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Success Stories in Microbial Management of Insect Pests in Oilseed Crops: Achievements and Challenges

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ABSTRACT

Oilseed crops—including Brassica species (rapeseed/mustard), sunflower (*Helianthus annuus*), soybean (*Glycine max*), sesame (*Sesamum indicum*), and groundnut (*Arachis hypogaea*)—are vital components of global agricultural economies, providing essential vegetable oils and protein meals. However, sustainable production is severely limited by complex insect pest complexes, including *Plutella xylostella*, *Helicoverpa armigera*, *Bemisia tabaci*, *Lipaphis erysimi*, and *Spodoptera litura*. The historical over-reliance on synthetic chemical insecticides has precipitated severe ecological repercussions, including insecticide resistance, residue accumulation, secondary pest outbreaks, and biodiversity loss. Microbial management using entomopathogenic bacteria (*Bacillus thuringiensis*), fungi (*Beauveria bassiana*, *Metarhizium anisopliae*, *Lecanicillium lecanii*), viruses (Nucleopolyhedroviruses), and entomopathogenic nematodes (*Steinernema* and *Heterorhabditis* spp.) offers a ecologically sound, highly specific alternative. This review synthesizes global success stories in microbial biocontrol across major oilseeds, with an in-depth examination of achievements, progress, and future prospects in Pakistan and South Asia. Key methodological advances in formulation technology, genomics, and integrated pest management (IPM) are critically analyzed, alongside persistent field challenges such as abiotic stress degradation, slow speed of kill, regulatory hurdles, and commercial supply chain constraints. Recommendations for policy reform, regional cooperation, and biotechnological integration are articulated.

Keywords: Microbial Biocontrol, Entomopathogens, Oilseed Crops, *Bacillus Thuringiensis*, *Beauveria Bassiana*, South Asia Insect Management, Pakistan Agriculture, IPM

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Introduction and Global Context

Background & Economic Significance: Oilseed crops represent a fundamental pillar of global agricultural ecosystems and human nutrition, supplying dietary lipids, bio-based industrial lubricants, and protein-rich animal feeds (Lacey *et al*., 2015). Globally, major oilseeds—including rapeseed/mustard (*Brassica napus*, *B. juncea*, *B. rapa*), sunflower (*Helianthus annuus*), soybean (*Glycine max*), sesame (*Sesamum indicum*), and groundnut (*Arachis hypogaea*)—occupy over 300 million hectares. In South Asia, oilseeds constitute the second largest agricultural sector after food grains (Ramanujam *et al*., 2020). However, average productivity in developing regions, particularly Pakistan and neighboring South Asian nations, remains markedly lower than world averages. A major bottleneck constraining potential yield is the severe damage caused by a diverse complex of insect pests throughout the crop growth cycle (Bussaman & Liu, 2021).

The Crisis of Chemical Over-reliance: Historically, oilseed pest management across intensive production regions relied almost exclusively on broad-spectrum synthetic chemical insecticides, including organophosphates, synthetic pyrethroids, and neonicotinoids. While initially successful, this chemical-centric approach created severe agroecological imbalances. Rapid evolution of insecticide resistance—exemplified by *Helicoverpa armigera* resistance to pyrethroids and *Plutella xylostella* resistance to virtually all synthetic classes—led to control failures and escalating application costs (Ahmad *et al*., 2008). Furthermore, chemical residues in oilseed cakes and edible oil fractions pose acute health risks to humans and livestock, while simultaneously decimating native natural enemy populations (parasitoids and predators) and pollinators such as *Apis dorsata* and *Apis mellifera* (Alves *et al*., 2008).

Rationale for Microbial Biocontrol: To counter these ecological and economic vulnerabilities, microbial pest management—utilizing insect-pathogenic bacteria, fungi, viruses, and entomopathogenic nematodes—has emerged as a scientifically robust, environmentally safe, and sustainable paradigm (Lacey *et al*., 2015). Microbial biocontrol agents (MBCAs) provide high target specificity, lower risk of resistance development due to complex multi-site modes of action, zero toxic residue hazards in harvested seeds and oil, and complete compatibility with integrated pest management (IPM) frameworks and organic farming standards.

Figure 1: Global vs. South Asian market distribution of microbial biocontrol agents in oilseed crops.

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Figure 1: Comparative Distribution of Microbial Biocontrol Agent Categories (Global vs. South Asia)

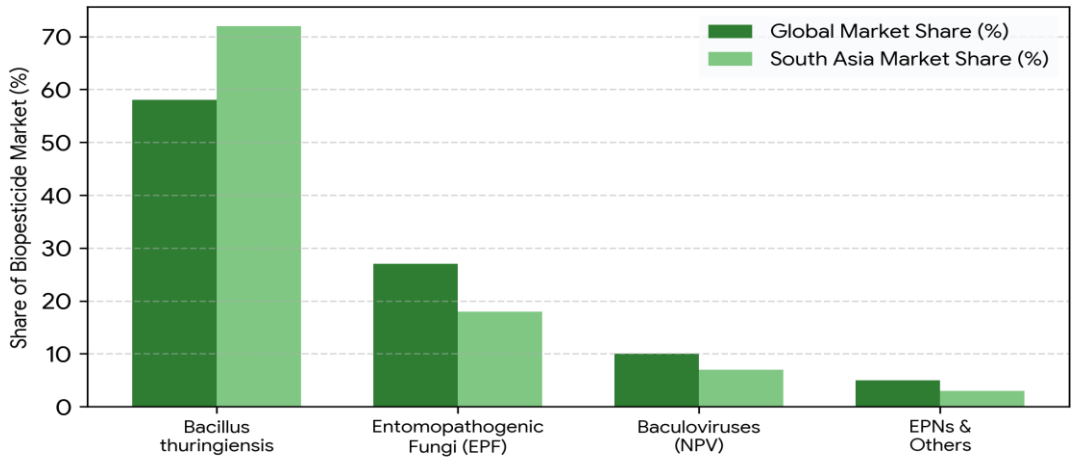


Figure 1 details the comparative global versus South Asian market shares of major microbial categories, highlighting that *Bacillus thuringiensis* dominates biopesticide adoption with ~58% globally and over 70% regionally (Lacey *et al*., 2015; Ramanujam *et al*., 2020).

Key Entomopathogens and Mechanisms of Action

Entomopathogenic Bacteria (*Bacillus thuringiensis*): *Bacillus thuringiensis* (*Bt*) is the premier bacterial pathogen utilized in oilseed protection. During sporulation, *Bt* produces crystalline parasporal inclusion bodies containing delta-endotoxins (*Cry* and *Cyt* proteins), alongside vegetative insecticidal proteins (Vip) secreted during vegetative growth. Upon ingestion by susceptible larvae, the alkaline midgut environment solubilizes these protoxins, which are then activated by midgut proteases. The activated toxins bind specifically to cadherin-like receptors and aminopeptidase N on the microvillar membrane of midgut epithelial cells, inserting into the membrane to form lytic pores. This destroys osmotic balance, causing gut lysis, septicemia, and larval death within 24–72 hours (Lacey *et al*., 2015).

Entomopathogenic Fungi (EPF): Unlike bacteria and viruses which must be ingested, entomopathogenic fungi (EPF) such as *Beauveria bassiana*, *Metarhizium anisopliae*, *Lecanicillium lecanii*, and *Isaria fumosorosea* infect target insects through direct cuticle contact. Hydrophobic conidia adhere to the insect epicuticle, germinate under humid conditions, and produce specialized appressoria. These structures secrete a cocktail of cuticle-degrading enzymes—including PR1 proteases, endochitinases, and esterases—allowing physical penetration into the hemocoel (Bussaman & Liu, 2021).

Inside the hemolymph, the fungus transitions to blastospores, avoiding host immune defense while secreting lethal secondary metabolites (e.g., beauvericin, bassianolide, and destruxins). Death occurs via mechanical tissue disruption, nutritional depletion, and toxicosis.

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Baculoviruses (NPV & GV): Baculoviruses, specifically Nucleopolyhedroviruses (NPVs) and Granuloviruses (GVs), are obligate, highly host-specific viral pathogens of lepidopteran oilseed pests. Insects ingest occlusion bodies (OBs) present on foliage. The high pH of the larval midgut dissolves the polyhedrin matrix, releasing occlusion-derived virions (ODVs) that infect midgut epithelial cells. Secondary systemic infection spreads via budded virions to the fat body and other tissues. Late in infection, the virus produces chitinases and cathepsins that liquefy larval tissues, releasing billions of OBs to infect neighboring pest populations (Alves *et al*., 2008).

Entomopathogenic Nematodes (EPNs): Entomopathogenic nematodes (EPNs) belonging to the families Steinernematidae (*Steinernema* spp.) and Heterorhabditidae (*Heterorhabditis* spp.) are obligate parasites of soil-inhabiting insect stages, such as cutworms (*Agrotis ipsilon*) and pupating larvae of *H. armigera*. Infective juveniles (IJs) seek out insect hosts using chemotaxis, entering through natural openings (spiracles, mouth, anus) or intersegmental membranes. Once inside the hemocoel, IJs release symbiotic bacteria (*Xenorhabdus* spp. for *Steinernema*; *Photorhabdus* spp. for *Heterorhabditis*). The bacteria multiply rapidly, secreting toxins and antimicrobial compounds that kill the host within 24–48 hours while preventing secondary saprophytic breakdown (Lacey *et al*., 2015).

Global Success Stories in Major Oilseed Crops

Global implementation of microbial biocontrol in oilseed production has yielded remarkable success across diverse agroecological zones (Alves *et al*., 2008).

Table 1 summarizes landmark international achievements that demonstrate the efficacy and economic viability of microbial management.

Crop	Target Insect Pest	Microbial Agent Applied	Country / Region	Efficacy & Field Impact
Soybean (Glycine	*Anticarsia gemmatalis*	AgNPV (Baculovirus)	Brazil (EMBRAPA)	Suppressed pest populations across >2 million hectares

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max)	(Velvetbean Caterpillar)			annually; reduced chemical insecticide applications by 75-80% (Alves *et al*., 2008).
Canola / Rapeseed (Brassica napus)	*Plutella xylostella* (Diamondback Moth)	*Bacillus thuringiensis* var. *kurstaki (Btk*)	Canada & North America	Controlled pyrethroid-resistant DBM populations; integration with parasitoids yielded 85-90% foliage protection (Lacey *et al*., 2015).
Sunflower (*Helianthus annuus*)	*Helicoverpa armigera* (Head Borer)	HaNPV + *Beauveria bassiana*	China & Eastern Europe	Combined application achieved >88% larval mortality in sunflower heads, preventing seed yield loss of up to 1.2 t/ha (Bussaman & Liu, 2021).
Groundnut (*Arachis hypogaea*)	*Spodoptera litura* (Tobacco Caterpillar)	SlNPV + *Metarhizium anisopliae*	India & Southeast Asia	Bio-formulations provided 80-85% reduction in defoliation, suppressing pod yield losses by 25-30% in rainfed areas (Ramanujam *et al*., 2020).
Sesame (*Sesamum indicum*)	*Antigastra catalaunalis* (Pod Borer / Leaf Roller)	*Bacillus thuringiensis* + *Trichogramma*	Sudan & Sub-Saharan Africa	Integrated biological control decreased leaf roller damage by 70%, yielding a 35% net economic return over chemicals (Syed *et al*., 2022).

Figure 2: Comparative field mortality efficacy of major entomopathogen categories against key oilseed pests.

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Figure 2: Efficacy Profile of Key Microbial Agents Against Major Oilseed Pests

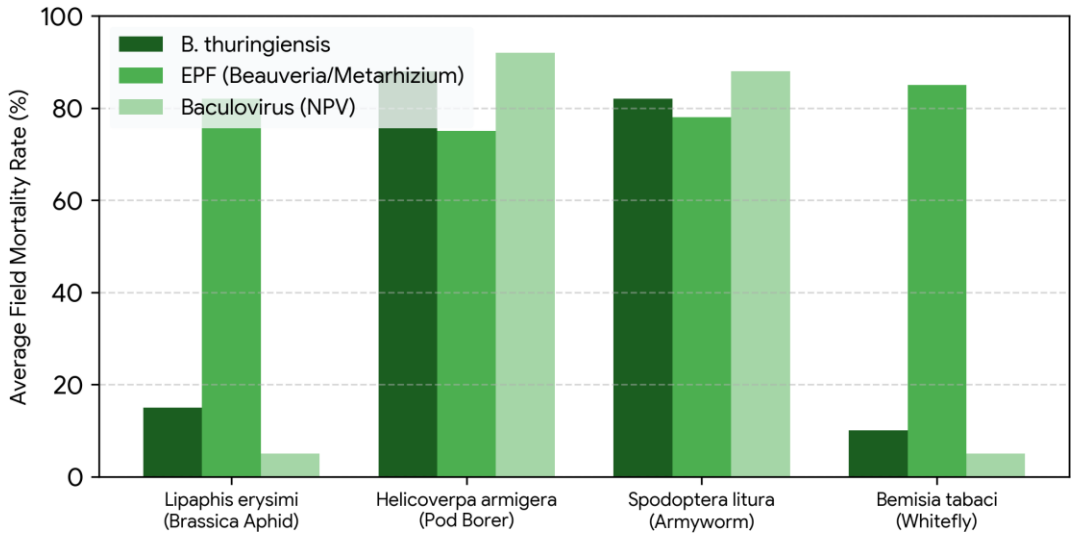


Figure 2 compares field mortality rates of *Bacillus thuringiensis*, EPFs, and Baculoviruses against four prominent oilseed pests, demonstrating that baculoviruses achieve superior performance (>90% mortality) against Lepidopteran pod borers, while EPFs provide stable control against sucking pests like whiteflies and aphids (Bussaman & Liu, 2021; Ramanujam *et al*., 2020).

Microbial Biocontrol in Pakistan and South Asia: Progress and Prospects

Lecanicillium lecanii **The Pakistan Agroeconomic Context:** In Pakistan, oilseeds represent a strategic agricultural sector imperative for national food security and trade balance. Currently, Pakistan imports over 85% of its edible oil requirement, consuming precious foreign exchange reserves exceeding $4.5 billion annually (UK AgriConsult, 2026; ExImPedia, 2026). To bridge the national edible oil deficit, the Federal and Provincial governments—led by institutes such as the Oilseeds Research Institute (AARI), Faisalabad—have prioritized expanding acreage of Brassica species (rapeseed, mustard, canola), sunflower, and sesame. However, insect pest pressure remains the single largest biotic barrier to achieving national yield targets.

Key Successes and Research Advances in Pakistan: Research efforts in Pakistan have increasingly focused on harnessing local microbial isolates adapted to high temperatures and arid conditions. The Mustard Aphid (*Lipaphis erysimi*) and Cabbage Aphid (*Brevicoryne brassicae*) cause severe yield damage (30–70%) in Brassica crops across Punjab and Sindh (Bakhetia & Sekhon, 1989; Kular & Kumar, 2011). Local strains of *Beauveria bassiana* and evaluated at AARI Faisalabad demonstrated 80–88% aphid suppression within 5–7 days under field conditions. Similarly, for *Helicoverpa armigera* in sunflower and chickpea/oilseed intercropping systems, indigenous *Bacillus thuringiensis* isolates enriched with *Cry*1Ac and *Cry*2Ab proteins showed high toxicity,

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achieving >85% larval mortality (Ahmad et al., 2008).

Broader South Asian Perspective: Across the broader South Asian subcontinent (including India, Bangladesh, and Sri Lanka), microbial biopesticides have transitioned from laboratory curiosities to core IPM components (Ramanujam et al., 2020). Commercial formulations of HaNPV and SlNPV are widely registered and mass-produced in India for legume and oilseed pod borers. Furthermore, *Metarhizium anisopliae* var. acridum has achieved successful field-scale control during desert locust (*Schistocerca gregaria*) outbreaks in border areas of Pakistan (Tharparkar, Cholistan) and Rajasthan (India), preventing catastrophic damage to oilseed and forage crops.

Table 2 outlines the major insect pests of oilseed crops in South Asia, along with validated microbial control agents and documented field impact.

Target Pest	Oilseed Host(s)	Dominant Microbial Agent	Regional Status / Adoption	Impact & Yield Benefit
Lipaphis erysimi (Mustard Aphid)	*Brassica juncea*, B. napus, Canola	*Beauveria bassiana* / *Lecanicillium lecanii*	Commercialized in India; Advanced field testing at	78-85% aphid reduction; prevents 20-35% seed yield loss; preserves Coccinellid predators

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			AARI, Pakistan	(Kular & Kumar, 2011).
Helicoverpa armigera (American Pod Borer)	Sunflower, Sesame, Soybean, Groundnut	HaNPV (1x10^9 OB/mL) + *Bacillus thuringiensis*	Widely commercialized in South Asia; Growing adoption in Punjab, Pakistan	Achieves 85-92% larval mortality; reduces chemical sprays from 5 down to 1 per season (Ahmad *et al*., 2008).
Spodoptera litura (Tobacco Caterpillar)	Groundnut, Soybean, Sunflower	SlNPV + *Metarhizium anisopliae*	Commercial formulations available; Included in National IPM Modules	80% reduction in defoliation; prevents yield loss of up to 400 kg/ha in groundnut (Ramanujam *et al*., 2020).
Bemisia tabaci (Whitefly)	Sesame, Sunflower, Soybean	*Isaria fumosorosea* / *Beauveria bassiana*	Pilot field trials in Pakistan (AARI) & ICAR institutes in India	Suppresses adult and nymphal whiteflies by 70-75%; interrupts CLCV and viral transmission (Bussaman & Liu, 2021).
Agrotis ipsilon (Black Cutworm)	Seedling Brassica, Young Sunflower	*Steinernema carpocapsae* (EPN) + Bt soil drench	Experimental / Pilot commercialization in South Asia	Provides 85-90% seedling stand preservation; replaces toxic organophosphate soil drenches (Lacey *et al*., 2015).

Critical Challenges and Bottlenecks

Overview of Field Barriers: Despite significant laboratory success and proven field potential, the widespread commercial adoption of microbial biopesticides in South Asia faces severe technical, environmental, and institutional bottlenecks (Syed *et al*., 2022):

Abiotic Degradation & Environmental Instability: South Asian oilseed-growing regions experience extreme microclimatic conditions during spring and summer seasons. Solar ultraviolet radiation (UV-A and UV-B) rapidly inactivates fungal conidia and viral polyhedra, reducing field persistence to less than 24–48 hours in unformulated products. Ambient field temperatures exceeding 40°C in Punjab and Sindh during late spring severely inhibit EPF conidial germination and hyphal growth. Furthermore, low relative humidity (<50%) severely limits fungal epizootic development.

Slow Speed of Kill & Delayed Efficacy: Unlike fast-acting synthetic pyrethroids or

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organophosphates that provide quick 'knockdown' mortality within hours, entomopathogens require an incubation period of 3 to 7 days to kill target insects. Farmers accustomed to immediate pest knockdown often perceive slow-acting biopesticides as ineffective, leading to premature chemical re-spraying (Syed *et al*., 2022).

Mass Production, Storage & Shelf-Life Constraints: Liquid or wettable powder formulations of EPF and baculoviruses often possess a short shelf-life (<6 months at room temperature), requiring cold-chain refrigeration during distribution and storage. In rural agro-retail networks across Pakistan and South Asia, continuous cold storage is rarely maintained, leading to rapid loss of microbial viability before reaching the farmer.

Regulatory Bottlenecks & Quality Control Deficits: In Pakistan, the regulatory framework under the Agricultural Pesticides Ordinance (APO) was historically designed for chemical molecules. The registration process for biological agents remains cumbersome, lengthy, and expensive, discouraging private sector investments in biopesticide mass production and commercialization (Syed *et al*., 2022).

Methodological Innovations and Future Horizons

Modern Formulation Engineering: To overcome field degradation and slow action, advanced formulation techniques are being integrated. Oil-based ultra-low volume (ULV) formulations, microencapsulation in biopolymer matrices (e.g., alginate, chitosan), and inclusion of natural UV protectants (stilbene compounds, optical brighteners, molasses) have been shown to double field persistence and enhance conidial adhesion to hydrophobic plant leaves under arid conditions (Syed *et al*., 2022).

Genomic and Biotechnological Approaches: Advances in molecular genetics, whole-genome sequencing, and CRISPR/Cas9 gene editing offer unprecedented opportunities to engineer superior microbial strains. Genetic modifications targeting insect cuticle-degrading proteases (e.g., overexpression of Pr1a in *Beauveria bassiana*) or inserting insect-specific neurotoxin genes into baculovirus genomes have reduced time-to-kill (LT50) by 30–50% (Bussaman & Liu, 2021). Furthermore, genomic screening allows rapid identification and selection of thermotolerant and UV-resistant indigenous strains.

Integrated Microbial Pest Management Frameworks: Microbial biopesticides must not be viewed as direct 'stand-alone' chemical replacements, but as core components of holistic IPM systems. Synergistic combinations—such as combining sublethal doses of botanical extracts (neem oil) or imidacloprid with *Beauveria bassiana*—weaken insect immune responses, resulting in accelerated fungal infection. Furthermore, integrating microbial applications with classical bio-agents (e.g., *Trichogramma chilonis* egg parasitoids) ensures multi-stage pest suppression (Ramanujam *et al*., 2020).

Conclusion and Strategic Recommendations

Microbial biocontrol represents a scientifically validated, ecologically sound, and

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essential pathway toward sustainable oilseed production in Pakistan and South Asia (Ramanujam et al., 2020). The technological transition from chemical dependence to microbial management is vital for mitigating insect resistance, protecting biodiversity, reducing environmental toxicity, and safeguarding human health (Lacey *et al*., 2015). To accelerate regional adoption, the following strategic actions are recommended:

Establishment of National Microbial Bio-Resource Hubs: Create centralized repositories for isolated, characterized, and thermotolerant indigenous microbial strains (Bt, EPF, NPV, EPNs) suited to local South Asian climates.

Regulatory Streamlining & Incentive Policies: Modernize pesticide registration acts in Pakistan and regional countries to create dedicated, expedited pathways for microbial biopesticides, accompanied by tax incentives for biopesticide manufacturers.

Public-Private Partnerships (PPP): Encourage collaboration between agricultural research centers (such as AARI Faisalabad) and private bio-factory enterprises to bridge the gap between laboratory strains and commercial-scale production.

Farmer Education & Capacity Building: Conduct extensive field demonstrations, Farmer Field Schools (FFS), and training workshops to educate growers on correct microbial application techniques, storage practices, and realistic efficacy expectations.

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