



Review Article

Biopesticides in Sustainable Agriculture: Importance, Production Technologies, Regulatory Landscape, and Future Prospects in Indian Sustainable Agriculture

Kamal Prasad

Privi Life Science, Research and Development, A-71, TTC Industrial Area, Thane-Belapur Road, Kopar Khairane, Navi Mumbai, Maharashtra, India.

*Corresponding author: Dr. Kamal Prasad, Email: kamal.prasad@privilife.co.in

Abstract

Biopesticides are emerging as sustainable alternatives to synthetic pesticides, offering environmentally safe and target-specific pest management solutions. This study examines the development, production, regulatory framework, and adoption challenges of biopesticides in India. It reviews microbial and botanical sources, along with current production techniques such as fermentation and plant extraction, and recent advancements including improved formulations, strain enhancement, and nano-based delivery systems. The analysis identifies key constraints such as limited shelf-life, inconsistent field performance, regulatory complexities, and low farmer awareness, which hinder widespread adoption. Despite these challenges, results indicate significant potential for biopesticides in enhancing sustainable agriculture, particularly when integrated into integrated pest management (IPM) systems. The study concludes that strengthening regulatory efficiency, improving infrastructure, promoting innovation, and enhancing farmer education are essential to accelerate the adoption and commercialization of biopesticides in India.

Keywords: Agriculture, Biopesticide, Innovation, Landscape, Regulatory, Sustainable, Production Technologies.

Citation: Prasad K. (2026). Biopesticides in Sustainable Agriculture: Importance, Production Technologies, Regulatory Landscape, and Future Prospects in Indian Sustainable Agriculture. *Mycological Spectrum* 02(02):85-133. <https://doi.org/10.64993/MS.2.2.4>

Received: 02 May 2026 | **Accepted:** 17 July 2026 | **Published:** 31 July 2026.

Handling Editor: Dr. S.K. Singh | **Reviewers:** Dr. Burla Sashidhar & Dr. Deepak Kumar.

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1. Introduction

The world-wide agricultural segment is facing increasing pressure to reduce reliance on synthetic chemical insecticides owing to their well-documented ecological and wellbeing risks. These compounds often persist in soil and aquatic systems, leading to long-term contamination, disruption of non-target organisms, and accumulation of residues in food products. In addition, widespread and repeated use has accelerated the development of resistance in major pest populations. Collectively, these challenges have intensified the search for securer and additional sustainable crop defence approaches (Kumar *et al.*, 2025). Biopesticides have emerged as promising alternatives to conventional agrochemicals. Derived from natural sources such as microorganisms, plant extracts, and biologically active metabolites, these agents are generally biodegradable, target-specific, and less harmful to non-target organisms. Their use is consistent with the principles of sustainable agriculture and evolving regulatory frameworks aimed at minimizing the ecological footprint of crop protection inputs. Biopesticides act through a range of mechanisms, including infection, parasitism, antibiosis, competition, and interference with pest growth and behaviour. Their compatibility with natural ecological processes supports the conservation of beneficial organisms, including pollinators, natural enemies, and soil microbiota. When integrated into pest management programs, they can reduce dependence on synthetic pesticides, delay resistance development, and enhance agroecosystem resilience.

Biopesticides are generally classified into three main categories: biopesticides, biochemical pesticides, and plant-incorporated protectants (PIPs). Biopesticides include bacteria, fungi, and viruses such as *Bacillus thuringiensis*, *Beauveria bassiana*, and *Trichoderma* spp. Biochemical pesticides consist of naturally occurring compounds, including pheromones and plant-derived secondary metabolites, that influence pest behaviour or physiology. PIPs are pesticidal constituents produced by genetically modified plants (Aioub *et al.*, 2024; Hezakiel *et al.*, 2024). These diverse categories provide multiple modes of action and contribute to dropping dependence on broad-spectrum chemical pesticides. In India, the biopesticide sector is expanding, although its contribution remains modest relative to conventional pesticides. Biopesticides account for approximately 9% of total pesticide consumption (Chakraborty *et al.*, 2023). Report from the Directorate of Plant Protection, Quarantine & Storage indicate that nearly 970 biopesticide products are registered under the Central Insecticides Board and Registration Committee (CIBRC), with fungal formulations comprising the majority, followed by bacterial, viral, and plant-based products (Directorate of Plant Protection, 2025). Government initiatives promoting organic farming, integrated pest management, and residue-free exports have supported this growth. However, adoption remains limited, indicating substantial scope for further expansion. Several constraints continue to hinder wider adoption. Key challenges include maintaining microbial viability during production, optimizing fermentation processes, and ensuring formulation stability during storage and distribution.



Many biopesticides are sensitive to environmental factors such as temperature, humidity, and ultraviolet radiation, which can reduce shelf life and field performance compared with synthetic alternatives (SkyQuest, 2025). In addition, fragmented supply chains, limited rural distribution networks, and low levels of farmer awareness restrict their accessibility and use (Custom Market Insights, 2025). Regulatory frameworks play a critical role in shaping the development and commercialization of biopesticides. In India, these products are governed by the Insecticides Act 1968, with registration overseen by the CIBRC. Although, stringent evaluation is necessary to ensure safety and efficacy, the registration process can be lengthy and resource-intensive, particularly for small and medium enterprises (BioBiz, 2024). Streamlining regulatory procedures and adopting risk-based approaches for low-risk biological products could facilitate innovation and improve market access. Advances in biotechnology, genomics, and formulation science are opening new avenues for the development of next generation biopesticides. Genome sequencing and molecular tools enable the identification and improvement of microbial strains with enhanced specificity, stability, and efficacy. These approaches support the development of novel bioactive compounds and optimized strains capable of overcoming resistance in pest populations, thereby strengthening the role of biopesticides in sustainable agriculture.

Next generation biopesticides represent a significant advancement over conventional biological control agents, integrating modern biotechnological tools to improve efficacy, stability, and field performance. These innovations encompass a range of approaches. Genetically improved microbial biopesticides, including *Bacillus thuringiensis* strains, have been developed to express novel or multiple toxin genes, thereby broadening their insecticidal spectrum and overcoming resistance in target pests. RNA interference (RNAi)-based biopesticides provide a highly specific mode of action by silencing essential genes in pest species; for example, double-stranded RNA (dsRNA) formulations targeting *Helicoverpa armigera* and *Spodoptera frugiperda* have shown considerable promise. Advance technologies in genome editing, mainly CRISPR-based methods, have enabled the development of improved fungal biocontrol agents, like *Beauveria bassiana* and *Metarhizium anisopliae* with improved stress tolerance and virulence. In parallel, formulation innovations, including nano-encapsulation of plant-derived compounds such as neem (*Azadirachta indica*) extracts, have improved stability, protection from ultraviolet degradation, and controlled release characteristics. Furthermore, biological consortia formulations combining compatible organisms such as *Trichoderma* spp. and *Pseudomonas fluorescens* offer synergistic effects that improve pest and disease destruction under field conditions. Collectively, these developments address key limitations of earlier biopesticide formulations, particularly with respect to shelf life, environmental sensitivity, and consistency of performance.



Recent progress in genomics and molecular biology has further accelerated the discovery and optimization of bioactive compounds and microbial agents. Genome mining has revealed previously unexpressed or 'silent' biosynthetic gene clusters in microorganisms, leading to the identification of novel metabolites with potential agricultural applications. For instance, genomic analysis of *Streptomyces* species has uncovered new antibiotic compounds with activity against resistant pathogens (Ling *et al.*, 2015). Similarly, sequencing of the marine bacterium *Salinispora tropica* facilitated the discovery of salinosporamide A, a potent bioactive molecule with highly specific biochemical activity (Udwary *et al.*, 2007).

Molecular characterization has also contributed to the identification of enzymes and metabolites with enhanced functional stability. A well-known example is the thermostable DNA polymerase derived from *Thermus aquaticus*, which has enabled advances in molecular diagnostics and biotechnology (Chien *et al.*, 1976). In addition, genomic studies of fungi such as *Aspergillus fumigatus* have identified gene clusters associated with the production of antifungal secondary metabolites, providing new opportunities for crop protection (Keller, 2019). Whole-genome analysis of beneficial microbes, including *Lactobacillus rhamnosus* GG, has similarly improved understanding of traits such as environmental persistence and host interaction, supporting their optimization for applied use (Segers & Lebeer, 2014).

Formulation technologies continue to evolve together with these biological advances. Techniques like microencapsulation and nano-delivery schemes improve the environmental persistence of active agents and empower controlled release under field conditions. Incorporation of biopesticides with meticulousness agriculture apparatuses, pest surveillance systems, and decision-support platforms can further optimize application timing and dosage, thereby improving both efficacy and economic viability. In India, the policy environment is increasingly supportive of sustainable agricultural practices, including organic farming, integrated pest management, and climate-resilient production systems. This provides a favorable context for expanding the use of biopesticides. However, large-scale acceptance will depend on continued investment in research and development, better quality control and regulatory efficiency, strengthened extension services, and increased farmer awareness. Public-private partnerships will also play a critical role in bridging the gap between innovation and field level implementation. Overall, with continued technological advancement and supportive policy frameworks, biopesticides are well positioned to play a dynamic role in sustainable and climate-resilient agriculture. The present manuscript therefore examines their importance, classification, production technologies, formulation strategies, regulatory considerations, application methods, associated challenges, and prospects in the context of Indian agriculture.



2. Importance of Biopesticides in Sustainable Agriculture

The intensification of crop production, coupled with prolonged dependence on artificial pesticides, has contributed to environmental deprivation, ecological disproportion, and growing public health anxieties. These challenges have accelerated the shift toward more sustainable pest management approaches. Biopesticides derived from microorganisms, plant-based materials, and naturally occurring bioactive compounds offer a viable alternative due to their biodegradability, target specificity, and comparatively lower ecological impact (Copping & Menn, 2020a; 2020b; 2020c; 2020d; PMC Biopesticides in India, 2019a; 2019b). Their relevance to sustainable agriculture, particularly in India, can be understood across several interrelated dimensions (Figure 1).

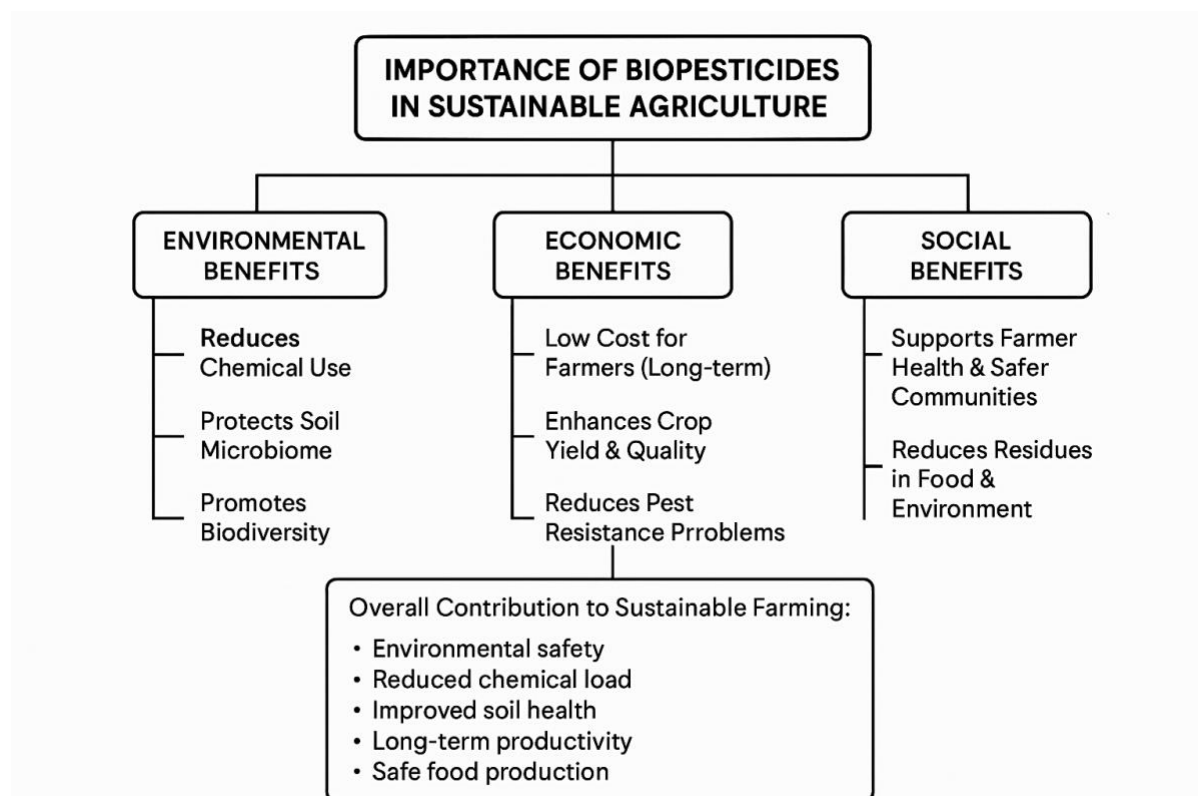


Figure 1. Importance of biopesticides in sustainable agriculture in India.

2.1. Environmental and Ecological Benefits: Biopesticides generally exhibit lower toxicity to non-target organisms, comprising natural enemies, pollinators, soil microbiota, and aquatic species, compared with conventional pesticides. Their rapid degradation in the environment reduces persistence and limits accumulation in soil and water systems, thereby minimizing long-term contamination risks (Kumar *et al.*, 2019; Kumar *et al.*, 2021). By supporting beneficial organisms and natural regulatory processes, their use contributes to biodiversity conservation and improved ecological balance within agroecosystems.



2.2. Food Protection and Human Health: The extensive use of chemical pesticides has been linked to a range of adverse health consequences, including neurological, carcinogenic, and endocrine effects. In contrast, biopesticides are typically associated with minimal residue levels on food products, making them a safer option for both consumers and agricultural workers (Kumar *et al.*, 2023a; Kumar *et al.*, 2023b; Zaina *et al.*, 2024; Victoria *et al.*, 2024). This is particularly important in India, where compliance with increasingly stringent food safety standards is essential for both domestic markets and export-oriented agriculture.

2.3. Compatibility with Integrated Pest Management: Biopesticides are well suited for integration into Integrated Pest Management (IPM) systems due to their selective activity and compatibility with biological control agents. Their application helps conserve natural enemies and enhances ecosystem resilience, thereby reducing dependence on chemical inputs (Damos, 2015; Singh & Gupta, 2016; Tonle *et al.*, 2024; Helps *et al.*, 2024; Victori *et al.*, 2024, Zainab *et al.*, 2024). When combined with cultural and mechanical practices, they contribute to additional stable pest suppression and reduce the likelihood of secondary pest outbreaks and resistance development.

2.4. Target-Specific Modes of Action: A main benefit of biopesticides is their specificity toward target pests, which limits unintended effects on valuable organisms. Microbial agents such as *Bacillus thuringiensis* and entomopathogenic fungi including *Beauveria bassiana* and *Metarhizium anisopliae* act through host-specific infection or toxin production (Copping & Menn, 2020c). Similarly, biochemical agents such as insect pheromones disrupt mating behaviour, offering precise pest control with minimal ecological disturbance.

2.5. Role in Organic and Sustainable Farming Systems: The growing demand for organic and residue-free produce has improved the importance of biopesticides in India. Organic certification frameworks largely prohibit synthetic pesticide use, making biological alternatives essential. Even in conventional systems, partial substitution with biopesticides can reduce chemical loads, improve soil biological activity, and support long-term sustainability (Arthurs, 2019; Kumar *et al.*, 2019; Mishra *et al.*, 2020; Bashan *et al.*, 2014; O'Callaghan, 2016). Their application aligns with national priorities related to sustainable and climate-resilient agriculture.

2.6. Resistance Management: The frequent use of chemical pesticides often leads to the quick emergence of resistant pest populations. Biopesticides, with their diverse and often complex modes of action such as infection, parasitism, and behavioral interference offer valuable tools for resistance management (Aioub *et al.*, 2024; Hezakiel *et al.*, 2024; Verma *et al.*, 2024). Their enclosure in pest management agendas can help prolong the efficiency of both biological and chemical control approaches.



2.7. Socio-Economic Benefits: Beyond environmental advantages, biopesticides offer important socio-economic benefits, particularly for smallholder farmers. Reduced exposure to toxic chemicals improves occupational safety, while lower input costs and reduced crop losses can enhance farm profitability. In addition, decentralized production of microbial biopesticides creates opportunities for rural enterprises and local employment. Access to premium markets for residue-free produce can further improve income and strengthen market competitiveness (Kumar *et al.*, 2023a; Kumar *et al.*, 2023b; Help *et al.*, 2024; Tonle *et al.*, 2024).

3. Classification and Production Methods of Biopesticides

3.1. Classification of Biopesticides: Biopesticides are generally classified into four major categories based on their origin and mechanisms of action. Microbial pesticides, biochemical pesticides, botanical pesticides, and plant-incorporated protectants (PIPs) (Copping & Menn, 2020b; 2020d; Aioub *et al.*, 2024; Hezakiel *et al.*, 2024; Verma *et al.*, 2024; Marrone, 2019; PMC Biopesticides in India, 2019a) (Figure 2). These categories encompass a wide range of biological agents that contribute to sustainable pest management.

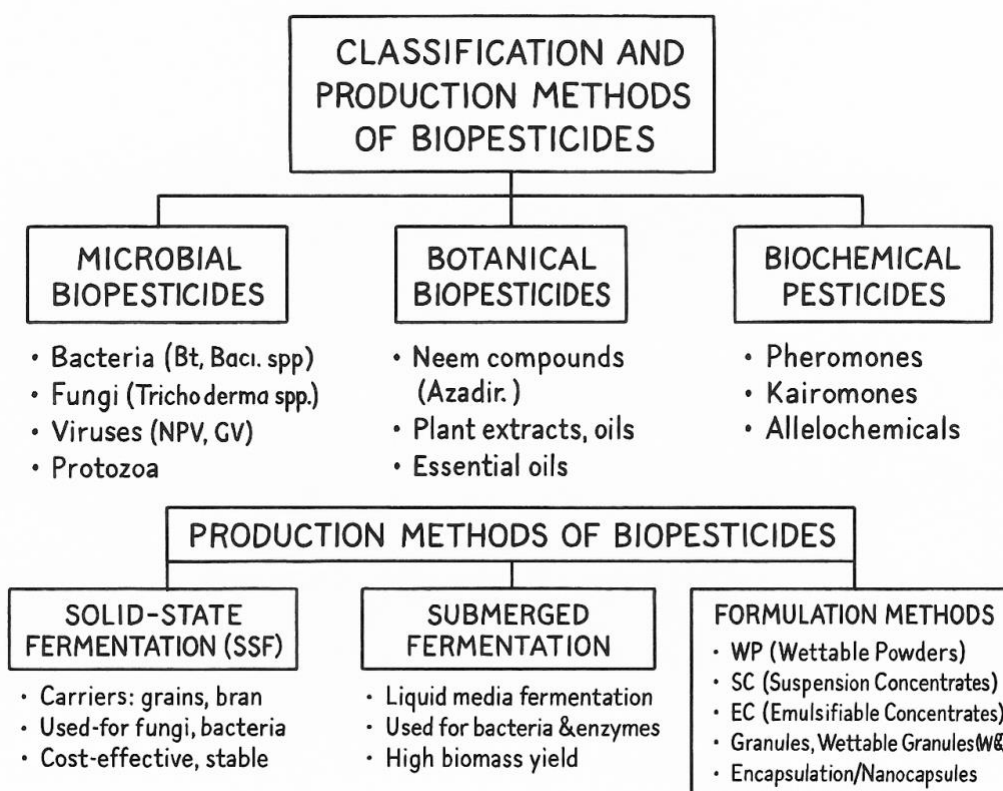


Figure 2. Systematic sketch of classification and production methods of biopesticides.



3.1.1. Microbial Biopesticides: Microbial biopesticides consist of living microorganisms or their metabolites that suppress pest populations. Depending on their target, they are further categorized as biofungicides, bioinsecticides, bactericides, and bionematicides. Their efficiency is largely attributed to mechanisms like parasitism, toxin creation, competition, and induction of host resistance.

3.1.2. Microbial Fungicides (Biofungicides): Biofungicides are broadly used for the management of plant pathogens, mostly soil-borne fungi. Representative organisms include *Trichoderma viride*, *Trichoderma harzianum*, *Pseudomonas fluorescens*, *Ampelomyces quisqualis*, and *Bacillus subtilis*. These agents operate through multiple mechanisms, including mycoparasitism, antibiosis, competition for nutrients and space, and induction of systemic resistance in host plants. *Trichoderma* species are particularly notable for their ability to colonize the rhizosphere, suppress pathogens, and encourage plant growth (Kumar *et al.*, 2019) (Table 1).

3.1.3. Microbial Insecticides: Microbial insecticides include bacteria, fungi, viruses, and protozoa that specifically target insect pests. Among these, *Bacillus thuringiensis* is widely used due to its production of crystalline (Cry) toxins that disrupt the gut lining of susceptible larvae. Entomopathogenic fungi such as *Beauveria bassiana*, *Metarhizium anisopliae*, *Lecanicillium* spp. (formerly *Verticillium lecanii*), *Paecilomyces* spp., and *Hirsutella thompsonii* infect insects through direct penetration of the cuticle. Viral agents, particularly nucleopolyhedroviruses (NPVs), are highly host-specific and are commonly applied against lepidopteran pests. These microbial systems provide effective pest suppression while minimizing impacts on non-target organisms (Copping & Menn, 2020b) (Table 2).

Table 1. Microbial Biofungicides, Principal Targets, Modes of Action, and Common Application Methods.

Biofungicide organism	Major target pathogen group/example diseases	Mechanisms of action	Common application methods
<i>Trichoderma viride</i>	Soil-borne fungi (<i>Rhizoctonia solani</i> , <i>Fusarium</i> spp., <i>Pythium</i> spp.); damping-off, root rots, wilts	Mycoparasitism; antibiosis (secondary metabolites); competition for nutrients/space; initiation of systemic resistance; rhizosphere colonization	Seed treatment; soil application (FYM/compost enrichment); Nursery media treatment; root dip; soil drench



<i>Trichoderma harzianum</i>	Soil-borne fungi (<i>Fusarium</i> , <i>Sclerotium rolfsii</i> , <i>Rhizoctonia</i>); collar/root rots, wilts	Mycoparasitism (cell-wall degrading enzymes); antibiosis; competitive exclusion; induced resistance; plant-growth promotion	Seed/seedling treatment; soil application; drip/soil drench; potting mix treatment
<i>Pseudomonas fluorescens</i>	Fungal/bacterial complexes in rhizosphere; seedling diseases; some foliar diseases (context dependent)	Antibiosis (phenazines, DAPG); siderophore-mediated iron competition; ISR (induced systemic resistance); biofilm/rhizosphere competence	Seed treatment; root dip; soil drench; seedling tray/nursery treatment; foliar spray in some crops
<i>Bacillus subtilis</i>	Broad spectrum against several fungi (<i>Botrytis</i> , <i>Alternaria</i> , <i>Fusarium</i>) and some bacterial diseases; seed/foliar diseases	Antibiosis (lipopeptides such as iturins/surfactins/fengycins); competition; biofilm formation; ISR	Seed treatment; foliar spray; soil drench; post-harvest dip (crop/product dependent)
<i>Ampelomyces quisqualis</i>	Powdery mildews (<i>Erysipales</i>) on grapes, cucurbits, ornamentals, etc.	Hyper parasitism of powdery mildew mycelium and conidia; reduction of sporulation	Foliar spray timed to early disease development; repeat sprays as needed

Table 2. Microbial Insecticides on Sustainable Agriculture on Target Insect.

Microbial group	Representative agent(s)	Typical target insect group(s)	Mode(s) of action	Common application method(s)
Bacteria	<i>Bacillus thuringiensis</i> (Bt)	Primarily Lepidopteran larvae (caterpillars); some strains active on Diptera and Coleoptera	Ingestion of Cry (and related) toxins; activation in alkaline midgut; binding to receptors and pore formation	Foliar spray targeting early instars; repeat applications due to limited persistence; compatibility with IPM programs



			leading to midgut epithelial disruption and septicemia	
Fungi (entomo-pathogenic)	<i>Beauveria bassiana</i> ; <i>Metarhizium anisopliae</i> ; <i>Lecanicillium</i> spp. (<i>Verticillium lecanii</i>); <i>Paecilomyces</i> spp.; <i>Hirsutella thompsonii</i>	Broad range: whiteflies, aphids, thrips, mites (species dependent), termites, beetles, and some caterpillars	Conidial adhesion to cuticle → germination and direct penetration; proliferation within hemocoel; production of cuticle-degrading enzymes and toxins; host death followed by external sporulation	Foliar spray; soil application against soil-dwelling stages (where relevant); apply in early morning/evening to reduce UV inactivation; best performance under adequate humidity
Viruses	Nucleopolyhedro viruses (NPVs; Helicoverpa NPV, <i>Spodoptera</i> NPV)	Highly host-specific, mainly Lepidopteran larvae	Ingestion of occlusion bodies; dissolution in midgut releases virions; systemic infection and replication; larval liquefaction and release of new occlusion bodies	Foliar spray; apply at early larval instars; often used with UV protectants/stickers to improve persistence
Protozoa / Microsporidia	Microsporidia (<i>Nosema</i> spp.)	Chronic infections in several insect pests (species dependent); often used where long-	Ingestion of spores; infection of gut tissues; reduced feeding, growth, fecundity and	Baiting or foliar application depending on target system; typically integrated with



		term suppression is acceptable	survival (slow acting)	other control measures due to slower action
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3.1.4. Biochemical Pesticides: Biochemical pesticides are naturally occurring compounds that stimulate pest behavior or development rather than exerting direct toxicity. These include insect pheromones used in mating disruption and monitoring, as well as allelochemicals and plant-derived secondary metabolites that interfere with feeding, reproduction, or growth processes. Their specificity and low environmental impact make them valuable components of integrated pest management programs (Table 3).

Table 3. Major Classes of Biochemical Pesticides and their common uses as IPM.

Biochemical pesticide class	Representative examples	Primary use in IPM	Mode of action	Common application
Sex pheromones (semiochemicals)	Species-specific pheromone blends for moths (lepidopteran pests)	Monitoring; mass trapping; mating disruption	Alters mate-finding behaviour via attraction or sensory confusion; reduces successful mating and population growth	Lure-baited traps; dispenser ropes/twist-ties; reservoir dispensers; controlled-release formulations
Aggregation pheromones / attractants	Attractant blends for certain beetles and other insects (species dependent)	Monitoring; attract-and-kill; mass trapping	Increases pest congregation at trap or bait point enabling removal or targeted treatment	Bait stations; lure-and-kill devices; trap crops with attractants (system dependent)
Repellents / antifeedants	Plant-derived deterrents (neem-derived limonoids as feeding deterrents; other terpenoids/phenolics)	Feeding deterrence; crop protection with reduced direct toxicity	Reduces probing/feeding and oviposition through gustatory/olfactory deterrence; may	Foliar sprays; seed/seedling treatments (product dependent); often used



			reduce vector transmission by limiting feeding	with other IPM tactics
Insect growth regulators (IGRs) of natural origin	Juvenile hormone analogs and related growth-disrupting compounds (examples vary by registration)	Population suppression by preventing normal development	Disrupts molting, metamorphosis, or reproduction; typically, slow acting but highly selective	Foliar sprays; larval habitat treatment; baits (depending on pest ecology)
Oviposition deterrents / kairomone-based tools	Host-plant volatiles or blends that deter/attract oviposition (species dependent)	Behavioral manipulation; push–pull strategies	Modifies host selection and egg-laying behavior to reduce infestation pressure	Lures and dispensers; push–pull layouts with repellent + attractant components
Plant defence elicitors (biochemical inducers)	Natural elicitors (chitosan; other elicitor molecules used to trigger plant defences)	Induced resistance; reduced disease/pest susceptibility	Activates plant defence pathways (e.g., SAR/ISR-like responses), increasing resistance rather than directly killing pests	Seed treatment; foliar sprays; soil drenches (crop dependent)

3.1.5. Botanical Pesticides: Botanical pesticides are derived from plant materials and contain bioactive compounds such as alkaloids, terpenoids, flavonoids, and phenolics. Neem-based products, rich in azadirachtin, are among the most widely used examples. These compounds exhibit multiple modes of action, including antifeedant activity, growth inhibition, repellency, and disruption of insect hormonal systems. Their rapid degradation and relatively low toxicity to mammals contribute to their suitability for sustainable agriculture (Victoria *et al.*, 2024; Zainab *et al.*, 2024) (Table 4).



Table 4. Major Botanical Pesticides Bioactive Compounds, Principal Modes of Action, and Typical Target Pests on Sustainable Agriculture.

Botanical Source	Bioactive compound(s)	Mode(s) of action	Typical target pests / use	Common formulation / application
<i>Azadirachta indica</i> (Neem)	Azadirachtin (limonoids), salannin, nimbin	Antifeedant; insect growth regulation (molting disruption); repellency; reduced oviposition and fecundity	Sucking pests (aphids, whiteflies), chewing insects (caterpillars), some mites; broad IPM use	<i>Azadirachta indica</i> seed kernel extract (NSKE); <i>Azadirachta indica</i> oil; azadirachtin-based EC/SC formulations; foliar spray
<i>Chrysanthemum</i> spp.	Pyrethrins (pyrethrin I/II, cinerins, jasmolins)	Neurotoxic action on sodium channels (rapid knockdown); contact insecticidal activity	Wide range of flying and crawling insects; household and crop protection (short residual)	Aerosols/EC formulations; foliar spray; often combined with synergists (product dependent)
<i>Derris</i> spp. / <i>Lonchocarpus</i> spp.	Rotenone	Respiratory inhibition (electron transport chain); contact and stomach action	Historically used against various insect pests; use restricted/limited in many jurisdictions	Dusts/plant extracts; foliar application (where permitted)
<i>Sophora</i> spp.	Matrine, oxymatrine (alkaloids)	Neurophysiological disruption; antifeedant and growth effects (compound dependent)	Aphids, caterpillars, and other pests (regional use patterns)	Botanical extracts/EC; foliar spray
<i>Capsicum</i> spp.	Capsaicinoids	Repellency/irritant effect; feeding deterrence	Repellent sprays against soft-bodied insects and some	Aqueous/ethanolic extracts; foliar



			vertebrate deterrence (context dependent)	sprays (often in mixtures)
<i>Allium sativum</i> (Garlic)	Allicin and sulfur- containing volatiles	Repellent/antifeedant ; antimicrobial activity (context dependent)	Sucking pests; supportive use in organic/IPM programs	Plant extracts; foliar spray
Essential-oil plants (<i>Cymbopogon</i> spp., <i>Eucalyptus</i> spp., <i>Mentha</i> spp.)	Terpenoids (citronellal/citral , eucalyptol, menthol; compound varies)	Repellency; fumigant/contact toxicity; oviposition deterrence	Stored-product insects, mosquitoes, and some crop pests (depending on oil/compound)	Essential-oil formulations (emulsions, sprays); fumigation/space treatment; foliar spray (crop dependent)

3.1.6. Plant-Incorporated Protectants (PIPs): Plant-combined protectants are pesticidal substances formed within genetically modified plants through the expression of specific genes that confer resistance to pests. For instance, crops engineered to express *Bacillus thuringiensis* toxins provide intrinsic protection against certain insect species. While PIPs decrease reliance on external pesticide applications, their deployment is governed by strict regulatory and biosafety requirements (Aioub *et al.*, 2024; Hezakiel *et al.*, 2024; Verma *et al.*, 2024) (Table 5).

Table 5. Plant Incorporated protectants (PIPs) for Sustainable Agriculture.

PIP Trait	Gene Source	Expressed Pesticidal product	Primary target pest group(s)	Representative crop	Stewardship / regulatory notes
Bt insect resistance (Cry proteins)	<i>Bacillus thuringiensis</i>	Cry proteins (Cry1, Cry2; protein type depends on event)	Mainly Lepidopteran larvae (caterpillars); some events	Cotton (Bt cotton); maize/corn (Bt maize); brinjal/eggplant (where approved);	Event-specific biosafety approval; resistance management (refuge strategy, trait



			target Coleoptera	other crops (event dependent)	rotation/stackin g); monitoring for resistance; compliance with labelling/seed stewardship
Bt insect resistance (Vip proteins)	<i>Bacillus thuringiensis</i>	Vegetative insecticidal proteins (Vip)	Lepidopteran pests, often complementa ry to Cry targets	Maize/corn and cotton (stacked traits in some systems)	Often deployed as stacked traits to delay resistance; stewardship like Bt Cry traits
Protease inhibitor- based resistance	Plants (cowpea/other legumes) or microbial sources	Protease inhibitors (trypsin inhibitors)	Chewing insects (larval stages) by reducing protein digestion	Experimental/limi ted commercial use (context dependent)	Requires food/feed safety assessment (allergenicity, digestibility); non-target and beneficial insect risk evaluation
Lectin- based resistance	Plants (snowdrop lectin and other lectins)	Lectins	Some sap- feeding insects (aphids, planthoppers) and chewing pests (variable efficacy)	Primarily research/limited deployment	Heightened food/feed and non-target testing due to potential toxicity; regulatory scrutiny typically higher
RNA interference (RNAi)- based PIPs	Designed dsRNA sequences targeting pest genes	Plant- expressed dsRNA/siR NA targeting	Highly species- specific; depends on target gene and uptake	Emerging traits; approvals and adoption vary by country	Molecular characterizatio n and off-target assessment; environmental fate of dsRNA;



		essential pest gene(s)	biology (commonly insects)		resistance management plans increasingly expected
Disease- resistance PIPs (pathogen- derived proteins)	Viruses/patho- gens (coat protein- mediated resistance)	Pathogen- derived proteins or resistance factors	Plant pathogens (certain viruses)	Papaya ringspot virus-resistant papaya (classic example); other systems as approved	Biosafety assessment for gene flow, non- target effects, and food/feed safety; post- release monitoring as required

4. Production Strategies of Biopesticides

The commercial success of biopesticides depends on efficient production systems that ensure consistent efficacy, stability, and safety. This involves a series of coordinated steps, including microbial cultivation, extraction of active compounds, formulation development, and rigorous quality control.

4.1. Microbial Cultivation and Fermentation: Large-scale cultivation of microorganisms forms the basis of microbial biopesticide production. Industrial production is typically carried out using either submerged (liquid-state) fermentation or solid-state fermentation, depending on the biological appearances of the organism. Critical process parameters such as temperature, pH, aeration, agitation, nutrient availability, and sterility must be carefully regulated to maximize biomass accumulation, sporulation, and metabolite production (Aioub *et al.*, 2024; Hezakiel *et al.*, 2024; Verma *et al.*, 2024; Mascarin *et al.*, 2024). Submerged fermentation is commonly employed for bacterial agents, including *Bacillus thuringiensis*, due to its suitability for controlled and scalable production. In contrast, solid-state fermentation is often preferred for filamentous fungi, where it supports higher spore yields and can be more cost-effective. Transitioning from laboratory-scale production to industrial-scale manufacturing needs cautious optimization of bioreactor design and operating conditions to maintain microbial viability and minimize contamination risks.

4.2. Extraction and Isolation of Bioactive Compounds: Production of biochemical and botanical pesticides includes the extraction and purification of energetic compounds from plant materials or microbial cultures. The optimal of extraction method depends on the



physicochemical properties of the target compound. Common techniques comprise solvent extraction, steam distillation, cold pressing, and supercritical fluid extraction. Among these, supercritical CO₂ extraction has gained attention for its ability to produce high-purity extracts with minimal solvent residues and reduced environmental impact (Victori *et al.*, 2024; Zainab *et al.* 2024). Consequent downstream processing steps such as filtration, centrifugation, concentration, and stabilization are essential to ensure uniformity and preserve biological activity.

4.3. Formulation Development and Stabilization: Formulation is a serious step in improving the practical performance of biopesticides under field conditions. Many biological agents are inherently sensitive to environmental stresses, including ultraviolet radiation, desiccation, and temperature fluctuations. Suitable formulation strategies are therefore required to improve shelf life and maintain efficacy. Common formulation types include wettable powders (WP), water-dispersible granules (WG), suspension concentrates (SC), oil-based formulations, and granular carriers. Progressive approaches, like freeze-drying (lyophilization), microencapsulation, and nano-based delivery systems, have been developed to improve stability, protect active ingredients, and enable controlled release. The incorporation of adjuvants such as surfactants, stickers, and protective polymers further improves adhesion to plant surfaces and prolongs biological activity after application.

4.4. Quality Control and Standardization: Ensuring consistent product quality is essential for the reliability and acceptance of biopesticides. Key quality parameters include viable cell or spore counts (expressed as colony-forming units, CFU), strain purity, absence of contaminants, moisture content, and stability under storage conditions. Bioefficacy against target organisms is also routinely evaluated. Standard analytical and microbiological techniques such as serial dilution plating, microscopic examination, molecular identification, and bioassays are used to verify strain identity and activity. Adherence to Good Manufacturing Practices (GMP) and regular quality audits further strengthen product consistency and regulatory compliance (Kumar *et al.*, 2019). Improvements in fermentation technology, formulation science, and molecular strain development are steadily enhancing the efficiency and reliability of biopesticide production systems. Continued innovation in these areas will be essential to address challenges related to scalability, environmental sensitivity, and product uniformity, thereby supporting the broader adoption of biopesticides in sustainable agriculture.

5. Production Methods and Formulations of Biopesticides

The field performance of biopesticides depends strongly on how effectively the active agents are produced, processed, and formulated. Unlike synthetic pesticides, biological products consist of living organisms or labile bioactive compounds whose stability and efficacy are influenced by environmental conditions, storage, and delivery systems. Accordingly, well-designed production and formulation strategies are essential to maintain viability, extend shelf



life, and ensure reliable performance under field conditions (Copping & Menn, 2020a; Aioub *et al.*, 2024; Hezakiel *et al.*, 2024; Verma *et al.*, 2024; Mascarin *et al.*, 2024).

5.1. Production of Biological Active Agents: Commercial production begins with mass multiplication of the active component, which may include microbial cells, spores, conidia, viral occlusion bodies, or secondary metabolites. Common sources include bacteria such as *Bacillus thuringiensis*, fungi such as *Trichoderma* spp., *Beauveria bassiana*, and *Metarhizium anisopliae*, and viruses such as nucleopolyhedroviruses (NPVs) (Glare *et al.*, 2012; Aioub *et al.*, 2024; Hezakiel *et al.*, 2024; Verma *et al.*, 2024; Mascarin *et al.*, 2024). Efficient production requires careful optimization of growth conditions, including nutrient composition, carbon-to-nitrogen ratio, temperature, pH, aeration, agitation, and dissolved oxygen levels. These parameters directly influence microbial growth dynamics, sporulation, and synthesis of bioactive compounds (Kumar *et al.*, 2019). Suboptimal conditions can lead to reduced viability, poor spore formation, or diminished pathogenicity, ultimately affecting product performance.

5.2. Fermentation Technologies: Industrial-scale production relies primarily on two fermentation approaches, selected based on the biology of the organism and economic considerations.

5.2.1. Solid-State Fermentation: Solid-state fermentation implicates microbial growth on moist solid substrates with imperfect free water. Materials like as rice bran, wheat bran, sorghum, and other agro-industrial residues are commonly used. This approach is particularly suitable for filamentous fungi, as it promotes efficient sporulation and often requires lower capital investment. Its relatively simple infrastructure makes it suitable for decentralized production systems, especially in developing regions (Pandey *et al.*, 2000).

5.2.2. Submerged Fermentation: Submerged fermentation is conducted in liquid media within controlled bioreactors, allowing precise regulation of environmental parameters. This technique is widely used for bacterial agents for instance *Bacillus thuringiensis* and supports large-scale, uniform production. Although it offers better process control and scalability, it generally involves higher operational costs (Glare *et al.*, 2012). In some systems, a combination of submerged and solid-state fermentation is employed to optimize both biomass production and sporulation. Such integrated strategies can improve overall yield and biological activity (Aioub *et al.*, 2024; Hezakiel *et al.*, 2024; Verma *et al.*, 2024; Mascarin *et al.*, 2024).

5.3. Downstream Processing and Stabilization

Following fermentation, the active material must be recovered, concentrated, and stabilized. Common steps include filtration, centrifugation, drying, and blending with suitable carriers. For viral products, purification of occlusion bodies is essential to maintain uniform potency. Drying is a critical step for extending shelf life. Freeze-drying (lyophilization) is effective in



preserving microbial viability but is relatively costly. Spray-drying offers a faster and more economical alternative, although process conditions must be carefully managed to minimize loss of activity (Brar *et al.*, 2006). Stabilization techniques aim to maintain viability and bioefficacy during storage, transport, and application.

5.4. Formulation Technologies

Formulation converts the active biological material into a stable and user-friendly product. It involves combining the active ingredient with carriers and additives that protect against environmental stress and improve delivery to the target organism (Kumar *et al.*, 2023a; Kumar *et al.*, 2023b; Victori *et al.*, 2024; Zainab *et al.*, 2024). A typical formulation includes (i) the active agent, (ii) carrier materials, and (iii) adjuvants like surfactants, stickers, UV protectants, and preservatives.

5.4.1. Solid Formulations: Solid formulations are widely used due to their stability and ease of handling. Common categories include wettable powders, water-dispersible granules, granules, and dusts. These products are typically prepared using carriers for instance talc, peat, lignite, charcoal, clay, or vermiculite, which help maintain moisture and support microbial survival. Talc-based formulations are commonly used for *Trichoderma* and *Pseudomonas* spp. in India due to their cost-effectiveness and availability (Kumar *et al.*, 2019).

5.4.2. Liquid Formulations: Liquid formulations suspend or dissolve the active ingredient in aqueous or oil-based systems. These formulations are increasingly preferred because of their ease of application, compatibility with spraying equipment, and improved field coverage. Examples include suspension concentrates, oil dispersions, emulsifiable concentrates, and aqueous suspensions. To enhance performance, liquid formulations often incorporate emulsifiers, surfactants, humectants, and UV stabilizers. However, they may require more stringent storage conditions to preserve microbial viability and product stability (Brar *et al.*, 2006). Overall, advances in fermentation processes, downstream processing, and formulation technologies have significantly enhanced the reliability and commercial feasibility of biopesticides. Continued revolution in these areas will be serious for overcoming constraints related to environmental sensitivity, shelf life, and large-scale production, thereby facilitating wider adoption in sustainable agricultural systems.

6. Critical Analysis and Interpretation of Biopesticide Use in Sustainable Agriculture

6.1. Field-Level Performance: Sources of Variability: Biopesticides frequently exhibit strong activity under controlled conditions; however, their performance under field environments is often less predictable. Environmental variables including temperature extremes, ultraviolet (UV) radiation, and relative humidity directly stimulus the existence and activity of biological agents. For instance, entomopathogenic fungi require adequate moisture for spore germination and host infection, whereas UV radiation can rapidly decrease propagule



viability (Kumar *et al.*, 2023a; Kumar *et al.*, 2023b; Help *et al.*, 2024; Tonle *et al.*, 2024; Mishra *et al.*, 2020). This environmental sensitivity represents a fundamental limitation. While biodegradability is desirable from an ecological perspective, it also reduces persistence and reliability compared with synthetic pesticides. Consequently, improving stress tolerance through strain selection and enhancing protection via advanced formulations remain key research priorities (Table 6).

Table 6. Field-level Sources of Variability in Biopesticide Performance and Mitigation Strategies through Strain Selection and Formulation Improvements

Field variable / stressor	Typical impact on biopesticide efficacy	Agent/type most affected)	Mitigation and improvement strategies
Temperature extremes (high/low; rapid fluctuations)	Reduced viability and infectivity; slower microbial growth; shorter shelf/field persistence	Entomopathogenic fungi and bacteria; many living microbial formulations	Select heat-/cold-tolerant strains; use protective carriers and stabilizers; optimize storage and transport; apply during cooler hours
Ultraviolet (UV) radiation / intense sunlight	Rapid inactivation of spores, conidia, and occlusion bodies; degradation of sensitive metabolites	Entomopathogenic fungi (conidia); viruses (NPVs); Bt on exposed foliage	Evening/early-morning sprays; UV protectants (lignin, carbon black, optical brighteners) where appropriate; microencapsulation/nano- or polymer coatings; use of stickers/spreaders to improve retention
Relative humidity and leaf wetness duration	Low humidity limits spore germination and infection; high humidity generally improves fungal infection but may increase wash-off risk when combined with rain	Entomopathogenic fungi (<i>Beauveria</i> , <i>Metarhizium</i>)	Time applications to periods of higher humidity; add humectants; use oil-based or water-retentive formulations; irrigation scheduling to extend leaf wetness (where feasible)
Rainfall and irrigation (wash-off)	Physical removal from foliage/soil surface; dilution and	Foliar-applied Bt, fungal conidia,	Avoid spraying before heavy rain; use adjuvants (stickers/spreaders); select granular/soil-directed



	reduced contact with target pest/pathogen	botanicals and semiochemicals	formulations where suitable; controlled-release matrices
Desiccation and low moisture in soil or canopy	Reduced microbial survival and establishment; decreased host contact; slower activity	Soil-applied microbes (rhizosphere antagonists) and foliar fungi under dry conditions	Moist carriers (peat/talc with protectants); microencapsulation; irrigation/soil moisture management; placement near root zone; use of consortia with better rhizosphere competence
Water quality (pH, hardness, chlorine) and tank-mix conditions	Loss of viability/activity during mixing; reduced dispersion and coverage	Microbial suspensions; some metabolites and botanicals	Use clean, non-chlorinated water; adjust pH if required; follow label compatibility guidance; minimize holding time in spray tank; use buffering agents as recommended
Application technology and coverage (droplet size, canopy penetration)	Insufficient deposition and poor contact reduces performance; uneven coverage leads to inconsistent control	Most foliar biopesticides, especially those requiring ingestion/contact	Optimize nozzle type and spray volume; target early pest stages; use spreaders/stickers; integrate with monitoring to improve timing
Biodegradability and inherently short persistence	Need for repeated applications; variable outcomes under fluctuating field conditions	Many botanicals and microbial products on exposed plant surfaces	Controlled-release formulations; protective encapsulation; selection of strains with better field persistence; integrate with IPM (rotation, thresholds, biological control)

6.2. Specificity Versus Operational Flexibility: The high degree of target specificity associated with biopesticides is central to their environmental safety, as it minimizes unintended impacts on beneficial organisms. However, this characteristic may constrain their utility in diversified cropping systems where multiple pests occur simultaneously. In such contexts, farmers often Favor broad-spectrum chemical pesticides that provide rapid and visible control (Isman, 2020; Arthurs, 2019; Kumar *et al.*, 2019; Mishra *et al.*, 2020). This



creates a practical trade-off between ecological selectivity and operational convenience. Current research suggests that combining compatible microbial strains or developing consortia-based formulations can broaden activity while maintaining environmental compatibility (Aioub *et al.*, 2024; Hezakiel *et al.*, 2024; Verma *et al.*, 2024; Mascarín *et al.*, 2024).

6.3. Resistance Dynamics (Opportunities and Caution): Biopesticides are frequently considered advantageous for resistance management due to their complex and multi-modal mechanisms of action. Microbial agents may infect hosts through several pathways, reducing the probability of resistance evolution. Nevertheless, resistance is not entirely absent. Repeated exposure to single-mode agents, such as toxins produced by *Bacillus thuringiensis*, has led to documented cases of resistance in target insect populations (Tabashnik & Carrière, 2017). Accordingly, biopesticides should be viewed as components of integrated resistance management strategies rather than standalone solutions. Rotational use, combination with other control measures, and adherence to integrated pest management (IPM) principles are essential for sustaining long-term efficacy.

6.4. Adoption Constraints and Economic Considerations: Despite clear environmental advantages, adoption of biopesticides remains uneven, particularly among smallholder farmers. Perceived limitations such as slower action, variable efficacy, and shorter shelf life often reduce user confidence. In addition, storage sensitivity and handling requirements may increase management complexity (Help *et al.*, 2024; Tonle *et al.*, 2024; FAO, 2022). From an economic standpoint, while biopesticides may reduce long-term environmental costs, their immediate cost-benefit ratio is not always evident to farmers. Adoption is therefore influenced not only by product performance but also by access to technical knowledge, extension services, and market incentives for residue-free produce.

6.5. Quality Assurance and Product Consistency: A persistent challenge in the biopesticide sector is variability in product quality. Unlike synthetic pesticides with defined chemical compositions, biological products are inherently variable and sensitive to production and storage conditions. Differences in strain quality, viable counts, and contamination levels can significantly affect efficacy (Mishra *et al.*, 2020). This variability underscores the need for robust quality control systems, standardized production protocols, and regulatory oversight. Without consistent product performance, farmer trust and large-scale adoption are likely to remain limited.

6.6. Regulatory Environment and Policy Context: Regulatory frameworks strongly influence the development and commercialization of biopesticides. While safety assessments are essential, complex and time-intensive approval processes can slow innovation and market entry. This is particularly restrictive for small and medium enterprises with limited regulatory capacity (Balog *et al.*, 2021). In India, policy initiatives promoting organic agriculture and



reduced pesticide residues have created a favorable environment for biopesticide adoption. However, regulatory streamlining particularly for low-risk biological products could further accelerate innovation and commercialization.

6.7. Emerging Technologies and Future Directions: Advances in molecular biology, genomics, and formulation science are reshaping the development of biopesticides. Genome-based strain improvement, RNA interference (RNAi)-based approaches, and nano-enabled delivery systems have demonstrated potential to enhance stability, specificity, and persistence under field conditions (Gong *et al.*, 2023; Koeppe *et al.*, 2023; Aioub *et al.*, 2024; Hezakiel *et al.*, 2024). Notwithstanding these advances, the transition from laboratory research to field-scale application remains a major challenge. Safeguarding affordability, scalability, and ease of use will be critical for translating these innovations into practical agricultural solutions.

6.8. Integration Within Agroecological Systems: The long-term value of biopesticides lies in their integration within broader agroecological frameworks rather than their use as direct substitutes for chemical pesticides. Their effectiveness is maximized when combined with crop rotation, resistant cultivars, biological control agents, and precision application strategies (Pretty & Bharucha, 2014). This systems-based approach emphasizes resilience and sustainability, positioning biopesticides as key components of integrated pest management rather than isolated interventions.

6.9. Overall Interpretation: Biopesticides represent an essential element in the transition toward environmentally sustainable agriculture, offering clear advantages in terms of ecological safety and reduced health risks. However, their broader adoption is constrained by challenges related to field performance, product consistency, and user perception. A balanced perspective proposes that biopesticides are maximum effective when integrated with complementary pest management approaches. Future progress will depend on advances in formulation science, regulatory reform, and targeted extension efforts that improve farmer awareness and confidence. Aligning technological innovation with practical field requirements will ultimately determine the role of biopesticides in achieving sustainable and climate-resilient agricultural systems. Improving the stability and field persistence of biopesticides remains a central challenge for their wider adoption. Current advances in formulation science have focused on protecting biologically active agents from environmental stress and improving their delivery efficiency under field conditions (Table 7).



Table 7. Recent Advances in Formulation Strategies to Improve Stability and Field Performance of Biopesticides

Formulation Approach	Description	Benefits	Limitations/Challenges
Microencapsulation	Encapsulation of active agents within polymeric or lipid-based shells	Protects from UV, temperature, and desiccation; controlled release	Higher production cost; scalability issues
Nano formulations	Use of nanoparticles or nano-carriers for delivery of bioactive compounds	Enhanced stability, targeted delivery, improved efficacy	Regulatory concerns; potential environmental risks
Oil-based formulations	Incorporation of biopesticides in vegetable or mineral oils	Improved adhesion and spreading on plant surfaces	May affect compatibility with some crops
Wettable powders	Dry formulations that can be mixed with water before application	Longer shelf life; ease of storage and transport	Dust formation; reduced viability if improperly stored
Emulsifiable concentrates	Liquid formulations forming emulsions in water	Better dispersion and coverage	Stability issues under extreme conditions
Granular formulations	Biopesticides embedded in solid granules for soil application	Targeted soil delivery; reduced drift	Limited use for foliar pests
UV protectants addition	Incorporation of UV-blocking agents (e.g., lignin, dyes)	Reduces degradation from sunlight	May increase formulation complexity and cost
Adjuvants and stickers	Additives that improve adherence	Enhances persistence and effectiveness	Possible phytotoxicity if misused



	and spread ability on plant surfaces		
Controlled-release systems	Slow and sustained release of active ingredients over time	Prolonged activity; reduced frequency of application	Complex formulation design; higher cost

7. Novel and Advanced Formulation Approaches

7.1. Microencapsulation: Microencapsulation has emerged as an actual strategy to improve the stability of biopesticides. In this approach, active agents are enclosed within protective polymeric matrices like alginate or chitosan. These materials shield microbial cells or bioactive compounds from environmental stressors, comprising ultraviolet radiation, desiccation, and temperature fluctuations. Encapsulation also enables gradual and controlled release of the active ingredient, which can prolong activity in the field and reduce the need for repeated applications. Encapsulated formulations frequently exhibit enhanced shelf life and improved viability of microbial propagules during storage and transportation (John *et al.*, 2011). Consequently, microencapsulation helps maintain product quality and supports more reliable performance across diverse environmental conditions.

7.2. Nano-Enabled Formulations: Nanotechnology-based delivery systems are gaining attention for their potential to improve the effectiveness of biopesticides. These systems include nano emulsions, nano capsules, and nanospheres, which enhance dispersion, solubility, and adherence of active ingredients on plant surfaces. Nano-enabled formulations can facilitate controlled and targeted release, increase the bioavailability and persistence of active compounds while reduce the quantity required for effective pest control. Their small particle size allows better interaction with plant surfaces and pest targets, improving overall efficiency. Notwithstanding these advantages, challenges connected to cost, large-scale production, and regulatory acceptance necessity be addressed before widespread adoption. Nevertheless, nano-formulations represent a promising direction for integrating biopesticides into precision agriculture and climate-resilient crop protection systems.

8. Importance of Formulation for Field Performance

Formulation is a critical determinant of the practical success of biopesticides, influencing not only product stability and shelf life but also ease of handling, transport, and field efficacy. Because biological agents are inherently sensitive to environmental stress, the formulation matrix plays a central role in preserving viability and ensuring effective delivery to the target organism (Brar *et al.*, 2006; Mishra *et al.*, 2020). Solid formulations, such as wettable powders



and granules, are generally more stable under ambient storage conditions and do not require refrigeration. This makes them particularly suitable for use in tropical and subtropical regions, where high temperatures and limited cold-chain infrastructure can compromise product quality. Their relatively longer shelf life and lower storage requirements are advantageous for smallholder farming systems (Help *et al.*, 2024; Tonle *et al.*, 2024). In contrast, liquid formulations offer operational advantages, including ease of dilution, uniform application, and compatibility with mechanized spraying equipment. These characteristics support more precise and efficient field application, particularly in large-scale or intensively managed cropping systems. However, liquid products are often more sensitive to storage conditions and may require additional stabilizers to maintain microbial viability over time (Victori *et al.*, 2024; Zainab *et al.*, 2024). In the Indian context, formulation strategies must reconcile performance with affordability and accessibility. Diverse agro-climatic conditions ranging from humid tropics to semi-arid regions necessitate the development of formulations that are resilient to temperature fluctuations and moisture stress. The absence of reliable cold storage in many rural areas further underscores the need for robust, temperature-tolerant products that retain efficacy during transport and storage (FAO, 2022). Recent advances in formulation science, including the use of protective carriers, encapsulation techniques, and improved adjuvant systems, have contributed to enhanced environmental stability and more consistent field performance. Nevertheless, variability in product quality remains a concern, highlighting the importance of standardized manufacturing practices and regulatory oversight. Overall, the effectiveness of biopesticides in real-world conditions is closely linked to formulation quality. Continuous progress in this area supported by rigorous quality assurance systems and context-specific product design will be crucial for improving farmer acceptance and safeguarding the long-term sustainability of biopesticide-based pest management approaches (Table 8).

Table 8. Importance of Formulation in Determining Stability, Handling, and Field Performance of Biopesticides.

Aspect	Solid Formulations (Wettable Powders, Granules)	Liquid Formulations	Implications for Field Performance
Stability & Shelf Life	Generally, more stable; longer shelf life; no refrigeration required	More sensitive to temperature and storage conditions	Affects product reliability and usability over time
Storage Requirements	Suitable for ambient storage; ideal for regions lacking cold-chain infrastructure	Often require stabilizers and controlled storage	Influences accessibility, especially in rural areas



Storage Requirements	Suitable for storage under ambient conditions, making it well suited for areas with limited or no cold-chain facilities	Generally, require the addition of stabilizing agents and appropriate storage conditions to maintain product quality	Plays an important role in determining accessibility in rural settings.
Handling & Transport	Easier to transport; less risk of spillage	Convenient to handle and measure; ready for dilution	Impacts adoption by smallholder vs. large-scale farmers
Application Efficiency	May require proper mixing; risk of uneven dispersion	Easy dilution; uniform application; compatible with sprayers	Determines precision and effectiveness of pest control
Suitability to Climate	More resilient under tropical and subtropical conditions	Performance may decline under extreme heat or storage stress	Critical for regions with diverse agro-climatic conditions
Operational Convenience	Requires additional preparation before application	Ready-to-use or easily mixable	Affects labor requirements and time efficiency
Cost & Accessibility	Generally, more affordable and accessible	May be costlier due to formulation complexity	Influences adoption in smallholder farming systems
Technological Advances	Improved carriers and drying techniques enhance stability	Use of stabilizers, adjuvants, and encapsulation improves performance	Supports consistent efficacy under field conditions
Challenges	Dust formation; potential viability loss if improperly stored	Shorter shelf life; higher sensitivity to environmental factors	Highlights need for improved formulation and quality control
Overall Impact	Reliable under low-resource conditions	Efficient for mechanized and large-scale agriculture	Formulation choice shapes real-world success of biopesticide



9. Regulatory and Registration Processes of Biopesticides in India

The commercialization and adoption of biopesticides in India are highly dependent on a structured regulatory framework that ensures product safety, efficacy, and quality while enabling market access and innovation. Biopesticides in India are presently regulated under the Insecticides Act, 1968, and the Insecticides Rules, 1971, which protect the registration, manufacture, import, sale, transport, distribution, and usage of insecticides, including biological pesticides (Government of India, 1968; Government of India, 1971). Although originally designed for synthetic chemicals, the Act encompasses biopesticides under the broad definition of “insecticides,” applying similar statutory oversight to microbial, biochemical, and botanical products (Figure 3).

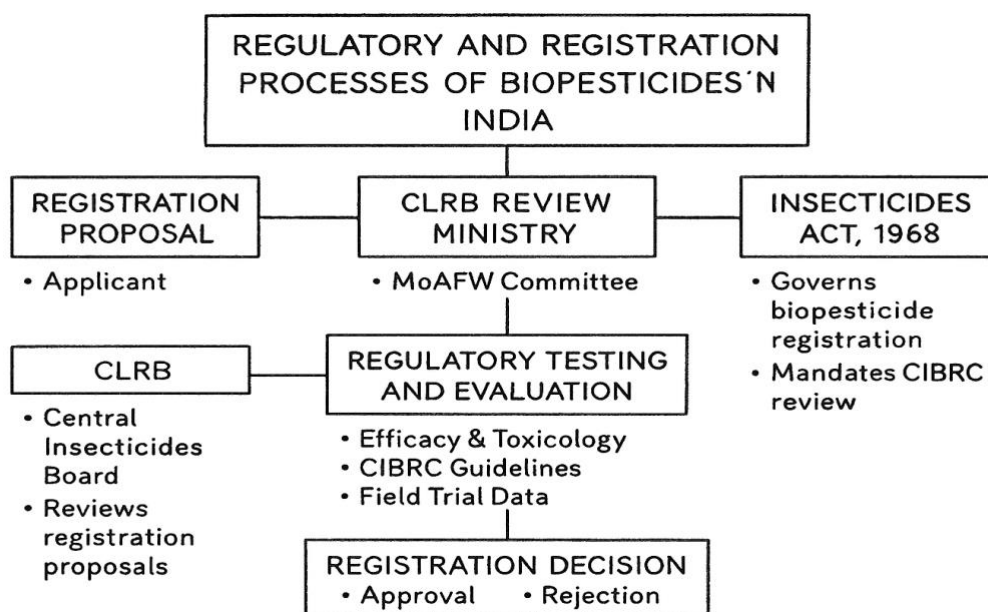


figure 3. Regulatory and registration processes of biopesticides in India.

9.1. Legal and Institutional Framework: The primary regulatory authority is the Central Insecticides Board & Registration Committee (CIBRC) under the Ministry of Agriculture and Farmers Welfare. CIBRC occupies through two interrelated bodies:

- **Central Insecticides Board (CIB):** Provides technical and scientific advice on insecticide safety and regulation.



- **Registration Committee (RC):** Evaluates product dossiers and grants registration based on efficacy, safety, and quality.

Administrative implementation, monitoring of compliance, and maintenance of registered products are handled by the Directorate of Plant Protection, Quarantine & Storage (DPPQS).

9.2. Registration Categories and Data Requirements: Biopesticides might be registered under Section 9 of the Insecticides Act through different pathways:

- **Section 9(3):** Registration of new products not previously approved in India.
- **Section 9(4):** “Me-too” registration for products similar to existing ones.
- **Section 9(3B):** Provisional, time-bound registration pending complete data submission.

Applicants must submit a detailed dossier comprising:

- **Product Chemistry and Composition:** Identification of microbial strains, source, production process, formulation type, and quality specifications, with molecular characterization increasingly required for genetic stability and traceability (CIBRC, 2024a).
- **Efficacy Data:** Multi-location field trials demonstrating activity against target pests under relevant agro-climatic conditions, following approved protocols (FAO & WHO, 2016).
- **Toxicological and Ecotoxicological Data:** Safety data comprising acute toxicity, pathogenicity, allergenicity, and influence on non-target organisms such as pollinators, natural enemies, birds, and soil microbiota.
- **Shelf-Life and Stability Studies:** Viable cell counts, spore viability, contaminant limits, and storage stability.
- **Label and Packaging Compliance:** Clear instructions on dosage, target pests, precautions, storage, and hazard classification.

9.3. Evaluation and Approval Process: Dossiers are evaluated by the Registration Committee, with expert review of toxicology, bioefficacy, and environmental risk. Applicants are asked for clarification or additional data as needed. Upon approval, products are assigned a unique registration number and listed in the official register maintained by DPPQS (CIBRC, 2024a, 2024b). Post-registration monitoring ensures adherence to quality standards, with state authorities empowered to conduct random sampling and enforce compliance.

9.4. Challenges in the Regulatory Landscape: Despite its structured framework, India’s biopesticide regulation faces several challenges:

- **Lengthy Approval Timelines:** Multi-stage dossier review and sequential expert consultations can extend over years, increasing costs and discouraging SMEs and startups from innovation (Keswani *et al.*, 2019, Mishra *et al.*, 2020, Meshram *et al.*, 2022, Biswas & Chakraborty, 2022).



- **Data Requirements Modelled on Chemical Pesticides:** Many regulatory tests are designed for synthetic pesticides, imposing disproportionate requirements on low-risk microbial and botanical products (Glare *et al.*, 2012).
- **Institutional Coordination Delays:** Multiple authorities are involved, and inconsistent interpretation at state levels can slow approval.
- **Quality Variability and Market Surveillance:** Maintaining viable microbial counts and preventing contamination remains challenging, risking substandard products and reduced farmer confidence.

9.5. Proposed Reforms and Policy Innovations: To address these challenges, several reforms have been suggested:

- **Risk-Based Evaluation Systems:** Tiered, hazard-based assessment proportionate to product risk can reduce redundant testing for low-risk biopesticides (FAO & WHO, 2021).
- **Fast-Track and Accelerated Pathways:** Conditional or provisional approvals for well-documented, globally used microbial strains can expedite market entry.
- **International Harmonization:** Alignment with FAO/WHO standards facilitates mutual recognition of test data and improves export potential.
- **Digitalization and Transparency:** Online dossier submission, tracking, and standardized timelines enhance predictability.
- **Capacity Building and Laboratory Strengthening:** Investment in molecular diagnostics, residue testing, and microbial identification tools supports post-registration quality control and risk assessment.

9.6. Post-Registration Compliance and Surveillance: Approved biopesticides must meet statutory labelling, packaging, and quality criteria. Periodic sampling by state laboratories verifies microbial counts, active ingredient content, and absence of contaminants. Surveillance also monitors resistance development and environmental impact. Farmer feedback and extension services are critical to adaptive regulatory governance.

9.7. Impact of Regulatory Reform on Adoption: Regulatory policy plays a decisive role in biopesticide adoption. While safety evaluations are essential, excessive bureaucratic delays and disproportionate testing requirements may slow access to low-risk alternatives. Science-based, streamlined, and transparent regulation, coupled with farmer awareness programs, can enhance market confidence, accelerate adoption, and support sustainable, climate-resilient, and residue-free agriculture in India.

10. Field Application Strategies in Indian Agriculture

The effectiveness of biopesticides in Indian agriculture depends not only on product quality and regulatory approval but also on strategically designed field application approaches that maximize efficacy under diverse agroecological conditions (Figure 4). India's varied climatic zones, cropping systems, and prevalence of smallholder farms necessitate application strategies



tailored to crop type, pest complex, environmental conditions, and integration with Integrated Pest Management (IPM) frameworks. Optimized application enhances pest suppression, improves cost-effectiveness, and minimizes unintended ecological impacts (Kumar *et al.*, 2019; Help *et al.*, 2024; Tonle *et al.*, 2024).

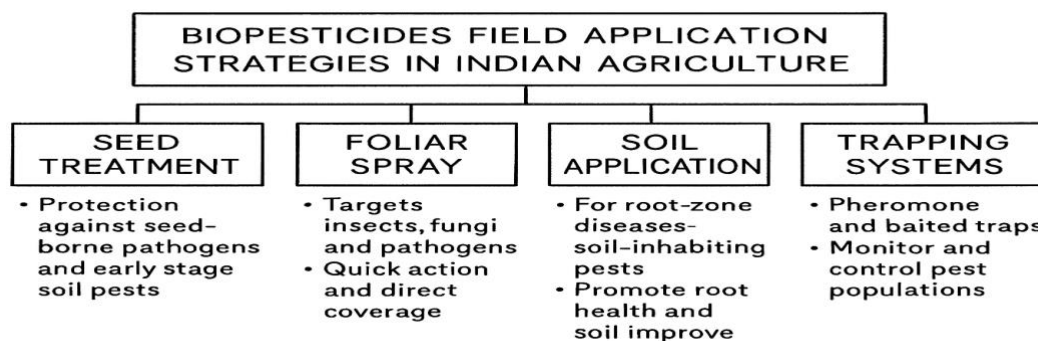


Figure 4. Field application strategies of biopesticides in Indian agriculture.

10.1. Targeted Application Timing and Pest Biology

Synchronizing biopesticide application with pest life cycles is critical for effective pest control. Unlike broad-spectrum chemical pesticides, many biopesticides require ingestion, cuticular contact, or favorable environmental conditions for optimal activity. Application timing should therefore coincide with the most vulnerable developmental stages of the pest, typically early larval or nymphal instars (Copping & Menn, 2020a; 2020b). For example, *Bacillus thuringiensis* (Bt) formulations are most effective against early instars of lepidopteran larvae, as the Cry toxins must be ingested to disrupt midgut epithelial cells. Delayed application reduces mortality rates significantly. Correspondingly, entomopathogenic fungi for instance *Beauveria bassiana* and *Metarhizium anisopliae* penetrate insect cuticles and perform best underneath moderate temperatures and high humidity. Applications are therefore recommended in early morning or late evening to decrease UV-induced degradation and desiccation stress (Glare *et al.*, 2012). Regular pest scouting, pheromone trapping, and phenological monitoring support precise timing, while decision-support systems and forecasting models further enhance application efficiency across India's agro-climatic zones.

10.2. Application Methods and Delivery Systems: The choice of delivery method strongly influences field performance. Common application approaches in Indian agriculture include:

- **Foliar sprays:** Applied to manage insect pests and fungal diseases affecting above-ground plant parts. Common formulations include *Bacillus thuringiensis* (Bt), entomopathogenic fungi, and plant-based extracts.



- **Seed treatment:** Seeds are treated with useful microorganisms such as *Trichoderma* spp. or *Pseudomonas fluorescens* to protect emerging seedlings from soil-borne pathogens and support healthy crop establishment.
- **Soil application/drenching:** Biological agents are incorporated into the soil or applied as drenches to suppress root-infecting pathogens and control soil-dwelling insect pests.
- **Root dipping:** Applied to transplanted crops (rice, vegetables) to promote beneficial rhizosphere colonization. Seedlings of transplanted crops, including rice and vegetables, are immersed in suspensions containing beneficial microorganisms before planting to enhance rhizosphere colonization and improve plant health.

Optimizing droplet size, uniform coverage, and compatibility with mechanized sprayers enhances delivery efficiency. The inclusion of stickers, spreaders, and UV-protectants improves persistence on plant surfaces and efficacy (Bashan *et al.*, 2014; O'Callaghan, 2016; Kumar *et al.*, 2019; AArthurs, 2019; Mishra *et al.*, 2020; Cardarelli *et al.*, 2022; Vega *et al.*, 2009; Ayilara *et al.*, 2023).

10.3. Integration with Integrated Pest Management (IPM): Biopesticides achieve maximal impact when used within IPM systems rather than as standalone interventions. Integration with cultural practices (crop rotation, resistant varieties, sanitation), mechanical controls (light traps, pheromone traps), and conservation of natural enemies enhances long-term pest suppression (Help *et al.*, 2024; Tonle *et al.*, 2024). In systems such as rice-wheat, cotton, and vegetable rotations, biopesticides reduce chemical pesticide dependency, delay resistance development, and complement selective chemical applications.

10.4. Environmental Considerations and Climatic Adaptation: Environmental factors strongly affect biopesticide performance. High temperatures, intense solar radiation, and low humidity in many Indian regions can reduce microbial viability. Application strategies should therefore consider:

- Spraying during cooler parts of the day.
- Avoiding application prior to heavy rainfall.
- Using formulations with UV protection, encapsulation, or stress tolerance.
- Developing region-specific guidelines reflecting agro-climatic diversity from humid coastal zones to arid interiors.

10.5. Farmer Training and Extension Support: Farmer awareness and technical capacity are essential for effective biopesticide use. Slow or less visible action compared to chemical pesticides can reduce confidence if expectations are not managed. Structured extension programs, field demonstrations, and participatory training initiatives significantly improve adoption (Arthurs, 2019; Kumar *et al.*, 2019; Mishra *et al.*, 2020). Training should emphasize correct dosage, storage, application timing, compatibility with other agrochemicals, and pest



threshold recognition. Mobile advisory platforms and digital alerts offer emerging support for timely, data-driven applications.

10.6. Precision Agriculture and Emerging Technologies: Precision agriculture technologies can further enhance field-level performance. Remote sensing, drone-assisted spraying, and spatial pest surveillance enable site-specific applications, reducing chemical use, minimizing environmental exposure, and improving uniform coverage (FAO, 2021a; 2021b). Integration of these tools with biopesticides supports resource-efficient, climate-resilient, and environmentally sustainable crop protection strategies. Overall, effective field application in India requires coordination across biological, environmental, technological, and socio-economic factors. When aligned with IPM, tailored delivery methods, climatic variation, and farmer training, biopesticides can substantially contribute to sustainable and resilient agricultural systems.

11. Field Application Strategies in Sustainable Agriculture

The effective deployment of biopesticides in Indian agriculture necessitates careful consideration of formulation, delivery methods, environmental conditions, and integration within Integrated Pest Management (IPM) systems. Tailored field approaches optimize biological stability, pest contact, and persistence, ensuring effective pest suppression while minimizing environmental disruption (Segers & Lebeer, 2014; Copping & Menn, 2020b; Copping & Menn, 2000; Kumar *et al.*, 2019).

11.1. Appropriate Formulation and Delivery Methods: Selecting suitable formulations and delivery systems is essential for maintaining biopesticide viability under field conditions. Biopesticides are sensitive to UV radiation, desiccation, and temperature fluctuations; therefore, application methods must align with pest ecology, crop phenology, and agro-climatic conditions. Common methods in India include:

11.1.1. Foliar Sprays: Liquid biopesticide formulations, comprising suspension concentrates (SC), oil dispersions (OD), and aqueous emulsions, are sprayed directly onto plant foliage using knapsack, compression, or motorized sprayers. Effective pest management depends on uniform spray coverage, appropriate nozzle selection, and suitable spray volume to ensure adequate deposition on target surfaces. While smaller droplets can improve leaf coverage and pest contact, their use should be carefully managed to minimize spray drift. Applications carried out during the early morning, or late evening are generally preferred, as these conditions reduce ultraviolet degradation and support the persistence and effectiveness of microbial agents (Kumar *et al.*, 2019).

11.1.2. Seed Treatment: Beneficial microbial agents, including *Trichoderma* spp. and *Pseudomonas fluorescens*, are commonly applied to seeds to protect young seedlings from soil-



borne diseases during the initial stages of crop growth. Methods such as slurry coating, film coating, and encapsulation facilitate effective microbial establishment in the rhizosphere, promote vigorous seedling development, and provide targeted protection while minimizing environmental contamination compared with broad-spectrum field applications (Bashan *et al.*, 2014; O'Callaghan, 2016; Kumar *et al.*, 2019).

11.1.3. Soil Application: Granular formulations, wettable powders, and liquid suspensions are commonly incorporated into the soil or applied as drenches around the root zone to manage soil-borne pathogens and root-feeding pests. This technique facilitates the establishment and persistence of valuable microorganisms in the soil environment, enhancing their ability to suppress pathogenic organisms through competition and supporting the activation of plant defense mechanisms, including induced systemic resistance (Glare *et al.*, 2012).

11.1.4. Root Dip and Nursery Treatments: In transplanted crops, including rice, vegetables, and various horticultural species, seedling roots are treated with suspensions containing beneficial microorganisms prior to transplanting. This practice encourages rapid establishment of beneficial microbes in the rhizosphere, providing early protection against root-associated diseases and promoting healthy plant growth. The method is especially suitable for high-value crops, as it delivers targeted protection while reducing the frequency of subsequent applications. Effective results depend on selecting appropriate formulations and application methods that correspond with the crop growth stage and the biology of the target pest or pathogen.

11.2. Integration with Integrated Pest Management (IPM): Biopesticides achieve their maximum impact when incorporated into IPM frameworks. In Indian systems, IPM integration includes:

Cultural Practices: Crop rotation, intercropping, sanitation, and resistant varieties reduce initial pest pressure and limit conditions favorable to pest proliferation (Gundredd *et al.*, 2024; Help *et al.*, 2024; Tonle *et al.*, 2024)

- **Mechanical and Monitoring Tools:** Pheromone traps, light traps, and sticky traps enable threshold-based decision-making and reduce unnecessary applications (Kumar *et al.*, 2019).
- **Biological Control Integration:** Compatibility with natural enemies, including predators and parasitoids, supports multi-tiered pest suppression without ecological disruption (Glare *et al.*, 2012).

Rotational use of biopesticides with selective chemical pesticides mitigates resistance development and prolongs the efficacy of pest management programs. Integration reduces chemical load, enhances biodiversity, and promotes agroecosystem resilience.



11.3. Training, Demonstrations, and Farmer Awareness: Farmer knowledge and technical capacity strongly influence biopesticide performance. Misconceptions about slower action or reduced efficacy relative to synthetic pesticides can hinder adoption. Effective strategies include:

- On-farm demonstrations and field days showcasing comparative performance.
- Capacity-building programs through State Agricultural Universities and Krishi Vigyan Kendras (KVKs).
- Preparation of localized extension materials detailing dosage, compatibility, and safety precautions.

Public-private partnerships to strengthen last-mile delivery and technical support (Arthurs, 2019; Kumar *et al.*, 2019; Mishra *et al.*, 2020).

Enhanced extension networks increase confidence and promote correct usage, thereby improving adoption rates and sustainability.

11.4. Consideration of Environmental Conditions: Biopesticide activity is influenced by environmental variables including temperature, humidity, rainfall, and solar radiation. Field strategies must address these constraints:

- Apply microbial formulations during cooler periods (early morning or late evening) to reduce UV degradation.
- Avoid application prior to heavy rainfall to minimize wash-off losses.
- Use formulations with UV protectants or encapsulation for stress-prone regions, particularly arid and semi-arid zones (Victori *et al.*, 2024, Zainab *et al.*, 2024).
- Develop region-specific agro-advisories incorporating seasonal climate variability to improve scheduling accuracy.

11.5. Use of Decision Support and Digital Tools: Digital agriculture tools and decision-support systems enhance precision in biopesticide applications. Integration of pest forecasting models, remote sensing, and local weather data enables threshold-based interventions, reducing unnecessary pesticide use (FAO, 2021a; Help *et al.*, 2024; Tonle *et al.*, 2024). Pilot projects in India demonstrate that mobile advisories, automated pheromone traps, and drone-assisted spraying improve pest prediction accuracy, optimize input use, and ensure uniform coverage in large-scale cropping systems. Overall, field-level success of biopesticides in India requires harmonization of formulation, application timing, IPM integration, environmental adaptation, farmer training, and digital support systems. Collectively, these measures enhance efficacy, sustainability, and climate resilience of crop protection strategies.



12. Challenges, Opportunities, and Future Perspectives of Biopesticides in India

The adoption of biopesticides in Indian agriculture represents a key pathway toward environmentally sustainable and climate-resilient crop protection. Despite their ecological and health advantages, adoption remains constrained by technical, structural, and institutional barriers. At the same time, innovations in microbial technology, supportive policy frameworks, and evolving market dynamics provide significant opportunities for growth. A nuanced understanding of these interacting factors is critical for researchers, policymakers, industry actors, and farming communities (Glare *et al.*, 2012; Help *et al.*, 2024; Tonle *et al.*, 2024).

12.1. Challenges

12.1.1. Limited Awareness and Technical Knowledge: One of the most significant barriers is inadequate farmer understanding of biopesticide mechanisms, application timing, and storage requirements. Unlike synthetic pesticides that provide rapid knockdown effects, biopesticides operate through infection, competition, or induced systemic resistance, requiring precise timing aligned with pest life stages. Misalignment reduces efficacy and undermines farmer confidence. Weak extension services and insufficient on-farm demonstrations exacerbate misconceptions, particularly among smallholders in remote regions (Arthurs, 2019; Kumar *et al.*, 2019; Mishra *et al.*, 2020).

12.1.2. Quality Control and Standardization: Sustaining consistent product quality is a persistent constraint. Microbial formulations are delicate to environmental stresses such as temperature, humidity, and ultraviolet radiation, which can decline viable colony-forming units (CFUs) during storage and transport. Variability in microbial counts, contamination risks, and inadequate cold-chain infrastructure compromise field performance. Unlike synthetic chemicals with uniform active ingredient content, biopesticides require stringent monitoring of viability, purity, and shelf-life parameters. Establishing robust standardization protocols and strengthening laboratory testing capacity is therefore essential (Glare *et al.*, 2012).

12.1.3. Regulatory and Institutional Barriers: India regulates biopesticides under the Insecticides Act, 1968, and accompanying rules, nevertheless the registration process is often perceived as time-consuming and resource intensive. Data requirements modelled on synthetic pesticides impose disproportionate burdens on low-risk biological products. Small and medium enterprises (SMEs), which form a large share of the sector, face financial and technical constraints in meeting extensive dossier requirements. Streamlining regulatory pathways through risk-based assessment frameworks could enhance innovation and diversify the market (Keswani *et al.*, 2019; Mishra *et al.*, 2020; Meshram *et al.*, 2022; Biswas & Chakraborty, 2022).



12.1.4. Economic Constraints and Market Competitiveness: The production of microbial biopesticides involves fermentation, downstream processing, formulation stabilization, and quality assurance, increasing manufacturing costs. Consequently, biopesticides often appear less economically attractive in price-sensitive markets dominated by inexpensive chemical pesticides (Marrone, 2019). Limited retail penetration in rural areas, fragmented distribution networks, and inconsistent demand forecasting further constrain market growth. Addressing these supply chain inefficiencies is critical for scaling adoption.

12.2. Opportunities

12.2.1. Supportive Policy Environment: India's policy emphasis on sustainable agriculture, natural farming, and residue-free produce provides fertile ground for biopesticide expansion. Government-led initiatives for organic certification, national biocontrol programs, and capacity-building initiatives strengthen awareness, technical expertise, and infrastructure for biological crop protection (Help *et al.*, 2024; Tonle *et al.*, 2024).

12.2.2. Technological Innovations: Advances in molecular biology, genomics, and formulation technology enhance biopesticide efficacy and stability. Marker-assisted strain selection, genome editing, and omics-based screening allow identification of highly virulent and environmentally tolerant microbial strains (Marrone, 2019). Nano inventions and microencapsulation shield energetic ingredients from environmental degradation and enable controlled release, refining persistence under field conditions. Precision agriculture apparatuses, including pest forecasting models, GIS, and remote sensing, facilitate site-specific application, optimizing input use and ecological safety (FAO, 2021a; 2021b; Victori *et al.*, 2024, Zainab *et al.* 2024).

12.2.3. Growing Market Demand for Residue-Free Produce: Increasing consumer awareness and stringent international Maximum Residue Limits (MRLs) are driving demand for safer crop protection solutions. Export-oriented sectors such as fruits, vegetables, spices, and tea increasingly require low-residue pest management systems. Biopesticides facilitate compliance with regulatory standards while maintaining environmental safety, offering a competitive advantage for Indian agriculture.

12.2.4. Public–Private Partnerships and Research Collaboration: Collaborative frameworks between universities, research institutes, government agencies, and private biotechnology firms accelerate product development and field validation. Extension partnerships through Krishi Vigyan Kendras (KVKs) provide contextualized advisory support to farmers, bridging laboratory research and on-farm adoption.

12.2.5. Tailored Regulatory Reforms: Risk-based regulatory frameworks that differentiate low-risk biological products from conventional pesticides could reduce redundant data



requirements and accelerate approvals. Harmonization with international guidelines from FAO and WHO facilitates mutual recognition agreements and enhances global trade competitiveness. Fast-track approvals for novel microbial strains would encourage private sector investment (FAO & WHO, 2021).

12.2.6. Enhanced Quality Assurance Systems: Establishing regional quality-testing laboratories and enforcing microbial viability and contamination thresholds strengthens farmer trust. Post-market surveillance, coupled with traceability frameworks, is essential to eliminate substandard or counterfeit products from supply chains.

12.2.7. Farmer-Centric Capacity Building: Participatory extension strategies, demonstration plots, mobile-based pest alerts, and digital advisory platforms tailored to local cropping systems improve farmer confidence. Experiential learning enhances proper handling, storage, and application practices, contributing to sustainable adoption (Arthurs, 2019; Kumar *et al.*, 2019; Mishra *et al.*, 2020).

12.2.8. Integration with Climate-Resilient Agriculture:

Climate change is altering pest distribution, phenology, and outbreak intensity. Biopesticides, due to their environmental compatibility and reduced non-target impacts, are well-suited for climate-resilient IPM systems. Incorporation into diversified agroecosystems supports biodiversity, soil health, and long-term ecological stability (Glare *et al.*, 2012).

12.3. Global Regulatory Perspectives

Globally, biopesticides are often subject to differentiated evaluation. The US Environmental Protection Agency (EPA) categorizes biopesticides into microbial pesticides, biochemical pesticides, and plant-incorporated protectants (PIPs), applying specialized guidance and expedited review processes due to favorable safety profiles (EPA, 2023; USEPA, 2023). Similarly, the European Union under Regulation (EC) No 1107/2009 adopts low-risk criteria for biologically active substances. India can benefit from adopting science-based, risk-proportionate regulatory frameworks to accelerate innovation and strengthen global competitiveness in the biopesticide sector.

13. Next-Generation Applications of Biopesticides in Indian Agriculture

The appearance of pest resistance, climate variability, and increasing consumer demand for residue-free agricultural produce has accelerated research into next-generation biopesticide applications (Table 9 and Figure 5). Innovations in formulation science, microbial genomics, precision agriculture, and enabling policy frameworks are creating new avenues to enhance efficacy, sustainability, and adoption of biopesticides in India (Victori *et al.*, 2024; Zainab *et al.*, 2024).



Table 9. Next-Generation Applications of Biopesticides in Indian Agriculture.

Application Area	Technologies/Approaches	Major Benefits	Relevance to Indian Agriculture
Advanced Formulation Technologies	Nano-encapsulation, microencapsulation, slow-release carriers, UV protectants, adjuvants	Improved stability, extended shelf life, enhanced field persistence, reduced applications	Suitable for semi-arid and high-temperature regions; improves consistency under variable climates
Genomics-Assisted Biopesticides	Whole-genome sequencing, metagenomics, CRISPR-based genome editing	Enhanced virulence, stress tolerance, host specificity; reduced non-target effects	Supports development of robust strains adapted to local agro-ecological conditions
Precision Agriculture Integration	Remote sensing, drones, IoT sensors, predictive pest modeling	Site-specific application, reduced input costs, improved efficiency, minimal environmental impact	Effective in diverse systems (rice–wheat, cotton, horticulture); improves resource use efficiency
Synergistic & Integrated Approaches	Combination with biofertilizers, PGPR, mycorrhizae; AI-based advisory systems	Multi-functional benefits (plant health + pest control), improved resilience, informed decision-making	Promotes adoption among smallholders; supports climate-resilient and sustainable farming systems

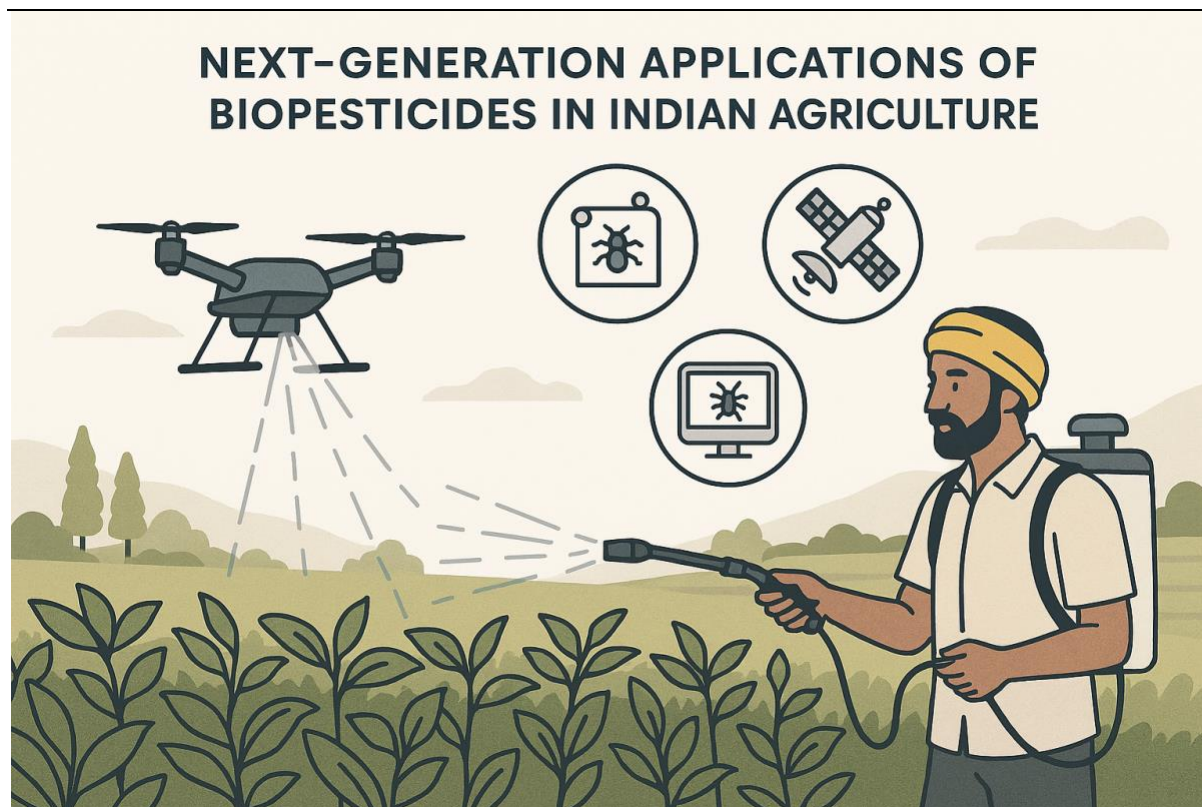


Figure 5. Next-generation applications of biopesticides for promoting sustainable development in the Indian agricultural system.

13.1. Advanced Formulation Technologies: Next-generation formulations aim to improve microbial survival, stability, and field persistence. Techniques such as nano-encapsulation, microencapsulation, and slow-release carriers protect bioactive compounds from ultraviolet radiation, temperature fluctuations, and desiccation. These technologies extend shelf life, reduce the need for frequent applications, and enhance performance under diverse agro-climatic conditions, particularly in semi-arid and high-temperature regions of India (Victori *et al.*, 2024; Zainab *et al.*, 2024). In addition, incorporation of adjuvants, UV protectants, and hygroscopic carriers further improves deposition on plant surfaces and microbial efficacy against target pests.

13.2. Genomics-Assisted Biopesticides: Developments in genomics are transforming biopesticide development. Whole-genome sequencing, metagenomics, and CRISPR-based genome editing enable the identification and engineering of biological strains with improved virulence, stress tolerance, and host specificity. For instance, *Bacillus thuringiensis* (Bt) strains can be optimized to broaden the insecticidal spectrum or improve Cry protein stability, while entomopathogenic fungi such as *Beauveria bassiana* can be engineered for greater tolerance to



heat, desiccation, or ultraviolet stress. Genomics-assisted strain selection also ensures compatibility with Integrated Pest Management (IPM) systems, reducing non-target impacts and sustaining ecological balance (Marrone, 2019; Aioub *et al.*, 2024; Hezakiel *et al.*, 2024).

13.3. Integration with Precision Agriculture: Precision agriculture apparatuses offer significant opportunities to optimize biopesticide application. Remote sensing, drone-assisted spraying, IoT-enabled soil and pest sensors, and predictive pest modeling allow site-specific and time-specific interventions. These approaches reduce chemical inputs, enhance coverage uniformity, and minimize off-target environmental exposure. In heterogeneous cropping systems such as rice-wheat rotations, cotton, and high-value horticultural crops, precision-guided biopesticide application improves cost-effectiveness, reduces wastage, and supports climate-resilient pest management strategies (FAO, 2021a; 2021b; Victori *et al.*, 2024; Zainab *et al.* 2024; Chauhan *et al.*, 2024).

13.4. Synergistic Approaches and Future Directions: Next-generation biopesticides are increasingly being integrated with other biological products, including biofertilizers, plant growth-promoting rhizobacteria, and mycorrhizal fungi, creating multi-functional formulations that simultaneously enhance plant health and pest resistance. Furthermore, AI-driven predictive models and digital advisory platforms can support farmer decision-making, enabling adaptive management of pests under variable climatic conditions. Such integrative approaches are likely to drive adoption in smallholder systems while dropping reliance on chemical pesticides, fostering sustainable and resilient agricultural practices across India (Victori *et al.*, 2024; Zainab *et al.* 2024).

14. Policy and Market Opportunities

Policy frameworks and market dynamics play a critical responsibility in promoting the adoption and commercialization of biopesticides (Figure 6). Strategic interventions that address regulatory, economic, and capacity-building dimensions can catalyse growth while ensuring sustainable and climate-resilient agricultural practices.



Figure 6. Systemic diagram of policy and market opportunities for biopesticides.

14.1. Incentive Structures: Targeted policy measures, including fiscal incentives, subsidies for biopesticide production, and fast-track approval processes for low-risk biological products, can significantly reduce barriers to entry for startups and small-scale enterprises. Certification schemes and quality standards for high-performance biopesticide formulations further encourage industry investment and innovation. Such measures can accelerate commercialization, promote domestic manufacturing, and enhance competitiveness in global markets (Mishra *et al.*, 2020; Meshram *et al.*, 2022; Biswas & Chakraborty, 2022). In addition, policies supporting research grants and tax rebates for environmentally sustainable crop protection technologies would strengthen the innovation ecosystem.

14.2. Export Potential: India's rich biodiversity and diverse agro-ecosystems provide a competitive advantage for the development of indigenous microbial and plant-based biopesticides. Rising global demand for residue-free, sustainable agricultural products presents opportunities for Indian biopesticides to gain international market share. Locally adapted microbial strains and botanical extracts can be positioned as high-value exports, catering to stringent maximum residue limit (MRL) standards in developed markets, thereby enhancing India's presence in the global biopesticide sector (Marrone, 2019; Custom Market Insights,



2024). Establishing robust quality assurance and traceability frameworks will be crucial to meeting international certification and regulatory requirements.

14.3. Training and Extension Services: The effectiveness of next generation biopesticides relies on farmer knowledge, technical capacity, and informed application practices. Comprehensive training programs, on-farm demonstrations, digital advisory platforms, and interactive learning modules help farmers and extension workers understand product benefits, application timing, dosages, and integration with Integrated Pest Management (IPM) approaches. Participatory approaches, including region-specific modules and hands-on workshops, enhance adoption, build confidence, and reduce misuse, particularly in smallholder-dominated landscapes (Arthurs, 2019; Kumar *et al.*, 2019; Mishra *et al.*, 2020; Bashan *et al.*, 2014; O’Callaghan, 2016).

14.4. Research–Industry Collaborations: Public–private partnerships between agricultural universities, research institutes, and biopesticide companies facilitate the translation of laboratory innovations into field-ready solutions. Collaborative frameworks support strain improvement, advanced formulation development, field validation, and commercialization tailored to regional cropping systems. These linkages accelerate innovation cycles, reduce technical risks, and ensure that products are scalable and context-specific, ultimately fostering sustainable pest management (Glare *et al.*, 2012; Victori *et al.*, 2024; Zainab *et al.*, 2024).

14.5. Strategic Outlook: The next generation of biopesticides in India is positioned to integrate technological innovation, supportive policy environments, and farmer-centric approaches. Convergence of advanced formulations, genomics-assisted microbial strains, precision delivery systems, and robust regulatory and market mechanisms can establish biopesticides as mainstream tools for sustainable crop protection. When coupled with climate-resilient IPM strategies and capacity-building initiatives, these interventions hold the potential to reduce chemical pesticide dependence, promote biodiversity, and support residue-free agricultural exports.

15. Conclusions

Biopesticides represent a transformative approach for advancing sustainable agriculture in India, offering targeted pest control while minimizing environmental contamination and conserving biodiversity. As living organisms or biologically active compounds, they provide specificity against pests, exhibit low toxicity to non-target organisms, and naturally degrade in soil and water, thereby reducing chemical residues in agroecosystems. In India, the biopesticide sector is gradually expanding under supportive policy frameworks that promote organic farming, integrated pest management (IPM), and residue-free crop production. Despite this growth, their overall market share remains limited, highlighting substantial potential for scaling adoption. The production and commercialization of biopesticides increasingly rely on



sophisticated microbial fermentation techniques and advanced formulation strategies, such as solid-state and submerged fermentation, microencapsulation, and nano-carrier systems, to maintain viability, stability, and efficacy under diverse agro-climatic conditions. Ensuring consistent quality, including adequate microbial counts, absence of contaminants, and extended shelf life, is essential for predictable field performance. Regulatory oversight provides structured pathways for product registration, efficacy validation, and environmental safety, ensuring both human health and ecological protection.

Effective field application strategies are crucial for realizing the benefits of biopesticides. Synchronizing applications with pest life cycles, selecting appropriate delivery methods such as foliar sprays, seed treatments, soil applications, or root dipping and integrating biopesticides into IPM programs enhance efficacy and sustainability. Environmental factors, including temperature, humidity, and ultraviolet radiation, must be carefully managed to prevent biological degradation. The adoption of decision-support tools, predictive models, and precision agriculture technologies further refines application timing and targeting, optimizing pest control while minimizing input waste. Farmer engagement is equally important. Structured training programs, on-farm demonstrations, and participatory extension initiatives are vital for building technical knowledge, confidence, and adoption of biopesticide technologies. Addressing adoption barriers requires coordinated efforts across research and development, quality assurance, regulatory frameworks, market support, and capacity-building initiatives. Despite these challenges, emerging opportunities provide a strong foundation for growth. Innovations in genomics, formulation science, controlled-release systems, and precision delivery are enhancing product performance, stability, and field efficacy. Supportive policy measures, coupled with rising consumer demand for residue-free produce, create favorable conditions for market expansion. Establishing decentralized production systems, risk-based regulatory frameworks tailored to low-risk biopesticides, and robust quality-testing infrastructure will accelerate commercialization and market penetration. Integration with climate-resilient agricultural practices ensures adaptability under changing environmental conditions, while collaborative research and public-private partnerships facilitate the translation of laboratory advances into scalable, field-ready solutions. In summary, biopesticides offer scientifically validated, environmentally sustainable, and economically viable alternatives to conventional chemical pesticides. Their target-specific action, compatibility with IPM systems, and suitability for organic and residue-free agriculture make them indispensable tools for sustainable crop protection in India. Strengthening production technologies, optimizing field application strategies, streamlining regulatory processes, and investing in farmer education will be critical for unlocking their full potential. With continued innovation, policy support, and market development, biopesticides can serve as foundational components of climate-resilient, safe, and productive agriculture, contributing to food security, environmental stewardship, and sustainable rural livelihoods.



16. Declarations

16.1. Competing Interests: The author of this manuscript confirms that there is not any conflict of interest associated with the manuscript

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