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Biological Pesticides as Viable Alternative to Synthetic Pesticides for Sustainable Agriculture and Nutrition: A Systematic Review

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ABSTRACT

The overuse of synthetic pesticides in agriculture has raised significant environmental and health concerns. Biopesticides have emerged as viable, environmentally compatible alternatives. However, recent comprehensive reviews integrating all biopesticide categories and emphasizing their contribution to synthetic-pesticide-free and health-safe products remain limited. This PRISMA-based systematic review synthesizes 98 peer-reviewed studies. It evaluates the main categories of biopesticides: microbial, biochemical, and plant-incorporated protectants (PIPs), their roles in sustainable agriculture and integrated pest management (IPM), as well as the future trajectory of biopesticides. Microbial agents (bacteria, fungi, viruses) show strong target specificity and reduced environmental persistence. Biochemical pesticides, derived from plant extracts and pheromones, disrupt the behavior or physiology of pests with minimal non-target toxicity. PIPs, developed through genetic engineering, provide crop-embedded protection and greatly reduce chemical inputs. Despite these advantages, inconsistent field performance, short shelf life, regulatory hurdles, and low farmer awareness limit commercialization. Innovations such as RNA interference (RNAi), Nano-formulations, and microbial consortia offer promising solutions. This review underscores the need for better delivery systems, harmonized regulations, and coordinated outreach to accelerate adoption. Overall, biopesticides are a scientifically robust and essential component of sustainable crop protection.

1 | Introduction

Synthetic pesticides have played a central role in modern agriculture. They boost crop productivity and reduce pest-associated losses. However, intensive and prolonged use has led to environmental contamination, soil and water degradation, food-residue accumulation, and rising public health concerns (Gu et al. 2021). Ecological risks include reduced biodiversity, disruption of beneficial arthropod communities, and contamination of surface and groundwater. These challenges have intensified global calls to reduce dependence on synthetic chemical inputs. Concerns, along with the growing demand for residue-free agricultural products, are shifting attention toward safer and more sustainable crop-protection strategies (Zhou et al. 2025).

Biopesticides now play a key role in this transition. Biological pesticides offer significant long-term advantages over conventional chemical pesticides and play a crucial role in sustainable crop protection systems. Their natural origin and biodegradability result in minimal environmental persistence, thereby reducing soil, water, and air contamination over extended periods. This contributes to improved ecosystem stability and environmental sustainability. Scientists broadly define biopesticides as pest-management agents that originate from natural sources, such as microorganisms (bacteria, fungi, viruses), bioactive metabolites, plant extracts, pheromones, and genetically engineered crops with pesticidal traits (Dar et al. 2021). Increasing consumer demand for environmentally responsible production, the growth of organic agriculture, and heightened regulatory oversight of chemical pesticides have intensified global interest in biopesticides (Bailey et al. 2010). Market analyses consistently indicate rising demand, driven by greater health awareness and supportive policy measures (Dar et al. 2021).

However, the broad adoption of biopesticides remains limited by factors such as inconsistent field efficacy, short shelf life, variability in product quality among manufacturers, and insufficient farmer training. Overcoming these barriers necessitates a rigorous scientific understanding of the biological mechanisms, formulation technologies, and regulatory factors influencing biopesticide development and implementation. To address these challenges, this PRISMA-guided systematic review synthesizes findings from 98 peer-reviewed studies to: (1) classify major biopesticide categories and describe their mechanisms of action; (2) examine formulation, application, and delivery systems; (3) summarize global market trends, regulatory frameworks, and adoption barriers. This comprehensive synthesis seeks to provide an integrated and current perspective on biopesticides as essential elements of contemporary crop protection systems.

2 | Methods

This systematic review was conducted in accordance with PRISMA standards, incorporating a structured process for identifying, screening, assessing eligibility, and selecting studies on biopesticides and their agricultural applications. The protocol was designed to ensure methodological rigor, transparency, and reproducibility, while providing a comprehensive synthesis of the current evidence base.

2.1 | Data Collection and Screening Procedures

A comprehensive literature search was conducted across major scientific databases, including PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar, to identify peer-reviewed articles published in English up to September 2025. To increase inclusiveness, additional sources were reviewed: institutional repositories, reference lists from relevant studies, and publications from regulatory agencies such as FAO, EPA, and the European Commission. The search used a combination of keywords and Boolean operators, according to the following core search string: ("biopesticide" OR "biological pesticide" OR "pesticide" OR "biocontrol agent" OR "microbial pesticide" OR "biochemical pesticide" OR "plant-incorporated protectant" OR "sustainable agriculture" OR "Insecticide"). Database syntax was modified as needed, and searches were conducted in titles, abstracts, and keyword fields.

Studies were included if they: (i) focused on microbial, biochemical, or plant-incorporated protectant (PIP) biopesticides; (ii) reported on mechanisms of action, efficacy, formulation, application systems, regulatory aspects, or market trends; (iii) were peer-reviewed research articles published in English; and (iv) provided extractable data relevant to the review objectives. Studies were excluded if they were non-scientific sources such as news articles or general websites, addressed only synthetic pesticides, lacked sufficient methodological detail, were duplicate records, had unavailable full texts, or were published before 2005.

2.2 | Study Selection

The initial search identified 265 records, which were organized in *Zotero* referencing software and then imported into *Rayyan*, a platform for systematic screening and collaborative review. After duplicate removal in *Zotero*, 217 unique studies proceeded to the title and abstract screening stage. The records were independently evaluated by the author and co-authors using predefined inclusion and exclusion criteria to reduce bias and screening errors. Of these, 126 studies were excluded due to irrelevance, non-agricultural focus, or insufficient information, resulting in 98 articles for full-text assessment. All 98 articles satisfied the eligibility criteria and were included in the final analysis. The complete study selection process is illustrated in Figure 1 (PRISMA flow diagram).

3 | Result and Discussion

3.1 | Overview of Synthetic Pesticides and the Need for Alternatives

The analysis of 98 peer-reviewed studies, this review evaluates the widespread application and inherent limitations of synthetic pesticides in contemporary agriculture. Synthetic pesticides, encompassing herbicides, insecticides, and fungicides, have substantially improved crop protection and agricultural productivity. However, their prolonged and extensive use has led to environmental contamination, residue persistence, toxicity to non-target organisms, and the accelerated development of resistant pest populations (Dar et al. 2021). Global data reveal that pesticide application is most concentrated in fiber crops (67%), followed by fruits (50%), vegetables (46%), spices (43%), oilseeds (28%), and pulses (23%) (Khursheed et al. 2022). This heavy dependence on inorganic chemical inputs has generated significant environmental and agricultural challenges, highlighting the urgent necessity for safer and more sustainable pest management approaches. In response, biopesticides have gained prominence as viable alternatives to conventional chemical pesticides, attributed to their biodegradability, target specificity, and compatibility with integrated pest management systems (Rhie et al. 2021). Biopesticides comprise microbial agents, biochemical substances, and genetically incorporated pest-resistant traits, with widely adopted examples including *Trichoderma* (biofungicide), *Phytophthora* (bioherbicide), and *Bacillus thuringiensis* (bioinsecticide) (Bailey et al. 2010). Therefore, adoption of biologically based pest control strategies constitutes a pivotal advancement in the pursuit of environmentally responsible and sustainable agriculture.

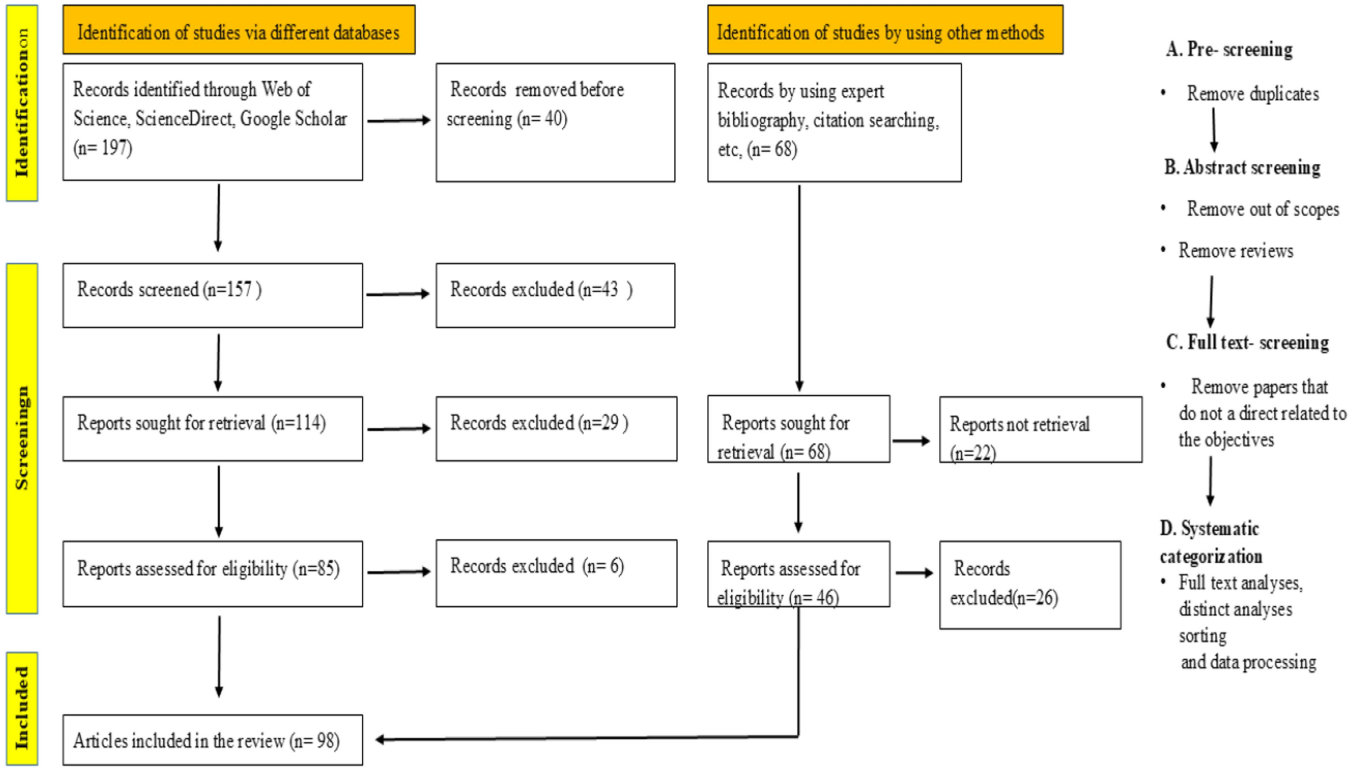

FIGURE 1 | PRISMA flow diagram depicting the study selection process, including records identified through database searching and other methods, duplicate removal, screening stages, eligibility assessment, and final inclusion of studies for qualitative synthesis.

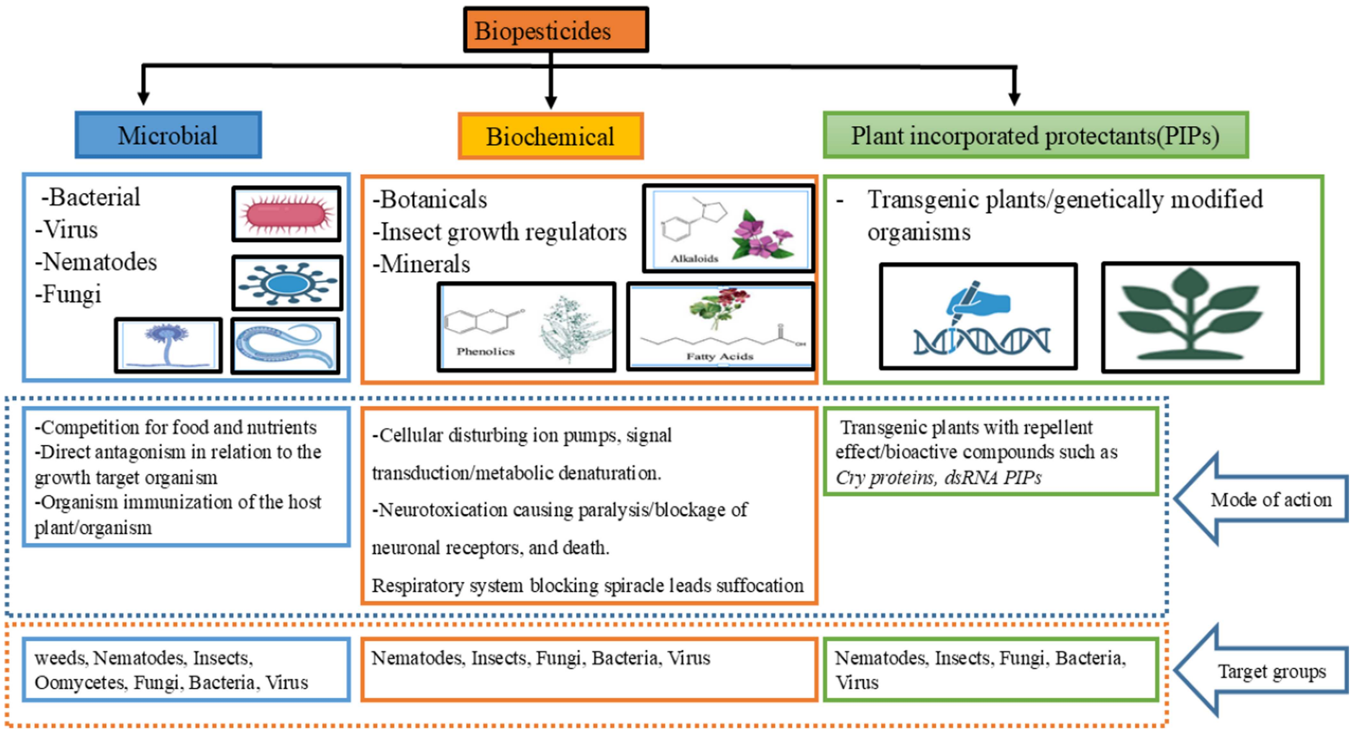

FIGURE 2 | Schematic representation of the three principal classes of biopesticides, their constituent types, physiological and molecular modes of action, and the corresponding target pest organisms.

3.2 | Major Categories of Biopesticides

All reviewed studies clearly classify biopesticides into three major group microbial, biochemical, and plant-incorporated protectants (PIPs) based on their origin and the nature of the active compounds (Figure 2). This classification helps us understand the variety and use of biological pest control in modern agriculture. Microbial biopesticides use living microorganisms, such as bacteria, fungi, viruses, or protozoa, to control pests. They work by infecting pests, competing with them, or producing toxic substances. Biochemical biopesticides are natural compounds, such as pheromones, plant extracts, or growth regulators. These control pests by altering their behavior or physiology, rather than directly poisoning them. Plant-incorporated protectants (PIPs) are substances made by genetically modified plants. These plants have genes added for pest resistance. The next sections will discuss these categories in more detail.

3.2.1 | *Microbial Biopesticides*

Microbial biopesticides reach crops through live or dead organism and spores. They comprise 41% global biocontrol agents, 33% macrobiotics, and 26% other natural products (Tadesse Mawcha et al. 2024). They use microscopic organisms for pest control. These viable microorganisms including spores or active organisms specifically target and infect pests. Recent research demonstrates that microbial isolates serve as an efficient bioresource for degrading various pesticides, including fungal isolates capable of degrading compounds such as lindane, methamidophos, endosulfan, chlorpyrifos, atrazine, cypermethrin, dieldrin, methylparathion, and heptachlor (Maqbool et al. 2016). Microbial bioremediation can be performed by three main strategies: natural attenuation (leveraging the inherent degradative capabilities of microorganisms present in the contaminated matrix, bioaugmentation (introducing non-native or genetically modified microorganisms to enhance degradation, and bio stimulation (supplying nutrients or electron acceptors to stimulate microbial activity. Microbial biopesticides are engineered from microorganisms such as bacteria (Table 1), fungi (Table 2), protozoa, algae, and viruses (Table 3). The working gene strain (active compound) of the above-mentioned microbes harms certain plant pathogens or worms. Bioinsecticides affect insects that feed on crops, whereas bioherbicides use microorganisms like fungi to control weeds. Bacterial biopesticides are the most used microbial pesticides, mainly targeting insect pests. Bacterial pathogens must contact or be ingested by the target, and then they release endotoxins, which disrupt the pest's digestion. *Bacillus thuringiensis* (*Bt*), the most common species, has controlled lepidopterans, hemipterans, and coleopterans in agriculture, forestry, and medicine since 1901 (Adang 2018). Bacterial insecticides control particular insects in cabbage, potato, and other crops. Bacterial entomopathogens are pathogens that kill or seriously disable insects, such as *pseudomonas*, *Yersinia*, *Chromobacterium*, and others. Mycopesticides are fungi and their cell components that naturally control pests. Their sticky spores attach to insects, germinate, and form tubes that penetrate the skin. They release enzymes, especially *chitinases* and toxins, disrupting physiology and causing death (Tadesse Mawcha et al. 2024). The most common fungicides include the following: *Beauveria bassiana*, *Metarhizium anisopliae*, *Verticillium*, *Lecanicillium*, *Hirsutella*, *Isaria fumosorosea, Hirsutella thompsonii*, *Phytophthora palmivora, Alternaria cassia*, and *Lecanicillium spp*.

Baculoviruses are the other important source of microbial pesticides; their infectiousness is attributed to the presence of crystalline occlusion bodies (crystalline protein matrices that occlude the nucleocapsid in some viruses), which are active against consuming insects. A body with baculoviral occlusion is essentially a virion mixed with the *Bt* toxin to produce recombinant baculovirus (*ColorBtru*s), which generates occlusion bodies that integrate the Bt insecticidal *Cry1Ac* toxin protein, increasing the speed of action and pathogenicity over the wild-type counterpart (Ulusoy et al. 2022). *Heliothis zea nucleopolyhedrosis virus (HzNPV)* was the first commercially successful broad-spectrum viral insecticide (Tomar et al. 2022).

3.2.2 | *Biochemical Pesticides*

Several naturally occurring compounds can control pests via nontoxic methods, like extracts of plants, fatty acids, or pheromones that repel or attract insects. In other words, biochemical pesticides are natural or synthetic chemicals that mimic naturally occurring compounds in terms of their structure and function. Plant growth regulators are biological pesticides that inhibit growth or mating, whereas pheromones repel or attract pests. These pesticides are further classified (Table 4) according to whether they use pheromones (semi chemicals), plant extracts/oils, or natural insect growth regulators to regulate insect pest infestations (Haseeb et al. 2022).

Insect Pheromones: Insects produce chemicals that can interfere with insect mating and, as a result, reduce the number of insect offspring. Pheromones are chemical signals secreted by organisms that influence the behavior of conspecific insects, rather than directly killing them. When released into the environment, pheromones can disrupt insect behaviors such as mating, aggregation, or host finding. Insects detect pheromones through their antennae, which contain sensilla microscopic hair-like structures with pores that allow pheromones to enter. Inside the sensilla, pheromone-binding proteins (PBPs) transport the molecules to specific olfactory receptor proteins (ORs) on the dendritic membranes of olfactory sensory neurons. Binding of the pheromone to an OR activates a signal transduction cascade, generating electrical signals that are transmitted to the brain, ultimately modifying the insect's behavior (Pelosi et al. 2018).

Oils and Extracts from Plant Bodies: Important oils and extracts from plants have emerged as viable alternatives to synthetic chemicals to kill insects and pathogens. These are naturally occurring insecticides, since they are derived from plants, and include a variety of bioactive components. Essential oils and extracts from plant bodies have a broad scale of anti-insect actions, which depend on the physiological features of target organisms and plant types. These important bioactive compounds can be repellents, attractants, or anti-feedants; they can also impair respiration, hinder insect recognition of host plants, prevent oviposition, and reduce adult emergence through ovicidal and larvicidal activities. In this regard, well-known examples are *neem* and *lemongrass* oil; both of these plants are widely accessible in the World Plants Shopping Centre. Numerous studies have demonstrated that the combined application of *Azadirachta indica* oil and *entomopathogenic fungi*, particularly *Beauveriabassiana*, is extremely effective in controlling pests that feed and suck on vegetables (Halder et al. 2021).

TABLE 1 | Known examples of biocontrol agents extracted from bacterial strains to tackle plant-pathogenic microorganisms: Reviewed from current literatures.

Bacterial Strains	Plants tested/Plant disease	Pathogens	Mode of action	References
Azospirillumbrasilense	Strawberry/anthracnose	*Colletotrichumacutatum*	Induces systemic resistance	Hungria et al. (2010)
Azotobacterchroococcum	Cotton and rice	*Rhizoctoniasolani*	Nutrient competition; antifungal metabolites; plant growth promotion	Wani et al. (2016)
B. subtilis BY-2	Oilseed rape	*S. sclerotiorum*	Lipopeptide antibiosis; root colonization	X. Hu et al. (2014)
Bacillus licheniformis BL06	Pepper	*Phytophthoracapsici*	Antimicrobial compounds; nutrient competition	X. Hu et al. (2014)
Bacillus megaterium	Citrus fruit	*Blue mold*	Antagonistic metabolites	X. Hu et al. (2014)
Bacillus methylotrophicus	Maize/stalk rot	*Fusariumgraminearum*	Antibiotic production	Cheng et al. (2019)
Bacillus subtilis 26DCryChS	Wheat	*StagonosporanodorumBerk.*	ISR induction; competitive colonization	Maksimov et al. (2020)
Bacillus thuringiensis	Sclerotiniose/*Brassica campestris* L.	*Sclerotiniasclerotiorum*	Insecticidal/crystal proteins	Bravo et al. (2011)
Brevibacillus brevis	Strawberry/gray mold	*Botrytis cinerea*	Antibiotic production	Wei et al. (2017)
Brevibacillus brevis	Tomato	*Fusariumoxysporumf.* sp. *lycopersici*	Antifungal metabolites	Wei et al. (2017)
Burkholderiacepacia strain BY	Tomato/damping-of	*Rhizoctoniasolani*	Antifungal compounds; biofilm formation	Vial et al. (2011)
Ochrobactrumanthropi BMO-111	Tea/blister blight	*Exobasidiumvexans*	Antimicrobial metabolites	Sowndhararajan et al. (2013)
P. chlororaphis	Canola plant	*S. sclerotiorum*	ISR induction	Gunther et al. (2005)
Paenibacillus alvei K-165	Cotton/black root rot	*Thielaviopsisbasicola*	Antimicrobial compounds; root colonization	Antonopoulos et al. (2008)
Paenibacilluspolymyxa BRF-1	Soybean/root rot	*Phialophoragregata*	Antibiotic production; competition for nutrients	Antonopoulos et al. (2008)
Pantoeaagglomerans	Wheat root pathogen	*Rhizoctoniasolani AG-8*	Antibiosis; niche competition	Gadissa et al. (2018)
Pantoeaagglomerans	Banana/crown rot	*Colletotrichummusae and Lasiodiplodiatheobromae*	Antifungal metabolites	Antonopoulos et al. (2008)
Pseudomonas and Burkholderia	NA	*Phytophthoracapsici*	Antibiotic production	Andolfi et al. (2008)
Pseudomonas fluorescens	Apple/mucor rot	*Mucor piriformis*	ISR induction; root colonization	Andolfi et al. (2008)
Pseudomonas parafulva JBCS1880	Soybean/bacterial pustule Rice/panicle blight	*Xanthomonasaxonopodispv. glycines*, *Burkholderiaglumae*	Antimicrobial metabolite production; competition for nutrients	Kakembo and Lee (2019)
Pseudomonas putida BP25	Blast disease/rice	*Magnaportheoryzae*	Antifungal metabolites	Ashajyothi et al. (2020)
Rhizobium japonicum	Soybean/root rot	*Fusariumsolani*; *Macrophominaphaseolina*	Production of antibiotics;	Al-Ani et al. (2012)

TABLE 2 | Known examples of biocontrol agents extracted from fungal strains to tackle plant-pathogenic microorganisms: Reviewed from current literatures.

Fungal Strains	Plants tested/Plant disease	Pathogens	Mode of action	References
Aspergillus fumigates	Cocoa/black pod	*PhytophthoraPalmivora*	Antagonistic metabolite production; mycoparasitism	Adebola and Amadi (2010)
Paecilomyceslilacinus	Cocoa/black pod	*Meloidogynejavanica*	Production of lytic enzymes; colonization of root zone	El-Saadony et al. (2022)
Penicilliumoxalicum	Tomato/wilt	*Fusariumoxysporum f.* sp. *Lycopersici*	Antifungal metabolite production; competition for nutrient	De Cal et al. (2000)
Penicillium sp. *EU0013*	Tomato and cabbage/wilt	*Fusariumoxysporum*	Antibiosis; root colonization	Alam et al. (2011)
Pochoniachlamydosporia	Carrot/root knot disease	*Meloidogyne incognita*	Nematode egg parasitism	Wesemael et al. (2011)
Purpureocilliumlilacinum	Vignaradiata/root knot disease	*Meloidogyne incognita*	Parasitism; lytic enzyme secretion	A. Khan et al. (2019)
Purpureocilliumlilacinum	Pineapple/root knot disease	*Meloidogynejavanica*	Parasitism	Kiriga et al. (2018)
Trichoderemahamatum	Cabbage	*S. sclerotiorum apothecia*	Mycoparasitism; lytic enzyme production	Jones et al. (2014)
Trichodermaasperellum	Beans	*S. sclerotiorum apothecia*	Mycoparasitism; secondary metabolite production	Brito et al. (2014)
Trichodermaasperellum	Onion	*Sclerotiumcepivorum*	Antagonistic metabolites; mycoparasitism	Rivera-Mendez et al. (2020)
Trichodermaasperellum T8a	Mango/anthracnose	*C. gloeosporiodes*	Mycoparasitism; induction	Rivera-Mendez et al. (2020)
Trichodermaatroviride	Beans	*Botrytis cinerea*	Mycoparasitism; competition for nutrients	Bogumił et al. (2013)
Trichodermaharzianum	Rice/brown spot	*Bipolarisoryzae*	Antifungal metabolites; ISR induction	Khalili et al. (2012)
Trichodermaharzianum T-22,	Soya bean	*Suppressive effect on S. sclerotiorum*	Mycoparasitism; induced systemic resistance	Dalacosta et al. (2022)
Trichoderma spp.	Tobacco/root rot	*Rhizoctoniasolani*	Mycoparasitism; lytic enzymes; ISR induction	S. M. Khan et al. (2019)
Trichodermavirens	Okra/root knot disease	*Rhizoctoniasolani*	Antifungal metabolite production; ISR induction	Lakshmy and Susannamma (2014)

TABLE 3 | Known examples of biocontrol agents extracted from viral strains to tackle plant-pathogenic microorganisms: Reviewed from current literatures.

Strains from virus	Type	Test plant/disease	Target pathogen	Mode of action	References
Cydiapomonella GV	Insecticide	Apples and pears	*Codling moth*	Infection of larval gut cells leading to mortality	Gómez Valderrama et al. (2018)
Zucchini yellow mosaic virus, weak strain	Anti-viral	Transplanted zucchini and cantaloupes, watermelons, squash	*Zucchini yellow mosaic virus*		

Insect Growth Regulators (IGRs): IGRs eliminate insects by interfering with specific life-sustaining systems based on several methods of action. IGRs have lately been categorized as *chitin synthesis inhibitors* (CSIs) and chemicals, e.g., juvenile *hormone* analogs and *ecdysteroids* that disturb insects' hormone function. Although IGRs are not directly lethal to adult insects, they can control insects such as fleas, cockroaches, and mosquitos. They are not harmful to humans, but hinder young insects from reproducing, hatching eggs, molting from one stage to the next, and killing adult insects when combined with other pesticides (Sarwar 2020).

3.2.3 | *Gmo Products and Plant-Incorporated Protectants (Pips)*

Compounds produced by GMOs through plant biotechnology can then be utilized for synthesizing biopesticides called plant-incorporated protectants (PIPs) (Table 5). PIPs are bioinsecticides that are directly expressed in the body of genetically modified crops to protect them against pests such as insects and viruses. *Cry* proteins are the most recent insecticidal proteins to be introduced into GM crops with *Bt* transgenes. In the insect gut, PIPs based on a gene called the *cry protein and on double-stranded ribonucleic acid* (*ds*RNA) exert a variety of impacts on the growth of insects or induce insect death (Vogel et al. 2019). Upon eating, the pest insect's dsRNA PIPs are delivered and enter into the cells of the target organism. Within the cell, dsRNA is broken down by tiny RNA-interfering molecules (siRNA, 20 sequences) that are subsequently employed to degrade complementary mRNA by the insect's endogenous RNA interference (RNAi) machinery. PIPs derived from *cry* proteins bind to target binding sites on the thin cell layer (epithelial) of an insect's digestive tract, and eventually form integral membrane proteins, i.e., transmembrane pores, resulting in cell lysis and pest death (Abdollahdokht et al. 2022). The so called, *Cry* proteins include the *Cry*1 toxin *Lepidoptera* (corn borer) and *Cry*3 poison *Coleoptera* (corn rootworm) forms, each with a unique structure and toxicity specific to certain insect species. In potatoes, tomatoes, tobacco, and cotton, resistance genes are indirectly integrated from *Bt* into plants (Singh et al. 2023).

The genetic modification of biological agents is a novel idea, and requires a deep knowledge of the organism's biology, ecology, and behavior. Recent research on GMOs has led to significant advancements across various fields, including food science and nutrition. In general, thanks to biotechnology and crop molecular science, the use of biopesticides has been enhanced, improving pest control, reducing chemical use, and promoting sustainability. Their key benefits are pest resistance, reduced chemical use, targeting of specific actions, higher yield and quality, environmental safety, and resistance management.

Engineered crops: To date, approximately 27 unique species of transgenic crop plants have been developed, including walnut, poplar, sugar beet, rice, soybean, corn, rapeseed, potato, and sunflower (Bharti and Ibrahim 2020). All of the major proteins involved in *Bt*'s insecticidal activities have been identified and sequenced. Recently, the nucleotide sequences of over 20 *Bt* genes encoding lepidopteran-specific insecticidal proteins were determined and characterized. It was found that eight genes encode proteins that are active against dipterans, and two genes

TABLE 4 | Exemplary biochemical pesticides used for insecticidal pest management: Reviewed from current literatures.

Categorization of biopesticides			
Derivatives of plants	**Target pests**	**Known ingredient (s)**	**Reference**
Neem tree, *Azadirachtaindica*	Majority of herbivorous insects	Azadirachtin	MordueLuntz and Nisbet (2000)
Chrysanthemum	Majority of herbivorous insects	Pyrethrum	Teixeira da Silva et al. (2013)
Thyme, *Thymus vulgaris*	Varroa mite (Varroa destructor)	Thymol	Mandal and DebMandal (2016)
Ageratum houstonianum	Heteroptera, Homoptera, and Orthoptera	Precocene I and II	Zeeshan et al. (2012)
Saponin	Mites, lepidopterans, beetles, and many other insects	IGR	Moghimipour and Handali (2015)
Basil, *Ocimumbasilicum*	Most field crop pests	Juvocimenes	Shahrajabian et al. (2020)
Garlic, *Allium sativum*	*B. brassicae*, *Sitotrogacerealella*, *S. lit*	Diallyl disulfide	Londhe et al. (2011)
Derivatives of insect pests	Pheromone type	Known ingredient(s)	Reference
Helicoverpaarmigera	Sex pheromone	(Z)-11-hexadecenal + (Z)-9-hexadecenal and (Z)-9-tetradecenal	J.-P. Zhang et al. (2012)
Spodopteralitura	Sex pheromone	(Z,E)-9,11- and (Z,E) -9,12-tetradecadienyl acetate	PLH et al. (2019)
Leucinodesorbonalis	Sex pheromone	(E)-11-hexadecenyl acetate, (E)-11- hexadecen-1-ol	Cork et al. (2001)
Fall armyworm *(Spodopterafrugiperda)*	Sex pheromone	7-dodecen-1-ol acetate, dodecan-1-ol acetate, (Z)-11-dodecen-1-ol acetate, (Z)-9- tetradecen-1-ol acetate, (Z)-11-hexadecenal, (Z)-9-tetradecenal, and (Z)-11-hexadecen-1- ol acetate	Hruska (2019)
Pink bollworm *(Pectinophoragossypiella)*	Sex pheromone	(Z,Z)-7,11- and (Z,E)-7,11-hexadecadienyl acetates	Mohan et al. (2016)
Japanese beetle, *Popillia japonica*	Sex pheromone	(R,S)-5-(1-decenyl)-dihydr0-2-(3H)- furanone	Saeki et al. (2005)
Cotton boll weevil, *Anthonomusgrandis*	Aggregation pheromone	Grandlure (cyclobutane alcohol (3 parts), cyclohexane alcohol (4 parts), and Z-and Epair of cyclohexane and acetaldehydes)	Almeida Garcia et al. (2017)
Leptinotarsadecemlineata, Colorado potato beetle	Aggregation pheromone	(S)-3,7-dimethyl-2-oxo-oct-6-ene-1,3-diol	Göldel et al. (2020)
Southern pine beetle, *Dendroctonus frontalis*	Aggregation pheromone	1,5-Dimethyl-6,8-dioxabicyclo[3.2.1]octane	Gomez et al. (2020)

encode proteins that are active against coleopterans (Abdollahdokht et al. 2022), (Su et al. 2022).

3.3 | Mechanism of Action of Biopesticides

Biopesticides achieve pest control through several complementary mechanisms that are fundamentally distinct from those of synthetic pesticides.

3.3.1 | *Microbial Biopesticides*

Microbial biopesticides comprise bacteria, fungi, viruses, and entomopathogenic nematodes that suppress pest populations through infection, toxin production, or host colonization. These agents generally invade hosts through ingestion or cuticular penetration, disrupting critical physiological processes and resulting in reduced feeding, paralysis, or mortality.

TABLE 5 | Some selected transgenics/plant-incorporated products applied for insect pest management: Reviewed from current literatures.

Selected plants	Genes	Target pests	References
Tomato	*cry* 1Ac, *cry* 1Ab	*M. Sexta*, *H. armigera*, *Heliothisvirescens*	Garavaglia et al. (2012)
Potato	*Cry*5, *cry*1*Ac*9, *cry*1Ab, *cry* 2a5, *cry* 3b, *cry* 3a, *cry* 3,	*Phthorimaeaoperculella*, *Leptinotarsadecemlineata*	Rani et al. (2021)
Soybean	*cry*1A(c)	*Cigarette beetle Pseudoplusia*, *H. zea*, *H. virescens*	Horikoshi et al. (2021)
Maize/corn	*cry* 34Ab1/*cry* 35 Ab1 + *cry* 3Bb, *cry* 1 F + *cry* 1Ab, *cry* 9 C, *cry* 3Bb, *cry*1F, *cry* 34Ab1/*cry* 35 Ab1, *cry* 1 Ab	*S. frugiperda,D. virgiferavirgifera*, *Diabroticaundecimpunctatahowardi*, *Ostrinianubilalis, Chilopartellus*, *Busseolafusca*, *H. zea*, *Diatraeagrandiosella*, *D. saccharalis*	Arora and Shera (n.d.)
Rice	*cry*1Ac, *cry*2a/*cry* 1 Ab, *cry* 1 Ac, *cry* 1Ab	*Cnaphalocrocismedinalis*, *Chilosuppressalis*, *Scirpophagaincertulas*	Li et al. (2023)
Cotton	*cry* 1Ac, *cry* 1Ab/*cry* 1Ac, *cry* 1Ac + *cry*2Ab, *cry*1C	*Trichoplusiani*, *Spodoptera* spp., *Helicoverpaarmigera*, *Earias* spp., *Heliothisvirescens*, *H. zea*, *Pectinophoragossypiella*	Rani et al. (2021)
Canola	*cry*1A(c), *cry* 1 C	*H. zea*, *S. exigua*, *Diamondback moth*, *H. zea*, *cabbage looper*, *Susumiaexigua*	Sayyed et al. (2003)
Poplar	*cry* 1Aa, *cry*3Aa	*Chrysomelatremulae F.*, *Lymantriadispar*	J. Hu et al. (2014)
Sorghum	*cry 1Ac*	*Chilopartellus*	Visarada et al. (2014)
Sugar cane	*cry 1Ab*	*D. saccharalis*	Arvinth et al. (2010)
Chickpea	*cry 1Ac*	*H. armigera*	Mehrotra et al. (2011)
Tobacco	*cry 1Ac*, *cry 1Ab*, *cry 1Aa*, *cry 2a5*, *cry 3*	*H. armigera*, *H. zea*, *Leptinotarsadecemlineata*, *H. virescens*, *Manducasexta*	Rani et al. (2021)
Brinjal	*cry 3b*, *cry 1Ac*	*Leptinotarsadecemlineata*, *Leucinodesorbonalis*	Sidhu et al. (2014)
Cabbage (Chinese)	*cry 1Ac*, *cry 1Ab*,	*Plutellaxylostella*	Zhu et al. (2015)
Broccoli	*cry 1 C*	*T. ni*, *P. xylostella*, *Pierisrapae*	Cao and Earle (2003)
Groundnut	*cry 1Ac*	*Elasmopalpuslignosellus*	Keshavareddy et al. (2013)
Alfalfa	*cry 1 C*	*S. littoralis*	Tang et al. (2006)

Spore-forming bacteria, especially *Bacillus thuringiensis* (Bt), synthesize insecticidal crystal (Cry) proteins that specifically target insect gut tissues. Upon ingestion, these toxins damage midgut epithelial cells, resulting in gut paralysis and death. The use of Bt formulations and Bt-expressing crops, such as cotton, has substantially decreased dependence on chemical insecticides (Adang 2018).

Entomopathogenic fungi manage insect populations by attaching to the insect's cuticle, germinating, and penetrating the host's tissues. After entry, they proliferate and secrete enzymes and toxins that interfere with host metabolism and immune function (De Maagd et al. 2003).

Baculoviruses are highly host-specific entomopathogenic viruses that infect insects after ingestion. Their occlusion bodies safeguard viral particles in the environment and facilitate efficient transmission. Viral replication disrupts host metabolism and development, resulting in mortality and population suppression (Adang 2018).

Entomopathogenic nematodes (EPNs) are soil-dwelling organisms that locate hosts using chemical and physical signals. Infective juveniles penetrate insects through natural openings and release symbiotic bacteria, which rapidly kill the host through the production of toxins (Y. Zhang et al. 2022). Detailed molecular targets (e.g., ribosomes, ion channels, neurotransmitters) are summarized in supplementary Table (Table S1).

3.3.2 | *Biochemical Pesticides*

Plants have developed and produced a plethora of compounds, like steroids, alkaloids, phenylpropanoids, phenolic, and terpenoid molecules that can assist in the fight against pathogenic bacteria during infection and assault. Microbicides impair pest metabolic functions, disrupt plasma membrane integrity, and limit conidial production. In contrast, botanical insecticides such as azadirachtin and nicotine act by altering respiratory processes, interfering with insect growth hormones, or binding

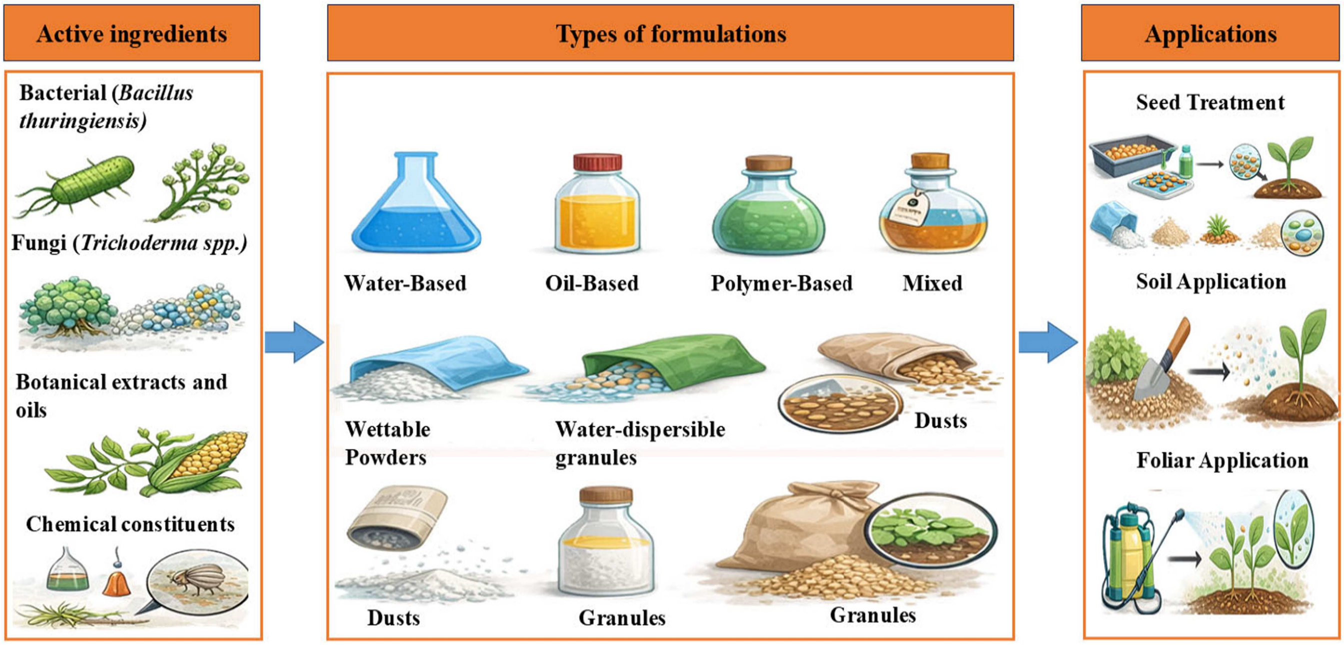

FIGURE 3 | Integrated framework depicting the relationship between active ingredients, formulation technologies, and application strategies in agricultural bioformulations. The diagram summarizes microbial and botanical inputs, physicochemical formulation types, and their deployment through seed, soil, and foliar applications.

to sodium channels in the nervous system (Gérardin et al. 2019).

3.3.3 | *Genetically Modified Organisms as Biopesticides*

When genes encoding *Bacillus thuringiensis* (Bt) toxins are introduced into plants, the transgenic crops produce insecticidal proteins that confer resistance against target pests. Bt-derived delta endotoxins are synthesized as protoxins and are activated by proteases in the insect midgut, after which the toxic proteins bind to specific epithelial receptors, causing cell swelling, membrane lysis, ion leakage, and ultimately insect death (Gérardin et al. 2019).

3.4 | Formulation and Application Systems of Biological Pesticides

Effective formulation and delivery are among the primary barriers to the large-scale adoption of biopesticides, as biological active ingredients are often sensitive to environmental stresses such as temperature, ultraviolet radiation, and desiccation. Formulation plays a critical role in enhancing product stability, prolonging shelf life, improving field performance, and ensuring compatibility with existing agricultural practices.

Formulation. Biopesticide formulations are categorized into liquid and dry types according to the carrier system and application method (Figure 3). They combine biologically active agents with carriers and additives to improve stability, delivery efficiency, and protection during use. Liquid formulations encompass a range of systems, including water-based, oil-based, polymer-based, and mixed systems, such as suspension concentrates, oil dispersions, suspo-emulsions, and capsule suspensions. These formulations typically incorporate stabilizers, surfactants, adhesives, UV protectants, and nutrients to enhance biological viability and field persistence. Dry formulations, such as wettable powders, water-dispersible granules, dusts, and granules, are commonly used for seed treatment (coating seeds before planting) or soil application due to their ease of handling and extended shelf life (Bharti and Ibrahim 2020). Detailed functional classes of formulation components used in biopesticide products for each component class are provided in the supplementary table (Table S2).

Application system: Biopesticides are applied through delivery systems that must be practical, cost-efficient, and compatible with standard agronomic equipment. Common application methods include seed treatment, soil application, and foliar delivery, depending on the target pest and crop growth stage.

Seed treatments allow beneficial microorganisms to colonize the spermosphere and rhizosphere, providing early-stage protection against soil- and seed-borne pathogens. Soil applications are particularly effective in suppressing overwintering pathogen propagules and promoting suppressive soil conditions. For example, *Trichoderma*-based formulations applied to soil have been widely used in vegetable and cereal systems to reduce root diseases while improving plant vigor (Bharti and Ibrahim 2020).

Selected case studies demonstrating the effectiveness of biopesticides in sustainable agriculture: **Case 1**. Field application of Bt formulations in row crops: Formulated Bacillus *thuringiensis* (Bt) products are widely utilized for managing lepidopteran pests (caterpillars from moth and butterfly larvae) in cotton, maize, and vegetable production systems. Field applications of Bt suspension concentrates (liquid products) and wettable powders (powdered formulations that mix with water) typically achieve 60%–90% reductions in caterpillar populations, contingent on pest pressure (the local abundance of pests) and environmental conditions. In cotton-growing regions, combining Bt-based sprays with Bt-expressing crops has resulted in a 30%–50% decrease in synthetic insecticide use, thereby enhancing environmental safety and supporting integrated pest management (IPM) programs. **Case 2**.

TABLE 6 | Marketed microbial pesticides.

Pathogens	Products available	Reference
Bacteria		
Bacillus thuringiensis var. kurstaki (Bt)	Bactur®, Bactospeine®, Bioworm®, Caterpillar Killer®, Dipel®, Futura®, Javelin®, SOKBt ®, Thuricide®, Topside®, Tribactur®, Worthy Attack®	Kumar et al. (2008); Sayed and Behle (2017)
Bacillus thuringiensis var. israelensis (Bt)	Aquabee®, Bactimos®, Gnatrol®, LarvX®, Mosquito Attack®, Skeetal®, Teknar®, Vectobac®	Boisvert and Boisvert (2000)
Bacillus thuringiensis var. tenebrinos	Foil®, M-One®, M-Track®, Novardo®, Trident®	Baliyarsingh et al. (2018)
Bacillus thuringiensis var. aizawai	Certan®	Lertcanawanichakul et al. (2004)
Bacillus popilliae and Bacillus lentimorbus	Doom¨, Japidemic¨ ® Milky Spore Disease, Grub Attack®	Rajamani and Negi (2021)
Bacillus sphaericus	Vectolex CG®, Vectolex WDG®	Brown et al. (2004)
Bacillus subtilis strain	Serenade®	Punja et al. (2019)
Bacillus pumilus strain	Sonata®	Serrano et al. (2011)
Fungi		
Beauveriabassiana	Botanigard®, Mycotrol®, Naturalis®	Garza-López et al. (2012)
Lagenidiumgiganteum	Laginex®	Kerwin (2007)
Protozoa		
Nosema locustae	Grasshopper Attack®, NOLO Bait®,	Sokolova and Lange (2002)
Viruses		
Gypsy moth nuclear polyhedrosis (NPV)	Gypchek® virus	Shapiro (2000)
Tussock moth NPV	TM Biocontrol-1®	Lucarotti et al. (2007)
Pine sawfly NPV	Neochek-S®	Lucarotti et al. (2007)

Seed and soil application of fungal biopesticides in horticultural systems: *Trichoderma* species, formulated as dry powders or polymer-coated seed treatments, are extensively employed for managing soil-borne diseases in cereals and vegetable crops. Seed-applied formulations facilitate early rhizosphere colonization, resulting in 40%–70% suppression of damping-off and root rot diseases in field trials. Beyond disease control, treated crops often exhibit improved root development and enhanced nutrient uptake, resulting in yield increases of 5%–15% under moderate disease pressure. These outcomes underscore the dual function of formulation and delivery in achieving both pest suppression and plant growth promotion. **Case 3**. Granular formulations of entomopathogenic nematodes for soil-dwelling pests: Granular and aqueous formulations of entomopathogenic nematodes (EPNs), including *Steinernema* and *Heterorhabditis* species, are effectively applied in turfgrass, ornamentals, and horticultural crops for the control of soil-dwelling insect pests. Under adequate soil moisture conditions, EPN formulations achieve 70%–90% control of target larvae, such as grubs and root-feeding insects. These approaches offer effective pest suppression while minimizing effects on non-target organisms and beneficial arthropods.

3.5 | Biopesticide Industry Trends, Advantages, and Limitations

The global biopesticides market is projected to expand from $6.72 billion in 2025 to $11.41 billion by 2030. This growth trajectory reflects increasing global awareness of environmental sustainability, the expansion of organic and integrated pest management systems, and growing demand for safer crop protection alternatives. Technological advances in microbial screening, strain optimization, and formulation science have further enhanced the efficacy, consistency, and commercial viability of biopesticide products, strengthening their position in modern agricultural input markets (Soetopo and Alouw 2023).

The global distribution and adoption of biopesticides are closely associated with the expansion of organic agriculture and sustainability-driven food systems. According to the FiBL and IFOAM (2023) report, the United States, Germany, and China represent the largest organic food markets worldwide, encouraging agrochemical and biotechnology companies to expand their biological crop protection portfolios to address region-specific pest pressures and improve yield stability. Currently, the European Union has authorized 34 microbial, 11 biochemical, and 23 semi-biochemical biopesticides (Table 6). In contrast, the United States maintains a substantially broader biological pesticide portfolio, comprising 102 microbial, 52 biochemical, and 48 semi-chemical products, with an estimated market value of USD 3–4 billion (Nahmias and Olsen 2015).

Despite strong market growth and technological progress, several non-regulatory barriers continue to limit large-scale adoption, particularly in developing countries. These challenges include limited farmer awareness and technical knowledge, concerns regarding inconsistent field performance under variable environmental conditions, relatively higher upfront costs compared with conventional pesticides, and formulation-related issues such as product stability and shelf life. Overcoming these constraints will require targeted extension and education programs, continued innovation in formulation and delivery technologies, and improvements in supply-chain and storage infrastructure. Collectively, these efforts are crucial to ensuring the effective integration of biopesticides into sustainable agricultural systems and to realizing their long-term benefits for environmentally resilient crop protection (Soetopo and Alouw 2023).

3.6 | Regulatory Frameworks of Biopesticides

For 50 years, crop protection has heavily depended on synthetic pesticides (Chandler et al. 2011). However, recent discoveries highlight the role of bioactive natural molecules in improving food production and pest management. While biopesticides offer sustainable pest control solutions, they face regulatory barriers originally designed for chemical pesticides, leading to high market entry costs. Therefore, global regulatory frameworks for biopesticides have been established in different countries. Biopesticide use in the European Union (EU) is governed by regulation (EC) No1107/2009, which oversees plant protection products, including biopesticides (Villaverde et al. 2014). The EU also focuses on integrated pest management (IPM), which may drive innovations in biopesticide regulations, integrating ecological science with genomic technology. Similarly, in the United States (US), the framework is regulated by the Environmental Protection Agency (EPA) under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). In China, biopesticide use is governed by the Ministry of Agriculture and Rural Affairs (MARA), under the regulation on pesticide administration. These regulatory bodies initiated by experts advocate for IPM and sustainable practices (Deguine et al. 2021).

In general, regulatory frameworks are essential for ensuring biopesticide safety and efficacy to protect humans and the environment, as well as for maintaining product quality and reliability. Therefore, streamlining approval processes, harmonizing international regulations, and reducing market entry costs are critical for unlocking biopesticides' full potential as a sustainable alternative to synthetic pesticides.

4 | Future Perspectives and the Way Forward

Although the biopesticide sector has experienced significant growth, various barriers still hinder its widespread adoption. Limited access to patented microbial strains and production technologies restricts innovation. This also constrains the practical application of publicly funded research, especially in low- and middle-income regions. There is also a lack of harmonized, long-term field data on adoption rates, efficacy, and performance consistency across different agroecological settings. Overcoming these obstacles will require better data collection, standardized evaluation protocols, and more effective information-sharing mechanisms among stakeholders. When these factors are collectively addressed, the likelihood of successful biopesticide development and commercialization increases substantially.

Generally, improving development efficiency and product reliability requires a structured evaluation pipeline. This should include systematic microbial isolation and selection, laboratory efficacy screening, and assessment of production scalability and economic feasibility. It should also cover characterization of modes of action and toxicological properties, validation in controlled environments, and multi-location field trials. Broader adoption will depend on greater collaboration among researchers, industry representatives, extension services, and end-users. Ongoing efforts to reduce reliance on high-risk chemical pesticides remain important. Future research should prioritize optimizing formulations and delivery systems, extending shelf life, reducing production costs, and increasing farmer awareness. These efforts will support the sustainable integration of microbial biopesticides into agriculture.

5 | Conclusion

This systematic review shows that biopesticides are credible and environmentally sound alternatives to synthetic pesticides. They are becoming increasingly important for sustainable agriculture. By integrating advances in microbial biotechnology, RNA interference (RNAi), and formulation strategies, this review goes beyond earlier studies. It critically assesses both the technological potential and practical challenges. The evidence shows that biopesticides reduce chemical inputs and lower resistance risks when used in integrated pest management programs.

Three key implications for policy and practice arise. First, establish streamlined, science-based regulations. Second, invest in commercializing advanced technologies, including RNAi-based and nano-formulated biopesticides. Third, strengthen extension services to address cost, technical training, and product access on farms. Major research gaps remain, including limited field-scale validation, formulation stability and mass production challenges, and a scarcity of socio-economic studies on adoption barriers. Resolve these issues through coordinated efforts among academia, industry, and policymakers, so that biopesticides become competitive and scalable for sustainable pest management.

Author Contributions

Drafts and final article written by **Molalign Assefa**, editing and drawing figures by **Mohammed Tariq Saeed**, drafts checked, boosting comments added and suggestions made by **Tahira Naz** and **Youpeng Fan**, and all supervision, refinement of ideas/comments, and final reviews including project administrations carried out by **Xiangyu Zhao** and **Yuanda Song**. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data sets used and/or analyzed during the current review study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Table S1: Detailed mechanistic modes of action of biopesticides. **Supplementary Table S2:** Functional classes of formulation components used in biopesticide products.