AGROTECH

ISSN: 2773-4870 **eISSN:** 2821-3106

DOI: https://doi.org/10.53797/agrotech.v4i2.2.2025

Biopesticides for Sustainable Agriculture: Formulations, Mechanisms, Regulations, and Market Trends

Parwiz, Niazi[1*] & Abdul Bari, Hejran[2]

[1]Department of Biology, Faculty of Education, Kandahar University, Kandahar, 3801, AFGHANISTAN.

[2]Department of Biology, Faculty of Education, Helmand University, Helmand, 3901, AFGHANISTAN.

Corresponding author: parwiz60@gmail.com

Received 28 July 2025; Accepted 24 December 2025; Available online 28 December 2025

Abstract: Insects along with plant diseases present substantial obstacles to agricultural operations because they create risks to food safety standards across borders while damaging ecological stability. Biopesticides obtained from microorganisms, plant extracts and natural compounds allow farmers to utilize secure substances which function as alternative substitutes for synthetic pesticides. The broad application of these substances remains limited due to manufacturing price issues combined with rapid degradation under changing environmental elements. This study examines modern biopesticide creation methods that stabilize their operational qualities for wider natural pest management deployment capabilities. A comprehensive research connects available knowledge of pesticides that derive from microorganisms with genetically-modified farming chemicals and their relationship to four microbial groups (bacteria, fungi, viruses, and nematodes) and natural plant products and signal molecules and microbial bioactive substances. Modern biopesticide formulation techniques using nanoencapsulation combined with microencapsulation technologies and emulsifiable concentrates and bio-based carriers enhance biopesticide decay resistance time and improve coverage distribution capabilities. Results demonstrate both government support and local backing for green pest management allowing biopesticides to integrate into integrated pest management (IPM). The review unites regulatory documents and academic research with business examples to review improved biopesticide formulations. New technologies in delivery systems make biopesticide formulations work more effectively while simultaneously conserving environmental quality and enhancing their use in agricultural fields. Better biopesticide performance and practical use results from the combination of new biostimulants and adjuvants into synergistic formulations.

Keywords: Biopesticides, formulations, pests, phytochemicals, control

1. Introduction

Biopesticides derive from natural sources including microorganisms combined with plants and animals along with particular minerals. These products function as environmentally beneficial pest management solutions because they target specific pests without causing significant harm to non-target organisms. The application of biopesticides remains essential for constructing sustainable agriculture systems and integrated pest management techniques (Upadhyay et al., 2024). Pesticides offer significant advantages in managing pests that threaten crops; however, their use is associated with considerable risks due to potential harmful effects (Tiwari, 2024). Consequently, public demand is increasing for safer alternatives to traditional pesticides for crop protection. Throughout all growth stages and even during storage, plants are susceptible to various pathogens that can inflict severe damage on crop yields (Manzoor et al., 2024). Biopesticides are a more specific and safer alternative to chemical pesticides since they have very few threats to both human life and the environment (Reyes-Ávila et al., 2024). They are an important part of pest management programs aimed at decreasing the chemical dependency and enhancing the health of crops (Joshi et al., 2024). Different categories of biopesticides possessing different characteristics have been created and packaged as different commercial formulations (Gała-Gundreddy et al., 2024). The existence of biological products in agriculture is not recent, and Bacillus thuringiensis formulations are some of the most common products in insect control (Vermelho et al., 2024). Viruses and fungi are also other microbial and botanical biopesticides that have been used successfully in crop protection. As an example,

*Corresponding author: parwiz60@gmail.com

Polversum (*Pythium oligandrum*) and F-stop (*Bacillus subtilis*) are employed to fight the diseases of plants (Hamrouni et al., 2024).

Although biopesticides are very target specific and environmentally safe, the ability to sustain their efficacy in the long term has been a fundamental formulation problem. A large number of goods are less stable, have short shelf life, and unstable field performance (Gundreddy et al., 2024). The biopesticides designed should have positive physical properties, and their agents must retain biological activity during storage and their application (Verma et al., 2024). These products should also be cost-effective, user friendly and functional in varying agricultural conditions in order to be successful in commerce. There is an ever-growing need to use biopesticides because synthetic pesticides are faced with increasing concerns like resistance, regulatory suppression, and environmental degradation (Fusar-Poli and Fontefrancesco, 2024).

Pests including pathogens, insects, and weeds have severely affected agricultural productivity, causing substantial crop losses (Junaid & Gokce, 2024). Moreover, factors such as unfavorable weather, limited access to technical knowledge for farmers, and poor soil conditions further jeopardize food security. Effective pest management is therefore vital for ensuring food production for the expanding global population while preserving environmental and human health (Monib et al., 2024). In recent decades, pest control has heavily depended on chemical pesticides (Galli et al., 2024). However, new regulations and the rapid rise of resistance among pest populations have significantly reduced their long-term efficacy (Zhou et al., 2024). Approximately 200 weed species have developed herbicide resistance, and over 500 species of arthropods are now resistant to insecticides. Moreover, synthetic pesticides are often costly for small-scale farmers and may adversely impact beneficial organisms (Jambagi et al., 2024; Bommarco, 2024). The challenges have spurred the interest in more environmental friendly alternatives such as biopesticides, which are biodegradable and have no persistent residue (Youvan, 2024).

Globally, bacteria, fungi, weeds, and insects are some of the pests that lead to approximately 40% deductions in agricultural production (Nget et al., 2024). Although chemical pesticides have been effective in the past, the extensive use of pesticides has caused pollution, the extinction of bio-diversity, and the development of resistance posing a threat to the food safety and the health of people (Singh, N. et al., 2024; Mawcha et al., 2024). Formulation science is advancing in the recent past, especially nanotechnology, encapsulation, and bio-based carriers, which is contributing to the stability, shelf life, and activity of biopesticides under different field conditions (Butu et al., 2022). Due to increased organic and sustainable farming, biopesticides like *Bacillus thuringiensis (Bt)* and neem-based products are increasingly becoming popular in developed and developing countries (Anjum et al., 2024). Overall, biopesticides should be adopted to guarantee the sustainability in agricultural production and the environment. They are able to significantly lower the number of pests before they attain economic levels hence promoting crop health and food security. Bio-pesticides should be integrated into the Integrated Pest Management (IPM) schemes since they are non-phytotoxic, do not leave any residues, and maintain ecological balance to help them enhance their effect (Hejran et al., 2024; Gupta et al., 2024).

New formulation technologies are being developed globally to improve application ease, safety, and effectiveness while reducing toxicity, pollution, and costs; these innovations include nano-pesticides, controlled-release formulations, microemulsions, gels, tablets, and water-dispersible granules, all aimed at enhancing sustainable pest management (Garg et al., 2024). Recently, pesticide formulations have shifted from traditional wettable powders (WP) to more advanced types like water-dispersible granules (WG), emulsions in water (EW), and suspension concentrates (SCs), which are water-based and environmentally friendly as summarized in Table 1 (Akoijam et al., 2024). However, they face challenges, including potential efficacy issues compared to chemical pesticides, formulation difficulties to maintain biological activity, and market acceptance among growers accustomed to traditional pesticides; biopesticides are subject to regulatory approval, similar to conventional pesticides, ensuring their safety, efficacy, and environmental impact, biopesticides represent a significant shift towards more sustainable pest management practices, harnessing natural processes and materials to control pests while minimising negative impacts on human health and the environment (Kaur et al., 2024).

2. Methodology

A broad search on the literature on the topic of biopesticide formulations and management was performed with the help of such databases as Web of Science, Google Scholar, and ScienceDirect. The search terms used, biopesticides, biopesticides available, and current scenario of biopesticide use were used to find the relevant publications. The search was done on studies published within the period of 2004 to 2025. About 400 articles were first retrieved, and 12 more sources were gathered in the books, reports, and unpublished theses. The review included 202 studies after the screening of the studies, duplication of studies and the screening criteria was relevance and quality.

3. Advances in Biopesticide Formulation Technologies

3.1. Nanobiopesticide

Nanobiopesticides are biopesticides that incorporate nanotechnology-based delivery systems (such as nanoemulsions, nanocapsules, or nanoparticles) to improve efficacy, stability, and controlled release. Additionally, biological entities play a crucial role in synthesizing nanoparticles with enhanced pesticidal properties, further improving efficacy. These attributes position biopesticides as indispensable components of sustainable agriculture, contributing to ecological balance and long-term environmental health (Abdollahdokht et al., 2022). Nanoscale particles (1–100 nanometers) have unique properties that improve pesticide delivery and effectiveness, enabling slower, controlled release of active ingredients for more sustainable pest management (Khandelwal et al., 2016).

Nanotechnology has diverse applications in agriculture, medicine, cosmetics, and more. Initially, mesoporous silica nanoparticles (MSNs) were used as water-soluble pesticides, while alumina nanoparticles targeted pests in stored food. Silver nanoparticles are found in food packaging, disinfectants, and disease prevention. Plants, a rich source of organic compounds, are widely used in medicine and pesticides, yet research remains incomplete. Exploring ethnobotanical and anthropological knowledge can guide future studies on plant-based pest control, benefiting the environment and society (Malik et al., 2023).

Various nanodelivery systems such as nanoemulsions, nanoencapsulation, and nanocages are used with biopesticides like *nucleopolyhedrovirus* (NPV), *Bacillus thuringiensis* (Bt), and *entomopathogenic* fungi (EPF) to increase their efficacy and longevity, nanoparticles improve these agents' stability, penetration, and targeted pest control, reducing the need for traditional pesticides. With their high surface area and mobility, nanoparticles offer better efficacy while eliminating toxic solvents found in conventional pesticides. These particles can be created using both top-down (Laser ablation) and bottom-up (Chemical reduction) methods, with biological synthesis providing a sustainable, low-cost alternative. Nanotechnology thus supports the goal of safer, more effective, and sustainable pest control solutions (Vurro et al., 2019).

Emulsions and suspensions stabilise hydrophobic and insoluble biopesticides, improving their solubility, bioavailability, and distribution. Neem oil emulsions effectively target pests like aphids, while *Beauveria bassiana* suspensions ensure uniform application (Ullah et al., 2024). Nanoemulsions of essential oils, like citronella, demonstrate rapid pest control and environmental protection; these formulations protect sensitive compounds from UV and oxidation but may face challenges like phase separation or sedimentation, mitigated through optimised stabilisers, future innovations, such as smart-release systems, promise improved stability and sustainability (Somala et al., 2023).

3.1.1. Innovative Carrier Materials

Advanced carriers, including biodegradable polymers (polycaprolactone and chitosan), natural materials (clay, starch, cellulose), and nanomaterials, improve biopesticide stability, targeted delivery, and environmental compatibility, biodegradable systems reduce residue risks. In contrast, natural carriers ensure cost-effectiveness and environmental safety (Biondo et al., 2024). Nanomaterials enable precise delivery, such as nano-encapsulated essential oils providing sustained release; these carriers minimise environmental impact and enhance sustainability, with future research focusing on renewable resources for safer and more efficient pest management (Chiriac et al., 2021).

Table 1 compares five advanced agricultural technologies. Microencapsulation focuses on protecting and gradually releasing active ingredients for targeted pest control, while emulsions and suspensions improve hydrophobic agents' stability, solubility, and application. Bio-stimulant integration enhances plant growth, pest resistance, and nutrient uptake and is often used alongside biopesticides. Innovative carrier materials utilise biodegradable and eco-friendly carriers for controlled release and environmental safety. Finally, nanobiopesticides leverage nanotechnology for enhanced delivery, stability, and precision in pest management, reducing chemical usage. Each method offers unique advantages like improved efficacy and environmental friendliness but varies in cost, complexity, and regulatory challenges.

Table 1: **Advances in Biopesticide Delivery and Integration.**

Aspect	Microencapsulation	Emulsions and Suspensions	Bio-Stimulants Integration	Innovative Carrier Materials	Nanobiopesticides
Definition	Encapsulation of active ingredients (microbial spores, plant extracts) in a protective matrix to control release, improve stability, and enhance efficacy.	A mixture of two immiscible liquids (emulsions) or solid particles dispersed in a liquid (suspensions) to improve solubility, stability, and distribution of biopesticide active ingredients.	Natural substances or microorganisms that stimulate plant growth, enhance pest resistance, improve nutrient uptake, and promote plant stress resilience are often combined with biopesticides.	Materials used to stabilise, protect, and release biopesticide active ingredients efficiently, often biodegradable or environmentally friendly. Examples include biodegradable polymers, clays, and nanomaterials.	Pesticides that incorporate nanotechnology to enhance the delivery, stability, and controlled release of biopesticides, often using nano-sized carriers for improved interaction with pests and plants.
Key Components	Active agents (*Bacillus thuringiensis* spores, essential oils), encapsulating polymers (alginate, chitosan, gelatin), and biodegradable materials (polyvinyl alcohol).	Active ingredients (neem oil, *Bacillus thuringiensis* spores, essential oils), stabilisers (surfactants), liquid carrier.	Plant growth-promoting substances (*Trichoderma* spp., seaweed extracts, humic acids), microorganisms, and bioactive compounds.	Biodegradable polymers (polycaprolactone, poly (lactic acid), chitosan), natural carriers (clay, starch, cellulose), advanced materials (nanomaterials, nanoencapsulations).	Nano-sized carriers (liposomes, nanoparticles, dendrimers), active ingredients (microbial agents, essential oils, biocontrol agents), stabilisers and surfactants for nanoformulations.
Main function	Protects active ingredients from degradation, ensures controlled release, and targets specific environmental conditions (pest gut conditions).	It enhances the solubility, bioavailability, and stability of active ingredients and improves uniformity in application, especially for hydrophobic or insoluble compounds.	Enhances plant resistance to pests, promotes growth, nutrient uptake, and stress tolerance; can be used alone or integrated with biopesticides to enhance pest control.	It stabilises and protects active ingredients, ensures controlled release, offers eco-friendly alternatives to synthetic carriers, and minimises environmental impact.	Improves the effectiveness and longevity of biopesticides by using nanoparticles for controlled release, better dispersion, and targeted delivery, enhancing bioactivity and reducing chemical usage.
Examples	Mmicroencapsulation of Bacillus thuringiensis in alginate, neem oil encapsulated in gelatin, and essential oils encapsulated in biodegradable polymers.	Oil-in-water (O/W) or water-in-oil (W/O) emulsions of neem oil, *Bacillus thuringiensis* spores, citronella oil,	*Trichoderma* spp. (ISR inducer), seaweed extracts (nutrient enhancer), humic acids (root and shoot development), and *Ascophyllum nodosum* (stress tolerance).	Polycaprolactone (biodegradable polymer), clay-based carriers (*Trichoderma* delivery), starch and cellulose-based carriers for insecticidal proteins, and nano-encapsulated essential oils.	Silver, gold, or silica nanoparticles loaded with biopesticides, liposomal formulations for essential oils, *Bacillus thuringiensis*

		and *Beauveria bassiana* suspensions.			nanoparticles for better adhesion and efficacy, and nanoparticle encapsulation of plant extracts for pest control.
Application	Protects active agents from environmental degradation, allows for gradual release under specific conditions (pH, temperature), and improves pest-specific targeting.	It facilitates better dispersion of hydrophobic agents, ensures stable, uniform application, and extends the efficacy of essential oils, microbial spores, and other biological agents.	Increases plant health and resistance to pests, reduces reliance on synthetic chemicals, improves plant vigour, and promotes sustainable agriculture.	It provides precise delivery, improved stability, controlled release, and eco-friendly alternatives to chemical pesticides. It is particularly useful in sustainable farming practices.	Enhanced application of biopesticides by improving targeting, efficacy, and controlled release. Nanoparticles can increase shelf life, reduce environmental impact, and ensure better pest coverage.
Techniques	Spray drying, emulsion polymerisation, fluidised bed coating.	Spray drying, emulsification, homogenisation, fluidised bed coating.	Microbial inoculation, foliar application, root application, combined delivery with biopesticides, nano-encapsulation.	Spray drying, electrospinning, solvent evaporation, nanoencapsulation, fluidised bed coating.	Nanoparticle synthesis (sol-gel process), nanoencapsulation, high-energy ball milling, electrospinning, and surface functionalisation for targeted delivery.
Case studies/ applications	- Neem oil microcapsules for aphid control (sustained release for up to 14 days). - Bt spores are encapsulated for targeted release in the pest gut.	- Neem oil emulsion for aphid control. - *Beauveria bassiana* suspension for pest control. - Nanoemulsions of citronella oil for rapid mosquito control.	- *Trichoderma* spp. and humic acids reducing nematode infestations by 45%. - Seaweed extract reduces thrip damage in rice by 30%. - Humic acids improve maise resistance to root-feeding insects.	- Polycaprolactone is used to encapsulate beneficial fungi like *Trichoderma*. - Clay-based carriers for controlled release of biocontrol agents. - Nanoparticles for precise insecticide delivery.	- *Bacillus thuringiensis* nanoformulations controlling mosquito larvae. - Nano-silver-loaded biopesticides against plant pathogens. - Liposomal formulations of plant-based biopesticides for enhanced efficacy and stability.
Application	Protects active agents from environmental degradation, allows for gradual release under specific conditions (pH, temperature), and improves pest-specific targeting.	It facilitates better dispersion of hydrophobic agents, ensures stable, uniform application, and	Increases plant health and resistance to pests, reduces reliance on synthetic chemicals, improves plant vigour, and	It provides precise delivery, improved stability, controlled release, and eco-friendly alternatives to chemical pesticides. It is particularly	Enhanced application of biopesticides by improving targeting, efficacy, and controlled release. Nanoparticles

		extends the efficacy of essential oils, microbial spores, and other biological agents.	promotes sustainable agriculture.	useful in sustainable farming practices.	can increase shelf life, reduce environmental impact, and ensure better pest coverage.
Advantages	- Prolonged release of active ingredients. - Enhanced stability and shelf life. - Reduced frequency of application. - Targeted delivery for improved efficacy. - Eco-friendly.	- Enhanced solubility and bioavailability of active ingredients. - Improved stability under various environmental conditions. - Better coverage and distribution of plants. - Effective for hydrophobic compounds.	- Strengthens plant defences, reducing pest damage. - Promotes plant growth and resilience against environmental stressors. - Reduces the need for chemical pesticides. - Improves nutrient uptake and overall plant health.	- Biodegradable and environmentally friendly. - Protects active ingredients from degradation. - Allows for sustained release. - Minimizes chemical residues in the environment. - Precision delivery of active agents.	- High bioactivity with minimal chemical use. - Enhanced stability and shelf life of biopesticides. - Targeted and controlled release. - Improved pest control with reduced toxicity. - Less environmental impact due to reduced pesticide use.
Disadvantages	- Stability issues in some environmental conditions. - Costs may increase due to the complexity of the formulation. - Requires careful control of release mechanisms.	- Stability challenges: phase separation in emulsions, sedimentation in suspensions. - Requires stabilisers and surfactants to maintain efficacy.	- Performance variability due to environmental factors. - Potential compatibility issues with chemical pesticides. - Regulatory hurdles in some regions.	- High production costs for advanced materials (nanomaterials). - Compatibility issues with some active ingredients. - Potential challenges in large-scale production of certain materials (nanomaterials).	The cost of synthesis and scale-up may be high. - Potential toxicity concerns if nanoparticles are not well-designed. - Complex regulatory framework for nanomaterials. - Potential environmental risks if not biodegradable.

3.1.2 Plant-Derived Nanobiopesticides

Plants serve as a vital source of nanoparticle-based biopesticides, offering various nanoparticles as practical components for pest management in agricultural applications (Ouassil et al., 2021). Nanoparticles are synthesised through two main approaches: bottom-up (building up from simpler substances) and top-down. Bottom-up methods include chemical and biological techniques like sol-gel, green synthesis, and biochemical (Yadav, 2024). Nanoparticles are inorganic (Metals, Metal Oxides, Quantum Dots) or organic (Carbon Nanotubes). Green synthesis uses plant extracts, metabolites, and essential oils as reducing and stabilising agents, offering an eco-friendly, cost-effective, and efficient alternative for nanoparticle production. Phytochemicals such as terpenoids, flavones, and carboxylic acids are critical to this process. Nanoparticles like silver, zinc, and copper are used in pest control, food packaging, and medical applications. Techniques like UV-Vis spectroscopy, SEM, and FTIR confirm nanoparticle synthesis Table. 2 (Lokole et al., 2024).

Table 2: Most diverse nanoparticles (nps) used in biopesticides are organized below for clarity

No	Plant name	Common name	Nanoparticle present	Part of the plant used	Application	Time management	References
1	*Anacardium occidentale*	Kaaju	Au, Ag, Cu, Pt	Shell Oil	White ants, insecticide	Seasonal, apply before pest infestation	Kuukyi, F. S. A. (2016).
2	*Gloriosa superba*	Flame lily	Ag, Au, Ce, Cu, Pt, Pd	Leaf	Lice in hair	Apply as needed, quick-acting	Krishnamurthy et al., 2020
3	*Mimosa pudica*	Shame plant	Ag, Zn, Fe, Au, Cu		Veterinary wound maggots	Immediate, for acute cases	Gandhi et al., 2023
4	*Calotropis procera*	Rubber bush	Ag, Zn, Ni, Fe		Larvicidal, insecticide	Apply during rainy seasons.	Abdullahi et al., 2020
5	*Vitex trifolia*	Arabian lilac	Ag, Zn, Au		Insect repellant	Apply during peak pest activity.	Islam et al., 2024
6	*Tagetes minuta*	Wild marigold	Ag, Au	Leaf, flower	Insecticides	Apply during the planting season	Kumar et al., 2022
7	*Capsicum annuum*	Hot pepper	Cu, Ag, Au	Leaf, fruit	Thrips, aphids, white flies	Apply during pest outbreaks	Ali, 2020
8	*Carica papaya*	Pawpaw	Ag, Zn	Leaves, seeds	General pest control	Year-round, apply as needed	Alam et al., 2022
9	*Cinnamomum camphora*	Camphor tree	Ag, Au, Pt, Pd	Bark powder	Protect clothes	Apply when storing clothes	Yang et al., 2010
10	*Azadirachta indica*	Neem tree	Ag, Cu	Whole plant	Insecticide, rice and wheat weevil	Apply early in the growing season	Wylie, M. R., & Merrell, D. S. 2022
11	*Artemisia japonica*	Mugwort	Ag, Au, Fe		Insecticide, housefly repellant	Seasonal, apply in early spring/fall.	Li et al., 2021
12	*Ruta graveolens*	Herb of grace	Zn, Ag		General insect control	Apply as needed, adequate for a short period.	Hunde Gonfa, M., & Lealem Birhanu, A. 2024
13	*Butea monosperma*	Sacred tree	Ag, Au, Zn	Seed and flower extract	White ants	Seasonal, apply before pest infestation	Kumari et al., 2022
14	*Strychnos nux-vomica*	Poison nut	Zn, Au, Ag	Fruit, seed		Apply before infestation	Behera et al., 2017
15	*Curcuma longa*	Turmeric	Ag, Zn	Rhizome	Drive away ants	Seasonal, apply during active ant season	Arya et al., 2023

3.2 Biostimulants Integration

Bio-stimulants, including *Trichoderma* species, seaweed extracts, and humic acids, enhance plant defences, nutrient uptake, and resilience against pests and environmental stresses; they induce systemic resistance pathways, improving pest resistance and plant health. For example, *Trichoderma* reduces nematode infestations, while humic acids improve root development and pest tolerance. Combining bio-stimulants with biopesticides enhances effectiveness, as shown in field trials; despite variability in performance and regulatory challenges, bio-stimulants offer sustainable alternatives to chemical pesticides and boost overall crop resilience (Rai et al., 2021).

Environmental stressors such as salinity, drought, extreme temperatures, and excessive rainfall significantly impede plant growth and development, thereby restricting agricultural productivity. Ensuring global food security amid these challenges necessitates the adoption of sustainable agricultural strategies. Biostimulants, encompassing both non-microbial compounds such as humic substances, protein hydrolysates, plant-derived formulations, and seaweed extracts and microbial inoculants including arbuscular mycorrhizal fungi (AMF), *Pseudomonas spp*., *Trichoderma spp*., and *Bacillus spp*. exhibit the potential to enhance plant vigor, flowering, nutrient uptake efficiency, and overall crop yield. These bioactive agents reprogram plant physiology at the biochemical and molecular levels, thereby enhancing tolerance to abiotic stressors. Optimal application methods and timing are critical for maximizing their efficacy.

Biostimulants, whether of natural or synthetic origin, play a pivotal role in optimizing nutrient absorption, translocation, and stress adaptation mechanisms in crops. Applied to seeds, seedlings, or directly to the rhizosphere, they facilitate sustainable growth by counteracting abiotic stressors that compromise plant survival, productivity, and resilience. Drought, salinity, extreme temperatures, and excessive rainfall can disrupt plant physiological pathways, reducing their resistance to pests and pathogens while impairing metabolic efficiency. As an eco-friendly alternative, biostimulants hold significant promise in reducing dependency on synthetic fertilizers and chemical pesticides by enhancing nutrient use efficiency (NUE) for both macro- and micronutrients (Rajesaheb et al., 2024).

Although the concept of plant biostimulants was first explored in 1933, its recognition as a viable approach to counteract climate change-induced agricultural challenges has gained momentum only in the past two decades. Derived from a diverse range of sources including plant extracts, humic substances, protein hydrolysates, seaweed and algal derivatives, as well as plant growth-promoting microbes biostimulants remain a dynamic and evolving field As indicated in Table 3 (Rai et al., 2021).

Table 3: Biocontrol Agents and Their Application:

Bioagent Control	Pathogen	Crop (Applications)	Recommended Quantity	Control Measures	Ref.
Trichoderma. viride	*Fusarium oxysforum* f. *spudum*, *Colletotrichu mtruncatum, Colletotrichum capsici, Phytophthora capsici, Alternaria porri, Macrophomina phaseolina,*	Pigeon pea, *in vitro*, chilli, black pepper, Sunflower	Seed treatment: 4-5 g/kg of seed; Soil application: 2.5 kg/ha mixed with 50 kg compost; Foliar spray: 5 g/liter	Apply *Trichoderma*-based bio fungicide as a seed treatment, soil drench, or foliar spray to suppress soil-borne pathogens and induce plant resistance.	(Choudhary et al., 2024).
Trichoderma. harzianum	*Phytophthoracapsici, Fusariumoxysporum*f. Sp*lycopersici, Fusariummoniliforme, Alternariaalternata, Pucciniasorghi, Pyriculariaoryzae, Macrophomina phaseolina,*	Chilli and tomato, maise, tobacco, rice, Sunflower	Seed treatment: 4-5 g/kg of seed; Soil application: 2.5 kg/ha with organic matter; Foliar spray: 5 g/liter	Use *Trichoderma harzianum* as a soil amendment, seed coating, or foliar spray to prevent pathogen spread and colonisation.	(Kumar et al., 2024).
Bacillus subtilis	*M. fructicola, M. laxa, Peronosclerosporasorghi, Ralstoniasolanacearum*	Peaches, maise, tomato	Seed treatment: 10 g/kg of seed; Soil application: 2.5-3 kg/ha; Foliar spray: 1-2 litres/ha (liquid formulation)	Apply *Bacillus subtilis* as a foliar spray or root inoculant to control bacterial and fungal	(Sarti et al., 2024; Niazi 2024).

				infections and promote plant resistance.	
Trichoderma spp.	*Botrytis cinera, Rhizoctoniasolani*	In vitro tomato	Seed treatment: 4-5 g/kg of seed; Soil drench: 2.5 kg/ha with compost; Foliar spray: 5 g/liter	Use as a soil drench or foliar spray to inhibit spore germination and hyphal growth, protecting crops from damping-off and other fungal diseases.	(Adhikari et al., 2024).
Pseudomonas aeruginosa	*Sclerotiniasclerotiorum*	Tomato	Seed treatment: 10 g/kg of seed; Soil application: 2-2.5 kg/ha; Foliar spray: 5 g/liter of water	Use *Pseudomonas aeruginosa* as a soil or seed treatment for biocontrol of *Sclerotinia*, promoting plant growth and reducing pathogen impact.	(Ayaz et al., 2024).

3.3 Biopesticide Formulation

Biopesticides are formulated similarly to synthetic pesticides, which simplifies usage for farmers since the same equipment can be utilised for various treatments (Devrnja et al., 2024; Abdou et al., 2024); many biopesticides rely on living organisms, necessitating that their viability be maintained throughout formulation and storage, for these organisms to be effective, they must revive from dormancy during application. The formulation process combines microbial agents with carriers and adjuvants to protect them from environmental factors, enhance their survival, control release rates, and improve bioactivity and stability; key formulation objectives include stabilising the microbial agents during distribution and storage, facilitating ease of use, protecting them from adverse conditions, and increasing their effectiveness against target pests (Hassand et al., 2024).

Biopesticide formulations can be categorised into liquid and dry types. Liquid formulations include water, oil, and polymer-based options, often requiring inert ingredients like stabilisers and surfactants. Dry formulations can be created using spray or freeze-drying technologies, typically incorporating binders and wetting agents (Hewitt et al., 2024). Common types of biopesticide formulations include specks of dust for direct application, powders for seed treatment, granules, water-dispersible granules (WG), and wettable powders (WP) (Chavana et al., 2024). Dusts are made by absorbing active ingredients onto finely ground minerals, while powders for seed treatment adhere to seeds during application. Granules consist of larger particles and can be used to control soil pests (Ahmed, 2024). Wettable powders are finely ground solids mixed with surfactants to create a suspension in water; water-dispersible granules minimise dustiness and offer better storage stability Table 4 (Kumar et al., 2024).

Liquid formulations such as emulsions and suspension concentrates mix solid active ingredients with a liquid phase. Emulsions can be oil-in-water or water-in-oil, requiring careful selection of emulsifiers for stability; suspension concentrates need agitation before application to keep solid particles evenly distributed; oil dispersions consist of active ingredients in oil, improving retention and penetration (Desu et al., 2024). Capsule suspensions involve microencapsulated active ingredients, protecting them from environmental stressors and allowing them to be released in a controlled manner (Mao et al., 2024).

Table 4: Control Agents and target pests

Formulation	Bio agent	Target Insect Pest	Formulation Type	Advantages of Formulation	Reference
Zinc Oxide Nanoparticles (ZnO), Gold Nanoparticles (Au)	*Bacillus thuringiensis*	*Callosobruchus maculatus*, *Aedes aegypti*, *Anopheles subpictus*, *Trichoplusia ni*	Nanoparticle	Enhanced pest targeting, stability, reduced chemical use	(Jampílek et al., 2019; Zanzana et al., 2024).
Nanosilver, Zinc Nanoparticles	*Beauveria bassiana*	*Aedes* larvae, *Leptinotarsa decemlineata*, *Trialeurodes vaporariorum*		Increased stability, specific targeting, prolonged activity	(Saranya et al., 2020).
Encapsulation	*Spodoptera littoralis NPV*	*Spodoptera littoralis*	Encapsulation	Long-lasting effect, low environmental impact	(Glazer et al., 2023).
Alginate, Gelatin and Gum Arabic	*Beauveria bassiana*, *Metarhizium anisopliae*	*Triatoma infestans*, *Aphids*, *Solenopsis invicta*		Biodegradability, extended-release	(Ozturk et al., 2023).
Microcapsules, CMC-Encapsulation	*Bacillus thuringiensis israelensis*	*Aedes aegypti*, *Trichoplusia ni*	Microencapsulation	Controlled, slow-release, environment-protective coating	(Viana 2024; Deschodt and. Cory 2024).
Water-Dispersible Granule (WG), Spray Drying	*Bacillus thuringiensis*	Caterpillar pests on vegetables, fruits; *Japanese beetle grubs*	Granule, Spray Dry	Ease of application, high stability, comprehensive coverage	(Lalah et al., 2022).
Microemulsion, Nanoemulsion	*Metarhizium anisopliae*	*Rhynchophorus ferrugineus*, *Plutella xylostella*	Emulsion/Nanoemulsion	Improved bioavailability, controlled release	(Gupta et al., 2013).
Hydrogel	*Metarhizium anisopliae*, *M. Riley*, *Beauveria bassiana*	*Spodoptera litura*, *Leptinotarsa decemlineata*	Hydrogel	Moisture retention, prolonged activity	(Nxitywa et al., 2023).
Oil Emulsion, Inverted Emulsion	*Beauveria bassiana*, *Metarhizium anisopliae*	*Diatraea saccharalis*, *Rhynchophorus ferruginous*, *Aedes albopictus*, *Culex pipiens*, *aphids*	Emulsion	Enhanced pest contact, rain resistance	(Nurcahyanti et al., 2024).
Capsule Formulation	*Beauveria bassiana*, *Metarhizium anisopliae*	*Odoiporus longicollis*, *Aphids*	Capsule	Controlled release, easy handling	(Yerukala 2019).
Self-Floating Slow Release	*Bacillus thuringiensis israelensis*	Culex quinquefasiatus	Slow Release	Ideal for water applications, reduced frequency	(Elleuch 2016).

Vectobac® DT	*Bacillus thuringiensis israelensis*	Mosquitoes	Commercial Formulation	Ready-to-use, highly effective	(Uragayala et al., 2018).
Water-Dispersible Powder	*Bacillus popilliae*	Japanese beetle grubs	Powder	Simple application, effective pest management	(Rana et al., 2024).

3.3.1. Dustable Powders (DP) and Granules (GR):

Dust formulations typically contain around 10% active ingredient, which is absorbed into finely ground solid mineral powders like talc or clay, with particle sizes between 50 and 100 microns. Inert ingredients may include UV protectants, adhesives to enhance adhesion and anticaking agents (Verma et al., 2024).

Granules contain active ingredient concentrations ranging from 2-20%; the active ingredients may either coat the exterior or be absorbed within the granules. To regulate the release rate of these ingredients, granules can be coated with resins or polymers; they are primarily used to control soil-dwelling insects, weeds, and nematodes and are composed of coarse particles between 100-600 microns made from materials such as kaolin, silica, and various plant residues (Kumara 2024).

3.3.2. Wettable Powders (WP) and Ultra-Low Volume Liquids (ULV):

Wettable powders are dry formulations that are finely ground and meant to be mixed with water before application; they are created by blending active ingredients with surfactants, dispersing agents, and inert fillers due to their dustiness, which can pose health risks during manufacturing and application, strict safety measures are essential, these powders have good storage stability, dissolve well in water, and can be used with conventional spraying equipment (Badawy et al., 2024). These formulations have a high concentration of active ingredients and are not meant to be diluted with water before use. They are easy to transport and can utilise suspended biocontrol agents as active ingredients.

The dataset illustrates various biopesticide formulation types and their defining characteristics, highlighting both traditional and advanced technologies. Seed treatments, soil applications, and foliar sprays emphasize basic protective functions against soil-borne and aerial pathogens, whereas advanced formulations like dustable powders (~10% active ingredient, 50-100 microns) and granules (2-20% active ingredient, 100-600 microns) provide precision in pest control. Wettable powders and water-dispersible granules focus on ease of application and stability, while emulsions and suspension concentrate (1-10 microns) prioritize uniform distribution.

3.4. Types of Biopesticides

3.4.1 Microbial Biopesticides

These pesticides utilise microorganisms like bacteria, viruses, fungi, and protozoa as their active ingredients for the biological control of plant diseases, harmful insects, and weeds. Entomopathogenic pathogens specifically target insects, leaving other animals and plants unharmed (Niazi & Monib, 2024). *Bacillus thuringiensis* (Bt) is the most commonly used microorganism in biopesticide production and acts as an insecticide for various groups, including *Lepidoptera, Coleoptera*, and *Diptera.* During its spore formation, *B. thuringiensis* produces protein crystals or toxins that can disrupt gut cells when ingested by susceptible insects. A more accurate term for *B. thuringiensis* would be biologically derived insecticide. Entomopathogenic fungi are more frequently employed as biological control agents than bacteria due to their limited host range, which prevents them from infecting vertebrates, Table 5 (Dimase et al., 2024).

The families of entomopathogenic viruses include *Baculoviridae, Poxviridae*, and *Reoviridae,* comprising around 1,200 species in total. Protozoa infect insects through the mouth and in the gut, such as Malamoeba locustae, Vairimorpha necatrix, and Nosema locustae. Additionally, entomopathogenic nematodes belong to the families *Steinernematidae* and *Heterorhabditidae*, which are associated with the bacteria *Xenorhabdus nematophilus* and *Photorhabdus luminescens* (Rowińska et al., 2024).

Table 5: The main types of formulated organisms and the environments to which they are applied

Formulated Organism	**Type**	**Environment Applied To**	**Distributed Life Stage**	**Mode of Action**	***References***
Microorganisms (Bacteria, Fungi, Viruses)	Beneficial microbes (*Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*)	Agricultural fields, orchards, forests, soil, foliage, water bodies	Egg, Larvae, Adult	Ingestion, contact, parasitism, infection via spores	(García-Espinoza 2024).
Nematodes	Parasitic nematodes (*Steinernema* species)	Soil, roots, agricultural fields	Larvae, Juvenile, Pupa	Parasitize and infect pests	(Matuska-Łyżwa et al., 2024).

				through penetration	
Plant Extracts	Natural insect repellents (neem)	Foliar applications, soil, vegetables, crops	Adult, Larvae	Repellent, growth regulator, or toxic effect	(Allison 2024).
Insect-pathogenic Viruses (NPV)	Nucleopolyhedrovirus (NPV)	Agricultural fields, crops, insect larvae	Larvae	Ingestion, virus replication inside host, kill larvae	(Skrzecz et al., 2024).
Algae and Seaweed Extracts	Algal and seaweed extracts for growth promotion and pest control	Agricultural fields, soil amendments, hydroponics	Adult, Larvae, Egg	Growth regulation, pest deterrent, or plant health booster	(Shashirekha et al., 2024).
Bacterial Endospores	Spore-forming bacteria (e.g., *Bacillus thuringiensis*)	Soil, plant surfaces, agricultural fields	Larvae, Eggs	Ingestion, release of toxins causing mortality in pests	(Fichant et al., 2024).

3.4.1.1 Mechanism of Action Bacteria (*Bacillus thuringiensis*)

Bacillus thuringiensis is a naturally occurring soil bacterium that has gained prominence as a biological insecticide due to its selective action against specific insect pests. It produces crystalline proteins known as Cry proteins, which are toxic to certain insect larvae, particularly those in the orders *Lepidoptera* (such as moths and butterflies), *Coleoptera* (beetles), and *Diptera* (flies). When these susceptible insects consume the Bt spores, the proteins are activated in their alkaline gut environment, leading to the disruption of gut cells, which ultimately results in the insect's death, this specificity makes Bt an environmentally friendly alternative to synthetic chemical pesticides, as it poses minimal risk to non-target organisms, including beneficial insects, humans, and other wildlife.

Bt is commonly used in various formulations, including sprays and granules, allowing for versatile applications in agriculture, horticulture, and home gardening. Its effectiveness is particularly valued in organic farming, where it helps manage pest populations without leaving harmful chemical residues, the widespread use of Bt, especially in genetically modified crops that express its toxins, has raised concerns about potential resistance development among target insect populations, to combat this, integrated pest management strategies that combine Bt with other control methods are recommended (Li et al., 2024).

The classification of biopesticides as environmentally friendly alternatives to synthetic pesticides does not remove their capacity to generate side effects. The fungal biopesticide *Beauveria bassiana* generates rising mortality rates together with behavioral changes in wasp species outside the targeted pest which causes colony death (Cappa et al., 2024).

Bacillus thuringiensis (Bt) exerts its insecticidal effects primarily through the production of crystalline proteins known as Cry proteins and cytolytic proteins; during the spore generation process, Bt creates these protein crystals, which are critical for the lysis of gastrointestinal cells in vulnerable insects (Moreira et al., 2024). When larvae consume the Cry proteins, the delta-endotoxins become activated in the alkaline environment of the gut, which typically has a pH between 9.0 and 11.0, the activated proteins then bind to specific receptor sites on the epithelial cells of the midgut, such as aminopeptidase N and cadherin-like proteins, this binding triggers the oligomerization of the Cry proteins, leading to the formation of pores in the gut cell membranes, the resulting disruption of the gut epithelium causes cell lysis and paralysis, which prevents the insect from properly digesting food and absorbing nutrients (Fu et al., 2024; Manriquez, 2024).

Infectious juvenile nematodes (0.4–1.5 mm long) enter insects through natural openings like the mouth, anus, or breathing holes. Once inside, they release symbiotic bacteria that kill the insect within a week by releasing toxins; the nematodes feed on the dead host, reproduce, and generate three generations of offspring. Juveniles then leave the cadaver in search of new hosts. In ideal conditions, nematode-infected pests appear 5–7 days after application; insects killed by *Steinernematidae* turn brown or tan, while those killed by *Heterorhabditidae* turn red **Table 6** (Ghoneim & Hassan, 2024).

Table 6. The subspecies of *Bacillus thuringiensis* and the toxins used against various pests are listed below

***Bacillus thuringiensis* Subspecies**	**Toxins Produced**	**Proto-toxin size (K Da)**	**Target Pests**
Bacillus. thuringiensis subsp. *Kurstaki*	Cry1A, Cry2A	71–140	Primarily *Lepidoptera* larvae (cabbage looper, diamondback moth (Verma et al., 2024; Wang et al., 2024).
Bacillus. thuringiensis subsp. *İsraelensis*	Cry4A, Cry4B, Cyt	68	*Diptera*, especially mosquito larvae (Aedes, Culex) and black flies (Manriquez, 2024).
Bacillus. thuringiensis subsp. *tenebrionis*	Cry3A	66-73	*Coleoptera,* including western corn rootworm and Colorado potato beetle (Manriquez, 2024).
Bacillus. thuringiensis subsp. *Woolworths*	Cry1C	40	Various *Lepidoptera* are often used in forestry applications (Olagunju, 2024).
Bacillus. thuringiensis subsp. *pakistani*	Cry2A, Cry1A	70	Certain *Lepidopteran* pests (Aswathi et al., 2024).
Bacillus. thuringiensis subsp. *aizawai*	Cry1F, Cry2A	135	Variety of *Lepidoptera* (cotton bollworm) (Durán-Lara, 2020).
Bacillus. thuringiensis subsp. *singhii*	Cry1F	65-145	Primarily *L*epidopteran larvae affecting vegetables and field crops (Ferreyra-Suarez et al., 2024).
Bacillus. thuringiensis subsp. *Berliner*	Cry I	130–140	Certain *Lepidopteran* pests (Bao et al., 2024).

3.4.1.2 Mechanism of Action Viruses (*Baculovirus*):

The mechanism of action of *Baculovirus* begins when an insect pest, typically a caterpillar, ingests virus particles while feeding on contaminated plant material, and these virus particles are protected by protein structures known as occlusion bodies, which dissolve in the alkaline environment of the insect's midgut. Once dissolved, the virus is released and enters the insect's gut cells. From there, the virus spreads to other tissues, particularly the fat body and blood cells, where it replicates extensively. As the virus multiplies, it disrupts the normal cellular functions of the insect, causing a range of symptoms such as loss of appetite, lethargy, and failure to moult; the insect eventually dies within a few days as a result of tissue destruction and the overwhelming viral infection (Hejran et al., 2024). Following the insect's death, the virus continues to replicate, turning the body into a liquefied mass, which releases new occlusion bodies into the environment; these OBs can then infect other susceptible insects, continuing the cycle, the specificity of *Baculovirus* ensures that it targets only the intended insect species, making it a safe and environmentally friendly option for biological pest control, without harming non-target organisms like beneficial insects, animals, or humans, **Table 7** (Jiménez-Ortega et al., 2024).

Table 7: **The subspecies of Viruses *(Baculovirus*) and the toxins used against various pests are listed below**

***Baculovirus* Subspecies**	**Type of Toxins/ Mode of Action**	**Target Pests**
Autographa californica multiple *nucleopolyhedrovirus* (AcMNPV)	Disrupts insect gut cells, leading to systemic infection	*Various Lepidoptera* species (cotton bollworm, cabbage looper) (Masoudi et al., 2024; Adamu, 2024).
Helicoverpa armigera nucleopolyhedrovirus (HearNPV)	Causes cell lysis, disrupting midgut and killing larvae	*Helicoverpa armigera* (cotton bollworm) (Galli et al., 2024).
Spodoptera exigua nucleopolyhedrovirus (SeMNPV)	Infects gut cells replicates, leading to larval death	*Spodoptera exigua* (beet armyworm) (Masoudi et al., 2024).
Lymantria dispar nucleopolyhedrovirus (LdMNPV)	Replicates inside the host, resulting in death and liquefaction	*Lymantria dispar* (gypsy moth) (Li et al., 2024).
Cydia pomonella granulovirus (CpGV)	Granulovirus infects larvae, disrupting normal functions	*Cydia pomonella* (codling moth) (Li et al., 2024).
Plutella xylostella granulovirus (PxGV)	Granulovirus disrupts insect cellular functions	*Plutella xylostella* (diamondback moth) (Joshi et al., 2024).

3.4.2 Botanical Biopesticides

Botanical biopesticides are natural pest control agents derived from plant materials, including extracts, essential oils, and phytochemicals with pesticidal properties; they target a variety of pests, such as insects, fungi, and weeds, while minimising harm to non-target organisms, including beneficial insects and humans, these biopesticides disrupt pest growth and reproduction, repel insects, and affect their feeding behaviour. They are biodegradable and generally pose lower environmental risks than synthetic pesticides, making them essential for sustainable agriculture and promoting integrated pest management (IPM) practices. In addition to traditional botanical biopesticides, Plant-Incorporated Protectants (PIPs), also known as genetically modified crops, are biopesticidal substances produced by plants that have been genetically engineered to express specific traits (Azizi et al., 2023). A notable example is Bollgard® cotton, which contains Bt Cry1Ac delta-endotoxins, providing resistance against pests like the tobacco budworm and cotton bollworm (Vitalis et al., 2023); these crops release crystalline proteins that damage the gut lining of sensitive insects, leading to their death while remaining safe for beneficial organisms, humans, and vertebrates, since their introduction in 1995, several PIPs have been approved for use in the United States, with ongoing enhancements through stacked genes to achieve multiple desirable traits in single crops (Ozturk et al., 2023).

3.4.3 Biochemical Biopesticides

Nature produces biochemical pesticides which use non-harmful pest control mechanisms based on insect pheromones and plant growth regulators including auxins and gibberellins. Plant-derived pesticides show pest-control effects by toxic action against target species although they share their natural origin with biochemical pesticides (Daraban et al., 2023). For instance, pheromones can confuse male insects and hinder reproduction, while insect growth regulators (IGRs) like methoprene and pyriproxyfen interfere with development, preventing maturation or reproduction. Biochemical biopesticides are generally less toxic to non-target organisms, including beneficial insects, humans, and wildlife, and are biodegradable, thus reducing the risk of environmental accumulation (Punniyakotti et al., 2024), and assessing whether a natural pesticide controls pests without toxic effects can be challenging, to address this, the Environmental Protection Agency (EPA) has established a committee to determine whether a pesticide meets the criteria for a biochemical pesticide, plants that produce secondary metabolites, such as insect growth regulators, chitin synthesis inhibitors, and juvenile hormone analogues, are also considered biopesticides, these substances are integral to sustainable agricultural practices and integrated pest management (IPM) strategies, providing effective pest control solutions while minimising environmental impacts (Orou-Seko et al., 2024).

3.4.4 RNA Interference (RNAi) Biopesticides

RNA interference (RNAi) biopesticides offer a revolutionary approach to insect pest management by explicitly targeting and silencing essential genes within pest species, leading to their death or reproductive disruption (Ortolá et al., 2024). Unlikeconventional pesticides, RNAi biopesticides are highly selective, targeting essential genes in specific pests without affecting non-target organisms, beneficial insects, or the environment (Hasan et al., 2024; Hanamasagar et al., 2024).This approach works by introducing double-stranded RNA (dsRNA) molecules that match particular pest genes, when the pest ingests or absorbs these dsRNA molecules, they initiate the RNAi pathway, which silences the expression of targeted genes by degrading the corresponding messenger RNA (mRNA).

As a result, the pest is unable to produce crucial proteins necessary for survival or reproduction, leading to its control. One notable example is the RNAi biopesticide targeting the Western Corn Rootworm (*Diabrotica virgifera virgifera*), a major pest of corn crops (Ma et al., 2024). By targeting the V-ATPase gene through dsRNA produced in genetically modified corn, this approach disrupts the pest's ion balance, leading to high mortality in larvae and providing adequate crop protection (Choudry et al., 2024), the product SmartStax PRO, developed by Bayer and Corteva, combines this RNAi mechanism with Bt proteins for enhanced pest resistance. Another example is the Colorado Potato Beetle (*Leptinotarsa decemlineata*), where RNAi sprays target genes like Snf7, essential for the beetle's survival; experimental formulations under development by Green Light Biosciences have shown reduced pest populations in potatoes (Manriquez et al., 2024). The RNAi biopesticides targeting Cotton Bollworm (*Helicoverpa armigera*) disrupt detoxification genes, rendering the pest vulnerable to toxins in the plant, effectively reducing its impact on cotton crops. Research is also underway on Soybean Aphids (*Aphis glycines*), where RNAi sprays targeting moulting genes like CHS have been shown to reduce reproduction rates and offer protection against aphid infestations (Choudry et al., 2024). Despite their promise, RNAi biopesticides face challenges such as environmental degradation of dsRNA, limited delivery efficiency into pests, and potential unintended effects on non-target species Table 8 (Dalakouras et al., 2024).

3.4.4.1 Forms and Availability of RNAi Biopesticides

1. Sprayable Formulations – The most practical and user-friendly approach, where double-stranded RNA (dsRNA) is formulated and applied as a foliar spray, much like traditional pesticides (Balafoutis et al., 2021)
2. Seed Treatments – Experimental coatings that release dsRNA to protect young plants from early pest damage (Sundaresha et al., 2022).
3. Genetically Modified (GM) Crops – Plants engineered to produce dsRNA internally, providing inherent pest resistance (e.g., GM maize targeting corn rootworm (Darlington et al., 2022). In terms of current availability, only GM RNAi crops such as *SmartStax PRO* (Bt + RNAi maize) are commercially released. Sprayable and seed treatment formulations are still in research and regulatory testing phases, not yet accessible for widespread agricultural use (Banik et al., 2024).

Table 8: Pest species, target genes, and outcomes using RNA ınterference (RNAi) biopesticides

Pest Species	Target Gene(s)	Delivery Method	Product Example	Outcome	References
Diabrotica virgifera virgifera	V-ATPase subunit A	Transgenic plant (corn)	SmartStax PRO	High mortality in larvae, effective crop protection	Pereira, A. E. 2016
Helicoverpa zea (Cotton Bollworm)	Chitin synthase (*chs*)	Transgenic crops	Bt Cotton	Reduced damage due to pest resistance	Karthik et al., 2021
Spodoptera frugiperda (Fall Armyworm)	Sodium channel (*Nav1.8*)	RNA interference (RNAi)	Sprayable RNAi products	Reduced pest survival through knockdown of target gene	Kenis et al., 2022
Aedes aegypti (Mosquito	Doublesex (*dsx*)	CRISPR-Cas9	Genetically Modified Mosquitoes	Sterile males leading to population suppression	Ranian et al., 2022
Leptinotarsa decemlineata	Actin, Snf7	Topical dsRNA spray	Under development by GreenLight	Reduced pest population; effective potato defence	Rodrigues et al., 2021
Helicoverpa armigera	CYP450 detoxification genes	Spray or transgenic	Under research	High mortality by disrupting the detoxification pathway	Zhang et al., 2022
Aphis glycines	CHS (moulting)	Foliar dsRNA spray	Experimental	Reduced reproduction; lower aphid density	Wei et al., 2024
Drosophila suzukii (Spotted Wing Drosophila)	Reproductive genes (*tra2*)	Gene drive	Engineered populations	Spread of sterility in wild populations	Li, J., & Handler, A. M. 2017
Locusta migratoria (Migratory Locust)	Wing development genes (*VG*)	RNA delivery via sprays	Biopesticide formulations	Inhibited flight capability, reducing crop damage	Kong et al., 2025

3.4.4.2 Mechanism of RNA Interference (RNAi) in Biopesticides:

RNA interference (RNAi) is a powerful molecular mechanism that can be harnessed in biopesticides to target and silence specific genes in insect pests, leading to their control; the process begins when double-stranded RNA (dsRNA), which is designed to match a pest-specific gene, is introduced into the pest's system through ingestion or absorption from plants that have been treated with RNAi biopesticides or engineered to produce the dsRNA. Inside the pest, the enzyme Dicer processes the dsRNA into smaller fragments called small interfering RNAs (siRNAs); these siRNAs are incorporated into the RNA-induced silencing complex (RISC), which guides the siRNA to bind to complementary messenger RNA (mRNA) of the targeted gene. The binding of siRNA to mRNA triggers the degradation of the mRNA, preventing the synthesis of the corresponding protein, **Table 9** (Quilez-Molina et al., 2024).

The disruption of crucial proteins, essential for digestion, metabolism, or reproduction, leads to pest mortality or sterility. For example, in *Diabrotica virgifera virgifera* (Western Corn Rootworm), dsRNA targeting the V-ATPase gene disrupts cellular ion regulation, ultimately causing larval death. RNAi technology ensures specificity, affecting only the target pest species while leaving beneficial organisms and the environment unharmed. Its precise gene-targeting ability, combined with its environmentally friendly nature, makes RNAi a promising alternative to traditional chemical pesticides (Zhang et al., 2024).

Table 9: Steps and processe in RNA interference (RNAi) mechanism for biopesticides

Step	*Process*	Example
Double-stranded RNA (dsRNA) Introduction	dsRNA is applied via foliar spray, root absorption, or through transgenic plants producing dsRNA.	Western Corn Rootworm feeding on transgenic corn expressing V-ATPase dsRNA (Sprayable RNAi targeting *Spodoptera frugiperda*)
Cellular Uptake	Cells take up dsRNA through endocytosis.	Absorption of dsRNA by gut cells of pests

dsRNA Processing (Dicer Enzyme)	The enzyme Dicer cleaves the dsRNA into small interfering RNAs (siRNAs).	siRNAs are generated from the dsRNA targeting pest genes
RISC Formation	siRNAs are incorporated into the RNA-induced silencing complex (RISC).	RISC with siRNA binds to complementary mRNA in the pest.
Target mRNA Degradation	RISC cleaves the mRNA, preventing protein synthesis and disrupting biological functions.	Disruption of ion transport in Western Corn Rootworm by targeting V-ATPase
Pest Mortality	Lack of critical proteins leads to the pest's death, sterilisation, or stunted development.	Mortality in rootworm larvae due to disrupted cell function (Effective control of *Helicoverpa armigera*)

3.5 Insect Pheromones and Growth Regulators

Insect pheromones and growth regulators are key components of biochemical biopesticides, offering innovative and environmentally safe solutions for pest control. Pheromones, natural chemical signals used by insects for communication, especially during mating, are utilized to disrupt these behaviors. By releasing synthetic pheromones into the environment, mating communication is interrupted, making it difficult for males to locate females, such approaches align with integrated pest management (IPM) principles and promote sustainable agriculture (Orou-Seko et al., 2024).

Insect Growth Regulators (IGRs) function differently by interfering with the normal growth and development of insects (Thabet et al., 2024). These compounds mimic or block hormones responsible for moulting and reproduction, leading to outcomes such as stunted growth, deformities, or sterility. For instance, chitin synthesis inhibitors prevent proper exoskeleton formation, causing death during moulting, while juvenile hormone analogues stop larvae from maturing into adults. This targeted mode of action allows IGRs to control pest populations with minimal impact on non-target species. Together, pheromones and IGRs represent a multi-faceted, eco-friendly strategy that enhances pest management efficacy while reducing dependence on synthetic pesticides. Their integration supports sustainable agriculture and ecological balance, contributing to safer and more resilient farming systems (Abbass et al., 2024).

3.6 Predatory Biopesticides (Semiochemical)

A semiochemical is a chemical signal produced by one organism, typically an insect that induces behavioural changes in individuals of the same or different species (Serdo, 2024). In agricultural contexts, the most commonly used semiochemicals are insect pheromones, which facilitate communication among members of the same species for various purposes, such as mating; these pheromones are synthesised for pest control strategies, including mating disruption, lure-and-kill systems, and mass trapping (Shashank et al., 2024).

Semiochemicals can be categorised into two main types: pheromones, which communicate within a species, and allelochemicals, which facilitate communication between species. Within pheromones, there are various examples, including sex pheromones (egossyplure, departure), aggregation pheromones (frontalis), and alarm pheromones (terpenes and formic acid). Allelochemicals also have distinct roles; for instance, allomones benefit the emitter but are detrimental to the recipient, while kairomones benefit the recipient at the emitter's expense (Upadhyay et al., 2024). Predatory biopesticides utilise natural predators to control pest populations effectively, and these biopesticides leverage the predation habits of certain organisms, such as insects and arachnids, to reduce pest damage to crops (El-Ghany, 2019). Common predatory biopesticides include ladybugs, which prey on aphids, lacewings that target soft-bodied pests, and predatory mites that feed on spider mites (Joshi et al., 2024).

Parasitic wasps also fall into this category, as they lay their eggs inside or on pests, leading to their eventual death; by encouraging the presence of these natural predators, predatory biopesticides help maintain ecological balance, reduce the risk of pest outbreaks, and enhance biodiversity, they also lessen the reliance on synthetic pesticides, promoting sustainable agricultural practices while effectively controlling pests without harming beneficial species or increasing the risk of pest resistance associated with conventional chemical pesticides, integrating semiochemicals and predatory biopesticides into pest management strategies offers a natural and sustainable approach to agricultural pest control (Pavithran et al., 2024).

3.6.1 Mechanisms of Action of Biopesticides

Microbial biopesticides encompass bacteria, fungi, and viruses that infect and eliminate pests; *Bacillus thuringiensis* (Bt) produces toxic crystal proteins that become active in the alkaline gut of specific insect larvae, leading to cell lysis and subsequent death. Fungi like *Beauveria bassiana* penetrate the exoskeleton of insects, germinate on their surface, and feed on the host while releasing toxic metabolites that ultimately cause mortality (Pandiyan et al., 2024). Also, insect viruses, particularly *nucleopolyhedroviruses* (NPVs), invade host insects by entering their cells, replicating within them, and causing cell lysis as viral loads escalate (Dhanapal et al., 2022). Plant-incorporated protectants (PIPs) are genetically engineered plants that express pest-resistant traits, producing toxic proteins to specific pests; when consumed, these proteins inhibit growth and reproductive success or induce death. Natural plant products, such as essential oils and extracts, contain active compounds like alkaloids and terpenoids that can be toxic to insects, disrupt their metabolic processes, act as repellents, or serve as antifeedants to decrease feeding activity. Biochemical biopesticides target essential biochemical processes vital for pest survival, focusing on hormonal systems or inhibiting critical enzymatic activities that lead to pest decline (Ali et al., 2024).

Competition involves biopesticides aggressively colonising substrates to outcompete pathogens for resources; an example is *Trichoderma* species are known to be effective competitors against *Fusarium* species (Mehmood et al., 2024). Hyperparasitism occurs when one microorganism directly parasitises another, leading to the latter's death; for instance, *Trichoderma lignorum* can parasitise the hyphae of *Rhizoctonia solani*, and soil inoculation with *Trichoderma* spores has been shown to control damping-off disease in citrus seedlings (Thepbandit & Athinuwat, 2024). Lastly, synergism involves the combined action of hydrolytic enzymes and antibiotic secondary metabolites produced by some biocontrol agents; the effectiveness of *Trichoderma* species as biocontrol agents and their environmental fitness often result from these synergistic effects, which include compounds like pyrones and coumarins, these diverse strategies and mechanisms underscore the critical role of biopesticides in sustainable pest management practices (Basaid et al., 2024).

Biopesticides utilise several specific mechanisms for pest control, including antibiosis, competition hyperparasitism, and synergism. Antibiosis refers to interactions with other microorganisms mediated by specific microbial metabolites, volatile compounds, lytic enzymes, or other toxic substances, producing antibiotics, bacteriocins, and other inhibitory compounds (Montoya-Martínez et al., 2024).

3.6.2 Application Techniques for Biopesticide Formulations

Biopesticide application technologies and methods encompass a range of techniques designed to optimise the delivery and effectiveness of biological control agents in agricultural and horticultural contexts (Ahmed et al., 2024), one of the most common methods is foliar spraying, where biopesticides are applied directly to plant leaves using various tools such as backpack sprayers, tractor-mounted sprayers, or drones, this technique is particularly effective for targeting pests that inhabit the foliage and can be enhanced with surfactants to improve the adhesion and penetration of the biopesticide into the plant tissue, the widely used method is soil application, where microbial formulations of biopesticides are incorporated into the soil through methods like broadcasting, banding, or drenching, this technique is beneficial for combating soil-borne pathogens and pests (Vishnu et al., 2024).

Seed treatment is another innovative application technology involving the coating of biopesticides onto seeds before planting; this method provides early protection against diseases and pests during germination and seedling establishment, significantly improving crop survival (Köhl et al., 2024). Additionally, seedling dipping involves immersing the roots of seedlings in a biopesticide suspension for a specified duration before transplanting, which is effective; for example, with species like *Trichoderma spp*, the use of baiting systems is also notable, allowing for the targeted delivery of biopesticides in concentrated forms that attract specific pests while minimising exposure to non-target organisms, the incorporation of biopesticides into integrated pest management (IPM) strategies further enhances their effectiveness by combining them with cultural practices, physical controls, and chemical pesticides as needed, thus improving overall pest suppression (Gao et al., 2024). Emerging technologies such as microencapsulation and nano-encapsulation provide advanced methods for protecting biopesticides from environmental degradation, allowing for controlled release and enhanced stability, which can prolong their activity in the field, the increasing use of drone technology enables efficient and precise application of biopesticides over large areas, providing accurate targeting while reducing the quantity of product required (Sabarivasan et al., 2024).

3.7 Regulations and Safety of Biopesticides

The regulation and safe use of biopesticides are vital for protecting human health, non-target species, and the environment (Guedes et al., 2024). Biopesticides, which encompass products like microbial pesticides, plant-incorporated protectants, and biochemical pesticides, are regulated through comprehensive frameworks (Malek et al., 2024). Agencies like the U.S. Environmental Protection Agency (EPA) and the European Food Safety Authority (EFSA) oversee these regulations, requiring rigorous testing for effectiveness, environmental effects, and toxicity (Leppanen et al., 2024). Safety assessments consider factors such as residue levels, allergenicity, and impacts on beneficial organisms (Adegbeye et al., 2024). While biopesticides are often less toxic and more eco-friendly than synthetic pesticides, detailed risk assessments are still essential to avoid unintended side effects (Sharma, 2024). Regulations also prioritise sustainability, ensuring that biopesticides align with Integrated Pest Management (IPM) and best agricultural practices (Walters et al., 2024). Safety and environmental assessments are fundamental to the regulatory process, safety testing examines acute and chronic toxicity, allergenic potential, and the presence of residues in food and water (Manful et al., 2024).

Compared to synthetic pesticides, biopesticides generally pose lower health risks due to their natural origins and specific targeting mechanisms, but comprehensive evaluations ensure they remain safe under typical usage (Agboola et al., 2022). Compared to conventional pesticides, biopesticides offer numerous health and environmental benefits, including lower toxicity that reduces exposure risks for farmers, consumers, and communities (Kostina-Bednarz et al., 2023; Niazi et al., 2023). Derived from natural materials like plants, bacteria, or minerals, biopesticides leave fewer harmful residues in food and water, making them safer for food crops. Environmentally, biopesticides have a smaller ecological footprint; their targeted action focuses on pests without impacting beneficial organisms like pollinators or natural predators, and they decompose quickly in the environment, reducing risks of long-term soil, water, and ecosystem contamination (Saleh et al., 2023).

Environmental assessments examine biopesticides' effects on non-target species, such as pollinators, aquatic life, and soil organisms; they also address concerns about persistence, bioaccumulation, and biodiversity (Daraban et al., 2023). Most biopesticides are more eco-friendly than synthetic options, breaking down more quickly and posing less risk for long-term environmental contamination (Barathi et al., 2024).

3.8 Economic Viability and Market Trends

The global production of biopesticides is approximately 3,000 tonnes annually, with a consistent growth rate of 10% per year (Waseem et al., 2024). Around 1,400 biopesticide products are marketed worldwide. The U.S. market offers more than 200 biopesticide products, significantly outnumbering the 60 products available in the European Union (Sridhar, 2024). The NAFTA region, comprising the USA, Canada, and Mexico, accounts for 45% of global biopesticide sales, whereas Asia lags, using only 5% of the global supply (Patel et al., 2024; Khairuddin, 2024). While many countries are adopting policies to reduce chemical pesticide use and promote biopesticides, regulatory systems often remain geared towards chemical pesticides, complicating approval processes. The European Union's lengthy registration requirements have resulted in fewer approved biopesticides than Brazil, the United States, China, and India (Ghimire, 2024; Madsen 2024; Singh et al., 2024). Regionally, biopesticide usage faces challenges; in Nigeria, usage remains low due to inadequate infrastructure, high costs, and restrictive government policies (Raghunandan, 2024). In contrast, China has progressed, registering 327 biopesticides, including 270 bacterial types from 11 microbial species, with 181 derived from *Bacillus thuringiensis* (Raghavan et al., 2024). In Kenya, *Bacillus thuringiensis* biopesticides alone generated $1.5 million in sales in 2002. Biopesticides hold a small but growing share of the global pesticide market. In 2009, they represented 3.5% ($1.6 billion) of the global pesticide market, increasing to 5% ($3 billion) by 2013 (Bisht, 2024). Projections suggest that in 2023, biopesticides will constitute 7% ($4.5 billion) of the market, with an annual growth rate of 8.64% (Singh et al., 2024). Market trends indicate a sharp increase in biopesticide demand, driven by rising consumer awareness of organic produce, stricter regulations on chemical pesticide residues, and a growing preference for sustainable farming practices **Figure 1** (Tamang et al., 2024). he biopesticide market, valued at approximately USD 4.3 billion in 2020, is projected to grow at a compound annual growth rate (CAGR) of over 15%, potentially reaching over USD 10.7 billion by 2027 (Singh, 2024), this growth is partly attributed to increased adoption in major agricultural regions like North America, Europe, and Asia-Pacific, where regulatory agencies are encouraging the reduction of synthetic pesticide use.

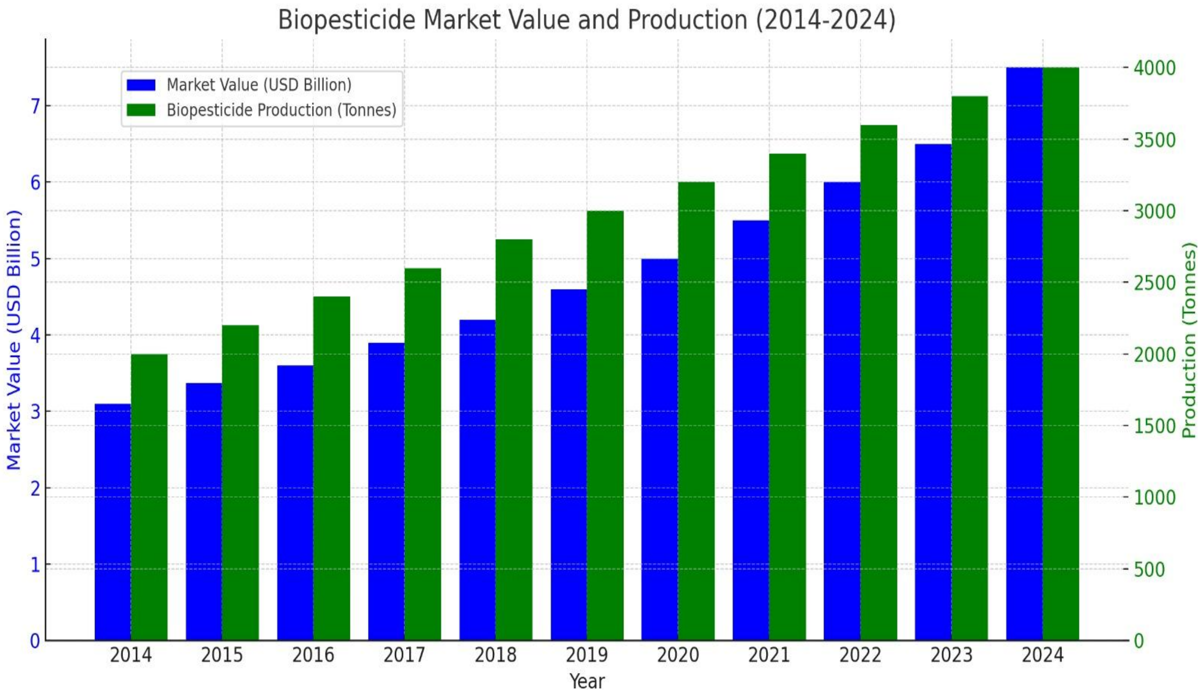

Figure 1. Biopesticide market value and production

From 2014 to 2024, the biopesticide market has demonstrated significant growth, with its market value rising from approximately $3.1 billion in 2014 to an estimated $7.5 billion in 2024, driven by an annual growth rate of 8.64% until

2023 and over 15% in 2024. Concurrently, production levels have steadily increased from 2,000 tonnes in 2014 to around 4,000 tonnes by 2024, reflecting a consistent annual growth of 10%. This expansion aligns with a rising market share, which has grown from 5% in 2013 to a projected 7% by 2024.

The economic viability of biopesticides continues to improve with increasing scalability and innovations in production and delivery methods. Though initially seen as a niche market, biopesticides are becoming integral to the broader agricultural market as farmers and policymakers prioritise environmental sustainability, crop yield enhancement, and soil health; the significant growth in this sector reflects a shift toward environmentally friendly pest control solutions, with the biopesticide industry set to play a substantial role in the future of agriculture, this streamlined overview highlights the production, market dynamics, regulatory hurdles, and regional disparities associated with biopesticides globally, Table 10.

Table 12. Some biofungicides have been developed and commercialized worldwide

Control Agent	Product Names	Formulation Type	Target Pathogens	Crops
Coniothryium minivans	CONTAINS WG	Wettable granule	*Sclerotinia sclerotiorum*, *S. minor*	Greenhouse ornamentals, vegetable transplants, herbs, soil treatment
Bacillus subtilis	QST 713 (CEASE), GB03 (COMPANION), EPIC, KODIAK (HB, A.T)	Liquid, dry powder	*Rhizoctonia solani*, *Pythium*, *Phytophthora*, *Fusarium spp.*, *Alternaria spp.*, *Aspergillus spp.*	Greenhouse ornamentals, vegetable transplants, cotton, legumes
Streptomyces griseovirdis	MYCOSTOP	Dry powder	*Botrytis*, *Rhizoctonia*, *Pythium*, *Phytophthora*, *Alternaria*	Greenhouse ornamentals, vegetable transplants
Trichoderma harzianum	PLANT SHIELD, ROOT SHIELD, T-22 PLANTER BOX	Wettable granule, dry powder	*Cylindrocladium*, *Fusarium*, *Rhizoctonia*, *Pythium*, *Thielaviopis*	
Gliocladium virens	GL-21 (SOIL GARD)	Wettable powder	*Rhizoctonia solani*, *Pythium*	
Streptomyces lydicus	ACTINOVATE		*Powdery mildew*, *Downy mildew*, *Botrytis*, *Rhizoctonia*, *Pythium*, *Phytophthora*	
Gliocladium catenulatum	JII-446 (PRESTOP WP)		*Botrytis*, *Rhizoctonia solani*, *Pythium spp.*, *Phytophthora*, *Fusarium*, *Verticillium spp.*	
Myrothecium verrucaria	DITERA		Root-knot nematodes, citrus cyst, stubby root, lesions, burrowing nematodes	Fruit vegetables, ornamental crops, tur
Fusarium oxysporum (nonpathogenic)	FUSACLEAN	Spores	*Fusarium oxysporum*	Asparagus, basil, carnation, tomato
Pseudomonas cepacian	INTERCEPT	Liquid	*Fusarium spp.*, *Rhizoctonia solani*, *Pythium*	Maize, vegetables, cotton
Agrobacterium radiobacter	K84, GALLTROL		*Agrobacterium tumefaciens*	Ornamental nursery stock, soil treatment
Reynoutria sachalinensis	REGALIA		*Botrytis*, *Leaf Spots*, *Powdery mildew*, bacterial diseases, *Fusarium*, *Rhizoctonia*, *Pythium*, *Phytophthora*, *Verticillium*	Herbs, spices, soil treatment, plant health promotion
Pseudomonas fluorescens	PHAGUS	Bacterial suspension	*Pseudomonas tolassii*	*Agaricus spp.*, *Pleurotus spp.*

The global pesticide market, valued at USD 56 billion, is seeing biopesticides proliferate. Their market is expected to reach between USD 3 billion and USD 4 billionaires, and it is predicted to grow at a compound annual growth rate (CAGR) of 14.1%, outpacing the development of chemical pesticides (Schering, 2024). In North America, the biopesticide market is estimated at around USD 205 million, with projections suggesting it will reach nearly USD 300 million by the end of the decade. North America consumes approximately 40% of global biopesticide production.

In Europe, the market grew from USD 135 million in 2005 to about USD 270 million by 2010, with European and Oceanic markets accounting for 20% of global biopesticide sales. In the South, biopesticide sales are expected to grow modestly, and these regions together represent 10% of the global market. The Asian market, although still small, is growing, with countries like China and India increasing their use of biopesticides. In India, biopesticides currently represent 2.89% of the total pesticide market, with an annual growth estimate of 2.3% (Morabadi et al., 2024).

Biopesticides derived from *B. thuringiensis* are dominant, accounting for over 53% of the global market, particularly in the U.S. and Canada. Bt-based products, followed by *B. subtilis* and *B. fluorescens*, are the most widely used bacterial products (Rege, 2024). Fungal biopesticides, mainly from *Beauveria* species, and viral biopesticides, particularly nucleopolyhedrosis virus, represent significant market share. Nematodes hold around 60% of the other biopesticide category, table 13. By 2023, biopesticides are over 7% of the global crop protection industry, valued at approximately USD 4.5 billion; as the market continues to expand, biopesticidected to compete with synthetic pesticides in market size by the late 2040s to early 2050s, though regional adoption rates, especially in Africa and Southeast Asia, introduce some uncertainty Table 11 (Malachova 2024).

Table 11. Global consumption and growth of biopesticides from 2014 to 2025

Year	Global Biopesticide Market Value	Annual Growth Rate	Market Share in Crop Protection	Key Drivers	Source
2014	~$3.5 billion	~10%	~3-5%	Growing demand for sustainable farming, safety concerns with chemicals.	(Sharma, 2024)
2017	~$4.5 billion	~12%	~5%	Increased adoption in organic farming, regulatory pressure.	(Scherin, 2024).
2020	~$5 billion	~14%	~5%	Shift towards eco-friendly alternatives, pest resistance issues	(Karakaya et al., 2024)
2025	~$8 billion	~14.1%	~8-10%	Environmental regulations, demand for safer food, government incentives	(Scherin 2024).

4 Conclusion

Farmers often face pesticide resistance, making microbial biopesticides key to Integrated Pest Management (IPM). Insects develop resistance to them more slowly than to chemical pesticides. The use and production of biopesticides are increasing due to their host-specific nature. Organic farming and demand for pesticide-free produce also drive their adoption. Increased awareness and support from farmers and policymakers are needed to boost their use and ensure food security. Biopesticides offer numerous benefits as an eco-friendly alternative to chemical pesticides, including lower toxicity, targeted pest control, and reduced environmental impact; their use aligns with the growing demand for sustainable agricultural practices, as they promote biodiversity and minimize harm to non-target organisms, with advancements in biopesticide formulations, such as nanoemulsions and encapsulation, their efficacy and stability have significantly improved, further boosting their potential in the agricultural sector, one of the most significant contributions of biopesticides is their role in reducing the reliance on harmful chemical pesticides, by integrating biopesticides into pest management strategies, growers can effectively control insect pests while minimizing the harmful effects of synthetic chemicals on food safety, human health, and the environment, this shift not only enhances crop protection but also supports long-term agricultural sustainability. Looking forward, biopesticides are poised to play a crucial role in the future of sustainable farming. As research and development continue to optimise their formulations and application methods, biopesticides can become a cornerstone of integrated pest management strategies; by embracing biopesticides, agriculture can move toward a more sustainable, efficient, and environmentally conscious approach to insect pest control, ultimately benefiting both producers and consumers.

Acknowledgement

The authors would like to acknowledge Kandahar University for their ongoing support.

Conflict of Interest

The authors declare no conflicts of interest.

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