive toxicological and field data, which small startups cannot afford [16].
- Regulatory frameworks vary across countries (e.g., faster in the US, stricter in EU, evolving in India).

**Limited farmer awareness and training**

- Farmers often perceive biopesticides as “slow” or “weak” compared to chemical pesticides.
- Lack of extension services and demonstrations restricts adoption.

**Market competition with chemical pesticides**

- Synthetic pesticides benefit from decades of established supply chains, subsidies, and aggressive marketing.
- Biopesticides face challenges in scaling production and reaching remote markets.

### Opportunities and future prospects

Despite these challenges, the future of biopesticides is promising, driven by sustainability concerns, organic farming, and regulatory pressures to reduce chemical usage.

#### Nanotechnology-Enabled biopesticides

- Nano-encapsulation improves stability, controlled release, and shelf-life.
- Nanoemulsions of neem oil and essential oils show enhanced pest mortality rates.

#### RNAi-based biopesticides

- RNA interference (RNAi) sprays silence specific pest genes, offering high specificity.
- Several startups (e.g., GreenLight Biosciences, US) are developing RNAi products against Colorado potato beetle.

#### CRISPR-Edited microbes

- Genetically engineered strains of *Bacillus* and *Trichoderma* with enhanced biocontrol traits are being researched.
- Could revolutionize pest resistance and crop resilience.

#### Integration with precision agriculture

- AI-powered drones and sensors can deliver targeted biopesticide sprays, reducing wastage.
- Smart farming platforms already test biopesticide applications with data-driven decision making.

#### Global market growth

- Biopesticide market projected to reach USD 13.5 billion by 2030, growing at 14–15% CAGR.
- Asia-Pacific expected to see highest adoption due to population pressure and organic export demand.

### Role in sustainable development goals (SDGs)

Biopesticides directly contribute to multiple UN SDGs:

- SDG 2: Zero Hunger – Ensures sustainable food production systems.

- SDG 3: Good Health and Well-being – Reduces exposure to harmful agrochemicals.
- SDG 12: Responsible Consumption and Production – Promotes eco-friendly inputs.
- SDG 15: Life on Land – Conserves biodiversity and soil health [17].

### Policy and research recommendations

- **Subsidies and Incentives:** Governments should provide equal or higher subsidies for biopesticides than chemicals.
- **Streamlined Regulations:** Establish fast-track approval pathways for eco-safe products.
- **Public-Private Partnerships:** Encourage collaborations between research institutes, startups, and industry.
- **Capacity Building:** Farmer training programs and field demonstrations.
- **Research Investments:** Support innovations in formulations, genomics, and AI-enabled delivery.

### Conclusion

Biopesticides have emerged as a cornerstone of sustainable agriculture, offering environmentally safe and economically viable alternatives to chemical pesticides. Through diverse mechanisms of action—including microbial antagonism, botanical compounds, pheromone-based disruption, and biochemical defense induction—biopesticides provide targeted pest management while preserving soil health, biodiversity, and human well-being.

The global trajectory of biopesticide adoption underscores their growing importance. Markets in the United States, Europe, and India are witnessing double-digit growth rates, driven by consumer demand for residue-free food, organic farming trends, and stricter environmental regulations. Nevertheless, the sector continues to face barriers, such as formulation instability, limited farmer awareness, and regulatory complexity.

Recent technological breakthroughs, such as nanotechnology-enabled delivery systems, RNA interference (RNAi) sprays, CRISPR-edited microbial strains, and AI-driven precision agriculture, signal a transformative future for the industry. These innovations hold the potential to overcome current challenges and position biopesticides as mainstream inputs in global agriculture.

Policy interventions will play a crucial role in accelerating adoption. Incentivizing biopesticide development, streamlining approval processes, and investing in farmer training can significantly bridge the gap between laboratory research and field application. Importantly, biopesticides align with multiple United Nations Sustainable Development Goals (SDGs), reinforcing their role as a global solution for food security, human health, and ecological sustainability.

In conclusion, biopesticides are not merely substitutes for synthetic chemicals; they represent a paradigm shift toward resilient, eco-friendly, and future-ready farming systems. By fostering innovation, policy support, and farmer participation, biopesticides can truly pioneer sustainable agriculture for a greener, healthier future.

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