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Microbial Biopesticides in Modern Agriculture: Current Status and Future Prospects

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Microbial biopesticides are an important component of modern biological pest management and provide alternatives or complements to conventional synthetic insecticides. They are based on microorganisms or their pesticidal metabolites and include bacterial, fungal, viral and entomopathogenic-nematode systems. Among the most established examples are Bacillus thuringiensis-based products, entomopathogenic fungi such as Beauveria and Metarhizium, baculoviruses and nematodes of the genera Steinernema and Heterorhabditis. Their major advantages include biological specificity, diverse modes of action, compatibility with integrated pest management and, for many products, relatively favourable environmental profiles. However, microbial biopesticides are living or biologically derived systems whose field performance can be strongly affected by temperature, humidity, ultraviolet radiation, rainfall, pest stage and application technology. Current research is therefore focused on strain discovery, genomics, microbial metabolites, improved fermentation, formulation, encapsulation, quality control, climate resilience and precision delivery. In India, microbial biopesticides have a substantial history of registration and use, although quality control, regulatory requirements, production capacity and farmer adoption remain important constraints. Recent research also shows that some entomopathogens may provide benefits beyond direct insect mortality, including plant-growth promotion and induced resistance. This review summarizes the current status of microbial biopesticides, their major groups and mechanisms, production and formulation technologies, integration with integrated pest management, key challenges and future prospects for sustainable agriculture.

Introduction

Modern agriculture faces the dual challenge of maintaining high productivity while reducing the environmental and health costs associated with excessive pesticide dependence. Synthetic insecticides remain important tools for crop protection, but repeated use can contribute to resistance, resurgence, residue concerns and disruption of beneficial organisms. Microbial biopesticides provide one pathway toward more ecologically compatible pest management because their active components are based on microorganisms or microbial products with biological modes of action. The US EPA classifies microbial pesticides as a major biopesticide category, alongside biochemical pesticides and plant-incorporated protectants. FAO guidance describes microbial biological pest-control agents as microorganisms such as bacteria, fungi, viruses, protozoa and other microscopic self-replicating biological entities, together with associated metabolites where the pest-control effect is attributed to them. These agents are intended to contribute to integrated pest management rather than simply reproduce the role of conventional chemicals. The importance of microbial products has increased with growing interest in sustainable crop protection and resistance management. A recent review of biopesticide research identified microbial agents from fungi, bacteria, viruses and nematodes as major areas of development and highlighted formulation, mode of action, efficacy factors, adoption challenges and IPM integration as central research themes. India provides an important example of microbial biopesticide development. A national review reported that microbial products included entomopathogenic fungi, Bacillus thuringiensis products, nucleopolyhedroviruses and entomopathogenic nematodes, while also identifying quality control, regulatory requirements and large-scale production as continuing challenges.

Major Groups of Microbial Biopesticides

Microbial biopesticides used against agricultural insect pests can be grouped broadly into bacteria, fungi, viruses and entomopathogenic nematodes. Each group has distinctive infection processes, host ranges, environmental requirements and production systems. Selection of the most suitable agent depends on the pest species, life stage, crop environment and timing of application.

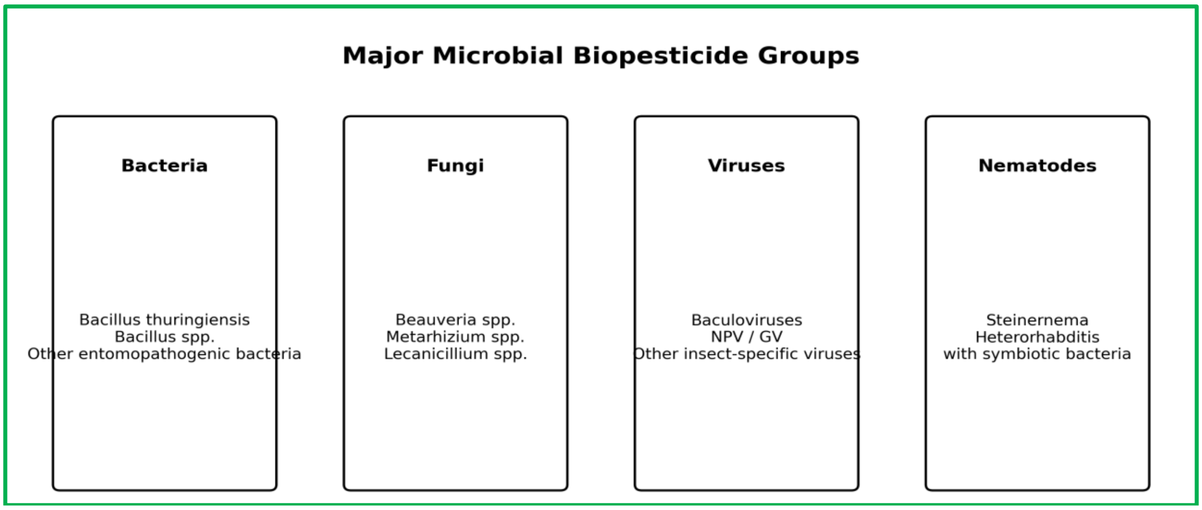

Figure 1. Major groups of microbial biopesticides used for agricultural insect-pest management.

Bacterial Biopesticides

Bacterial biopesticides are among the most established microbial products in agriculture. Bacillus thuringiensis (Bt) is the best-known example and produces insecticidal proteins that are active against susceptible insect groups. Different Bt strains and toxin combinations have been developed for specific pest targets, particularly lepidopteran larvae. Bacterial biopesticides may also include other entomopathogenic or antagonistic bacteria whose metabolites or toxins contribute to pest suppression. Recent reviews emphasize the diversity of bacterial toxins and the continuing search for new strains with useful insecticidal activity. Bacterial biopesticides can offer specificity and can be mass-produced through fermentation, but their performance depends on formulation, environmental persistence, target-pest susceptibility and resistance management. Research on Bt has increasingly focused on improving stability and delivery, including encapsulated formulations and approaches intended to extend activity under field conditions. Resistance evolution remains a consideration for bacterial products, particularly where the same toxin or mode of action is used repeatedly. Rotating or combining compatible modes of action, monitoring susceptibility and integrating Bt products with other IPM tactics can help preserve effectiveness.

Entomopathogenic Fungi

Entomopathogenic fungi are important microbial agents because they can infect insects through the cuticle, allowing them to affect pests that may not ingest a microbial toxin. Beauveria bassiana, Metarhizium spp. and Lecanicillium spp. are among the best-known taxa used in research and commercial development. After attachment and germination, fungal propagules penetrate the insect cuticle, proliferate internally and may produce enzymes and secondary metabolites that contribute to host death. Recent reviews continue to highlight the broad potential of entomopathogenic fungi as sustainable tools for arthropod pest management. A major advantage of fungal biopesticides is their potential to infect sucking and chewing pests through external contact. However, conidial viability and infection are sensitive to environmental conditions. Relative humidity, temperature, solar radiation and rainfall can strongly influence performance. Improved formulations, UV protectants, oil-based carriers and optimized application timing are therefore important for field reliability. Recent research has also expanded the functional view of entomopathogenic fungi. Some strains can interact with plants and may influence plant growth, nutrient acquisition or induced resistance in addition to direct insect mortality. A 2025 review of microbial entomopathogens emphasized these broader plant-beneficial functions and their potential integration into holistic crop health management.

Viral Biopesticides

Insect-specific viruses, especially baculoviruses, are important microbial control agents for several lepidopteran pests. Nuclear polyhedrosis viruses and granuloviruses are highly specific and can cause epizootics within susceptible pest populations. Their specificity can be advantageous for conserving non-target organisms, but it can also limit the range of pests controlled by a particular product. Baculovirus products are generally produced through insect-based or cell-based systems and require careful handling to maintain infectivity. They can be valuable where pesticide resistance has become problematic or where residue reduction is a priority. Earlier and current assessments have highlighted baculoviruses as safe, mass-producible and increasingly useful components of IPM. Research is directed toward improving viral formulation, UV protection, application efficiency and speed of action. Combining viral agents with compatible adjuvants or other IPM components may increase field performance, while resistance management remains important when a virus is used intensively.

Entomopathogenic Nematodes

Entomopathogenic nematodes (EPNs), particularly Steinernema and Heterorhabditis, are soil-associated biological control agents that operate in association with bacterial symbionts. The nematodes locate susceptible insects, enter the host and release or transport symbiotic bacteria that contribute to rapid host mortality. This nematode–bacterium partnership is a distinctive form of microbial pest control. Recent reviews have emphasized the importance of EPN population ecology, host interactions, rhizosphere relationships and agricultural practices in determining efficacy. EPNs are particularly relevant to soil-dwelling pests and can be applied through irrigation systems or other delivery methods. Commercial development has advanced, but storage stability, desiccation sensitivity, temperature dependence and field persistence remain important considerations. A 2025 review of commercial EPN use identified continued opportunities for improved production, formulation and application technologies.

Modes of Action and Host Interaction

Microbial biopesticides act through several mechanisms. Bacterial toxins may disrupt the insect gut after ingestion; fungal pathogens can penetrate the cuticle and colonize the host; viruses replicate within susceptible tissues; and EPNs operate through a coordinated nematode–symbiont infection process. Microbial metabolites, extracellular enzymes, secondary metabolites and immune-disrupting compounds can contribute to mortality or reduced pest fitness. Understanding mode of action is important for efficacy, resistance management and product development. Molecular studies can identify virulence factors and help select strains with desirable traits. However, laboratory virulence does not necessarily translate directly to field success because environmental exposure and host availability determine whether the agent can complete the infection process.

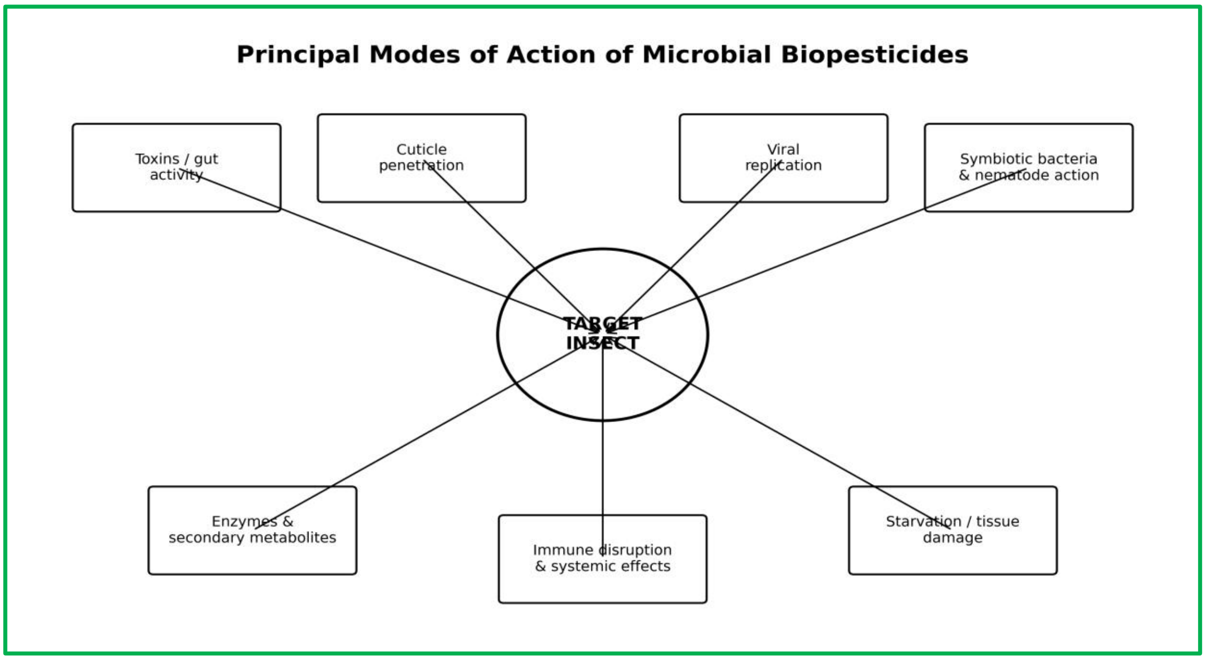

Figure 2. Simplified modes of action through which bacterial, fungal, viral and nematode-based microbial biopesticides suppress insect pests.

Strain Discovery, Screening and Molecular Characterization

Microbial biopesticide development begins with the discovery and characterization of effective strains. Sources include soil, infected insects, plant surfaces, rhizospheres and other agricultural environments. Screening typically involves laboratory bioassays followed by greenhouse and field evaluation. Important traits include virulence, host range, growth rate, sporulation or toxin production, environmental tolerance and compatibility with formulation processes. Molecular tools are increasingly important for accurate identification and quality assurance. In India, ICAR reporting has described the use of molecular identification and DNA fingerprinting as part of microbial biopesticide registration requirements, with the ICAR-National Bureau of Agriculturally Important Microorganisms supporting identity verification. The programme has processed samples representing organisms including Lecanicillium, Metarhizium, Beauveria, Trichoderma, Pseudomonas and Bacillus. Genomics, transcriptomics and metabolomics can further reveal genes and metabolites associated with virulence, environmental tolerance and host specificity. These tools may allow researchers to identify promising strains more efficiently than phenotype-only screening, while also helping to establish molecular markers for product authentication.

Fermentation, Mass Production and Formulation

Commercial success depends on the ability to produce microbial active ingredients at sufficient scale and cost while maintaining biological quality. Bacteria can often be produced through liquid fermentation, while fungal products may use submerged or solid-state systems depending on the organism and desired propagule. Viruses commonly require susceptible host systems, and EPN production may use in vivo or in vitro methods. Formulation is frequently the critical bridge between laboratory efficacy and field performance. Products must maintain viability or biological activity during storage, transport and application. Wettable powders, suspension concentrates, oil-based formulations, granules and other delivery systems can be designed according to the organism and target environment. Formulation research aims to protect microbial propagules from desiccation, UV radiation, temperature stress and other environmental hazards. Recent work on microbial bioproduct development emphasizes fermentation, formulation and stabilization as major areas of innovation. For microbial and nematode-based biopesticides, formulation quality can determine shelf life, field persistence and practical usability.

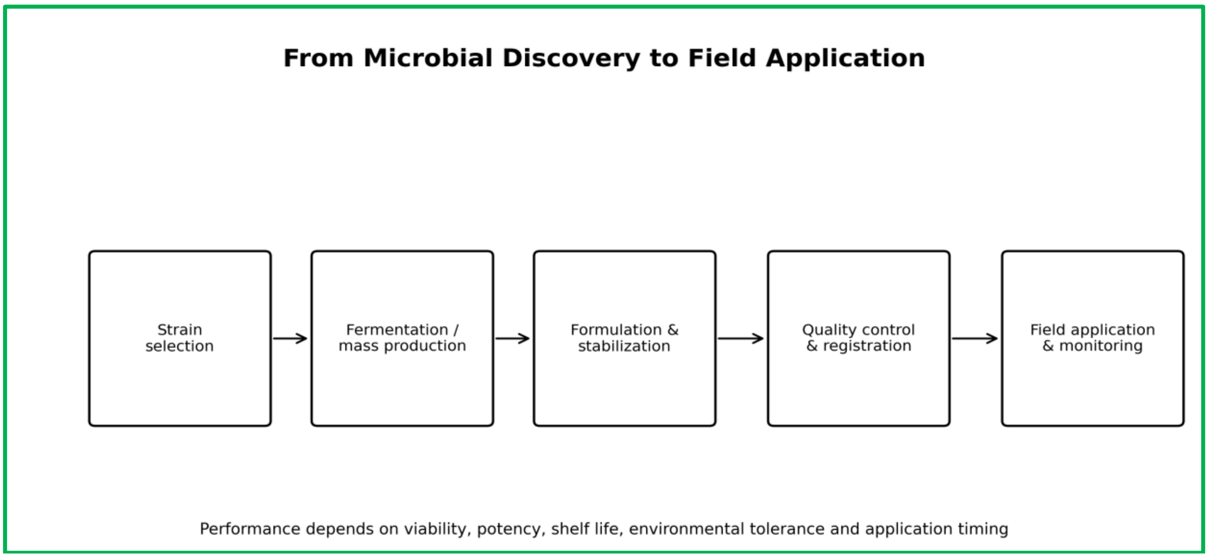

Figure 3. General pathway from microbial strain selection and production to formulation, quality assurance, registration and field deployment.

Quality Control and Standardization

Quality control should cover microbial identity, purity, viability, potency, contaminant status, formulation characteristics and shelf life. For fungal products, spore concentration and germination are important indicators; for bacterial products, viable counts and toxin or metabolite activity may be relevant; for viruses, infectivity and inclusion-body quality require assessment; and for EPNs, viability, infectivity and concentration are important. Standardized quality-control systems are especially important because inconsistent products can reduce farmer confidence and damage the credibility of biological pest management. Molecular authentication, batch testing and defined potency standards can reduce product variability. Registration systems therefore need to balance rigorous safety and efficacy evaluation with practical requirements appropriate to biological products.

Field Efficacy and Environmental Factors

Microbial biopesticides generally require closer attention to environmental conditions than many conventional chemicals. Temperature, relative humidity, rainfall, UV radiation, crop canopy and pest developmental stage can determine whether a microbial agent reaches and infects its target. Application timing is therefore critical. For fungal agents, adequate humidity and suitable temperatures can support germination and infection. For viruses and bacterial toxins, exposure of susceptible feeding stages may be important. For EPNs, soil moisture, temperature and soil structure influence movement and survival. These differences mean that recommendations should be based on organism-specific ecological requirements rather than applying one universal microbial-pesticide schedule. Climate change may further alter microbial biopesticide performance. More frequent heat waves, droughts and irregular rainfall could reduce persistence of some agents, while other conditions may favour infection. Climate-resilient strain selection, protective formulations and weather-based application decisions are therefore emerging research priorities.

Integration with Integrated Pest Management

Microbial biopesticides are most effective when incorporated into integrated pest management rather than treated as isolated replacements for all chemical pesticides. Monitoring, economic thresholds, crop sanitation, resistant cultivars, habitat management, pheromone-based methods, biological control and selective chemical interventions can be combined according to pest pressure. Compatibility with other pesticides is especially important. Broad-spectrum fungicides may inhibit entomopathogenic fungi, while some insecticides can affect beneficial microorganisms or natural enemies. Therefore, tank-mix compatibility and sequential-application studies should be conducted before recommending combined programs. A recent 2025 study of mycoinsecticides and fungicides in maize demonstrated that chemical compatibility can vary by formulation and exposure conditions, highlighting the need for specific compatibility testing. Microbial products can also help reduce selection pressure associated with repeated use of a single chemical mode of action. Rotating microbial agents with compatible chemical and non-chemical tactics can support resistance management. The objective should be durable pest suppression with minimum ecological disruption.

Current Status in India

India has developed a substantial microbial biopesticide sector, although adoption remains uneven. A detailed national review reported approximately 5% of the pesticide market represented by biopesticides at the time of its assessment and documented numerous registered microbial species and formulations, including fungal, bacterial, viral and nematode products. It also identified quality-control limitations, regulatory burdens and insufficient large-scale production as major constraints. Important microbial groups used in India include Beauveria bassiana, Metarhizium anisopliae sensu lato, Lecanicillium lecanii, Bacillus thuringiensis, Helicoverpa armigera nucleopolyhedrovirus, Spodoptera litura nucleopolyhedrovirus and entomopathogenic nematodes such as Heterorhabditis indica. Indigenous strain discovery and local adaptation remain important because climatic conditions and pest complexes vary substantially among Indian agroecological regions. ICAR's recent reporting on molecular identification and DNA fingerprinting for microbial registration indicates a movement toward stronger product authentication and quality assurance. Such systems can help reduce the circulation of misidentified or substandard microbial products and strengthen farmer confidence.

Challenges in Commercialization and Adoption

Despite their potential, microbial biopesticides face several practical constraints. Field efficacy may be slower or less consistent than that of fast-acting synthetic insecticides. Shelf life and storage conditions can be challenging, especially for living microorganisms. Production costs can be influenced by fermentation efficiency, substrate requirements, downstream processing and formulation technology. Regulation is another important consideration. FAO notes that biological pest-control agents can face regulatory approaches developed primarily around conventional chemical pesticides, creating requirements that may be disproportionate or poorly suited to biological products. Science-based, risk-proportionate regulatory frameworks can help facilitate responsible development without compromising environmental and human safety. Farmer adoption also depends on availability, technical knowledge, cost, reliability and extension support. Demonstration trials and farmer training can improve understanding of correct timing, storage, mixing and application. Microbial products should be accompanied by clear recommendations because poor application can lead to apparent failure even when the biological agent itself is effective.

Future Prospects

The future of microbial biopesticides is likely to depend on improved strain discovery, molecular characterization, formulation and precision application. Genomics and metagenomics can reveal new microbial resources and identify genes associated with virulence and environmental tolerance. Metabolomics can identify active compounds and support discovery of new microbial modes of action. AI-assisted screening may help prioritize strains from large microbial collections by integrating genomic, phenotypic and environmental datasets. Machine-learning models could potentially predict host range, virulence or environmental suitability before extensive field testing, although predictions must be validated experimentally. Microbiome-based approaches may further expand the role of microbial entomopathogens. Recent work suggests that some microbial agents can influence plant immunity, growth and nutrient acquisition in addition to direct pest mortality. This raises the possibility of multifunctional microbial products that contribute simultaneously to pest suppression and crop health.

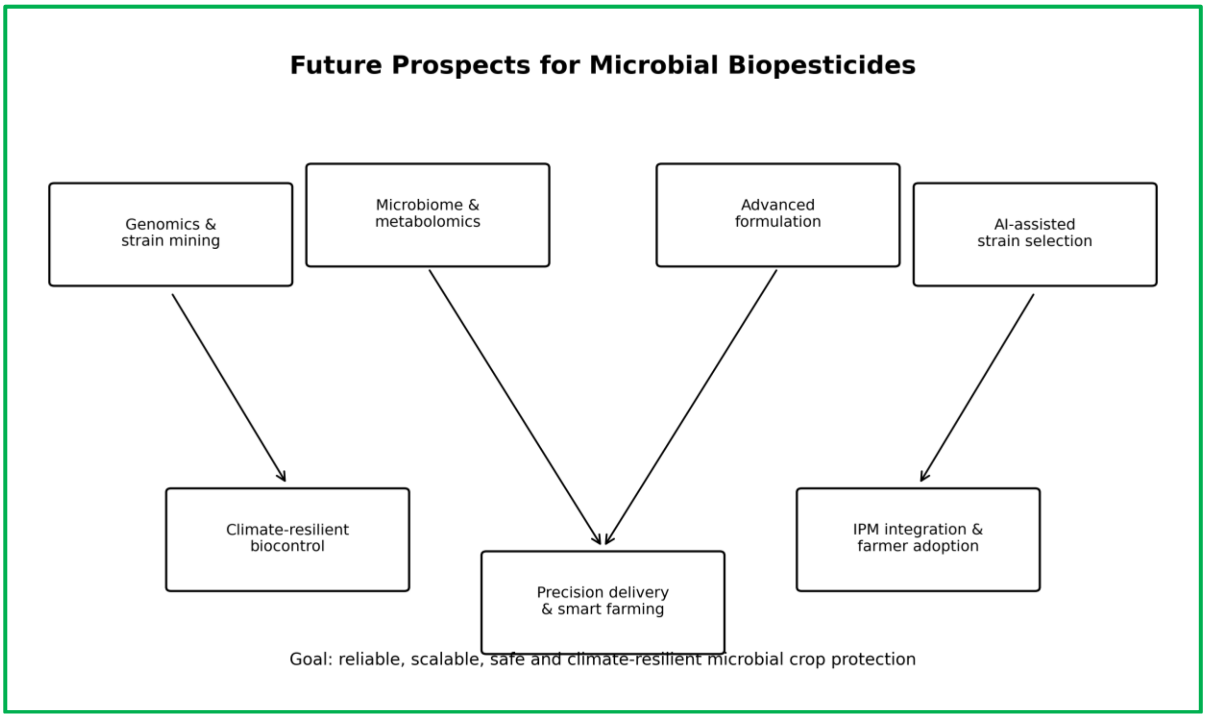

Figure 4. Emerging research directions for improving the reliability, scalability and sustainability of microbial biopesticides

Advanced formulation and precision delivery are equally important. Encapsulation, protective carriers, UV shielding, controlled release and targeted application could improve persistence and reduce the quantity of microbial material required. Integration with smart farming systems could allow applications to be timed using pest monitoring, weather data and crop phenology. Climate resilience should become a major selection criterion. Microbial strains and formulations that remain effective across realistic ranges of temperature, humidity and radiation will be increasingly valuable. Future research should therefore evaluate microbial products under combined environmental stresses rather than under single-factor laboratory conditions.

Conclusion

Microbial biopesticides have progressed from niche biological-control products to important components of modern sustainable pest management. Bacteria, fungi, viruses and entomopathogenic nematodes offer diverse modes of action and can reduce dependence on conventional insecticides when appropriately selected and integrated into IPM. Their value is particularly important where pesticide resistance, residue concerns and ecological impacts limit the long-term sustainability of conventional approaches. The principal challenge is to translate laboratory and greenhouse efficacy into consistent field performance. Better strain selection, molecular authentication, mass production, formulation, quality control, environmental forecasting and farmer-oriented application technology are essential. India has a strong base of microbial resources and registered products, but continued investment in quality assurance, domestic production and extension will be necessary to expand reliable adoption. Future microbial biopesticide systems are likely to combine genomics, microbiome science, advanced fermentation, formulation technology, AI-assisted discovery and precision agriculture. Multifunctional microbial agents that contribute to pest suppression, induced resistance and crop health may become increasingly important. With appropriate regulation, quality standards, field validation and integration with IPM, microbial biopesticides can contribute substantially to resilient, low-residue and environmentally responsible agricultural production.

References

1. FAO/WHO (2017). Manual on Development and Use of FAO and WHO Specifications for Pesticides. Food and Agriculture Organization of the United Nations and World Health Organization.
2. EPA (2026). Biopesticides. United States Environmental Protection Agency. https://www.epa.gov/pesticides/biopesticides
3. EPA (2025). Pesticide Registration Manual: Chapter 3 – Additional Considerations for Biopesticide Products. United States Environmental Protection Agency.
4. FAO (2026). Types of Biological Pest Control Agents. Pesticide Registration Toolkit. Food and Agriculture Organization of the United Nations.
5. Seethapathy, P., et al. (2018). Microbial biopesticides for insect pest management in India: Current status and future prospects. Journal of Invertebrate Pathology, 165: 74–85. https://doi.org/10.1016/j.jip.2018.10.002
6. Abeysekara, W.K.S.M., et al. (2024). Recent Advances in Biopesticide Research and Development with a Focus on Microbials. Journal of Agricultural and Food Chemistry / related review literature.
7. Alam, M., et al. (2024). Bacterial biopesticides: Biodiversity, role in pest management and beneficial impact on agricultural and environmental sustainability. Heliyon, 10: e31550. https://doi.org/10.1016/j.heliyon.2024.e31550
8. Hamrouni, R., Regus, F., Farnet Da Silva, A.-M., Orsiere, T., Boudenne, J.-L., Laffont-Schwob, I., Christen, P. and Dupuy, N. (2025). Current status and future trends of microbial and nematode-based biopesticides for biocontrol of crop pathogens. Critical Reviews in Biotechnology, 45(2): 333–352. https://doi.org/10.1080/07388551.2024.2370370
9. Saha, N., Sharma, A. and Bora, P. (2025). Expanding the functional landscape of microbial entomopathogens in agriculture beyond pest management. Archives of Microbiology, 207: 343. https://doi.org/10.1007/s12223-025-01251-x
10. Kankanamalage, H.P.A., Yang, J.-Y., Karunarathna, S.C., Tibpromma, S., Kumla, J., Wei, D.-P. and Lumyong, S. (2025). Entomopathogenic fungi: insights into recent understanding. World Journal of Microbiology and Biotechnology, 41: 179. https://doi.org/10.1007/s11274-025-04377-9
11. Ramakuwela, T., Tarasco, E., Chavarría-Hernández, N. and Toepfer, S. (2025). Entomopathogenic nematodes: Commercial use and future perspectives. Journal of Invertebrate Pathology, 212: 108388. https://doi.org/10.1016/j.jip.2025.108388
12. Faria, M.R. and Wraight, S.P. (2007). Mycoinsecticides and mycoacaricides: a comprehensive list with worldwide coverage and international classification of formulation types. Biological Control, 43: 237–256.
13. Lacey, L.A., Grzywacz, D., Shapiro-Ilan, D.I., Frutos, R., Brownbridge, M. and Goettel, M.S. (2015). Insect pathogens as biological control agents: back to the future. Journal of Invertebrate Pathology, 132: 1–41.