Journal of Applied and Natural Science
17(4), 1781 - 1798 (2025)
ISSN : 0974-9411 (Print), 2231-5209 (Online)
journals.ansfoundation.org

Review Article

A review on new horizons in biopesticide development highlighting microbial advances for Climate-smart agriculture

Shreya Brohma
Department of Plant Pathology, School of Agriculture, Lovely Professional University, Jalandhar-Delhi G.T. Road, Phagwara-144411 (Punjab), India
Anshu Guleria
Department of Plant Pathology, College of Agriculture, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur-1760620 (Himachal Pradesh), India
Sabyasachi Banerjee
Department of Genetics and Plant Breeding, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi-221005 (Uttar Pradesh), India
Sonika Kalia
Department of Biotechnology, School of Applied and Life Sciences, Uttaranchal University, Dehradun -248007, India
Rekha Sharma
Department of women and child development, UT Chandigarh-160021, India
Kinjal Mondal
Department of Molecular Biology and Biotechnology, Maharana Pratap University of Agriculture and Technology Udaipur-313001 (Rajasthan), India
Gurpreet Kaur*
Department of Plant Pathology, School of Agriculture, Lovely Professional University, Jalandhar-Delhi G.T. Road, Phagwara-144411 (Punjab), India

*Corresponding author. E-mail: gurpreetbchandel@gmail.com

Article Info
https://doi.org/10.31018/jans.v17i4.6987
Received: July 09, 2025
Revised: November 22, 2025
Accepted: November 29, 2025

How to Cite

Brohma, S. *et al.* (2025). A review on new horizons in biopesticide development highlighting microbial advances for Climate-smart agriculture. *Journal of Applied and Natural Science*, 17(4), 1781 - 1798. https://doi.org/10.31018/jans.v17i4.6987

Abstract

Sustainable plant protection is vital for continuing improved agricultural productivity and safeguarding global food security. Reliance on synthetic pesticides to mitigate pest outbreaks has led to unintended environmental and health-related concerns, including soil degradation, water pollution, and bioaccumulation within ecosystems. These challenges have accelerated the push for eco-friendly, sustainable pest management alternatives. Biopesticides derived from natural sources offer a promising solution due to their target specificity, environmental safety, and high compatibility with integrated pest management principles. Biopesticides include viruses, bacteria, fungi, parasites, predators, and pheromones, each with distinct mechanisms of action. Despite these advantages, limitations exist in registration, regulation and social acceptance of biopesticides. This review provides a comprehensive overview of biopesticide categories -microbial, phytochemical, and nanobiopesticides and their mechanisms of action, advantages, and limitations. Moreover, the emphasis is placed on microbial pesticides, which differ from their chemical counterparts in their ability to multiply in situ and exhibit long-lasting effects. This review further underscores the significance of biopesticides in fostering climate-smart agriculture, advancing public health, and achieving Sustainable Development Goal targets. This review also underscores the need for ongoing research, innovation, and public involvement to promote the acceptance and commercial success of biopesticide-based solutions in global agriculture.

Keywords: Climate smart agriculture, Formulations, Integrated pest management, Microbial biopesticide, Sustainable agriculture

INTRODUCTION

Since ancient times, synthetic pesticides have been used to manage crop pests and improve agricultural yields (Anani *et al*., 2020; Reddy *et al*., 2024). These pesticides are manufactured by combining chemical compounds with carriers, such as polymers (Rakhimol *et al*., 2020), and are specifically formulated to target specific pests. Although these pesticides enhance crop productivity, their prolonged use poses significant environmental and biological consequences (Farooq *et al*., 2019; Kariyanna *et al*., 2024). In animals, exposure to synthetic pesticides can adversely impact offspring development, immune competence, vitality, and reproductive performance (Syromyatnikov *et al*., 2020; Wan *et al*., 2025). Pesticides also degrade soil quality by increasing soil brittleness, reducing microbial and hampering the activity of beneficial soil organisms. (Pertile *et al*., 2020; Pelosi *et al*., 2021). Furthermore, pesticides adversely impact soil microbes (Steiner *et al*., 2024), by hindering their ability to perform crucial functions, such as siderophore production, nitrogen fixation, and indole-3-acetic acid synthesis (Kumar and Kumar, 2019).

Pesticides are introduced into the environment through multiple pathways, such as improper disposal, drift, vaporization, runoff (Chen *et al*., 2023), erosion, or leaching, causing damage to all environmental components, soil, air, water, and non-target organisms (Boateng *et al*., 2023), and humans also (Hashimi *et al*., 2020). This reduces crop efficiency and productivity and harms soil and water health. Contaminated water drains into nearby water bodies, leading to pollution of reservoirs, bioaccumulation of pesticides, and their eventual entry into the food chain (Zanchi *et al*., 2023). This bioaccumulation affects aquatic organisms, terrestrial animals, and humans, resulting in health complications such as kidney problems, skin disorders, cancer, and diabetes (Sabarwal *et al*., 2018; Manfo *et al*., 2020). In view of these challenges, biopesticides have come up as a valuable alternative for pest control, offering numerous environmental and health benefits (Lykogianni *et al*., 2021).

To mitigate the adverse effects of chemical pesticides, biopesticide derived from natural sources or their components have emerged as environmental friendly alternative with reduced risk to non-target organisms (EPA, 2023). Biopesticides include microbial forms like *Bacillus thuringiensis* (Bt), Plant-Incorporated Protectants (PIPs), produced by genetically modified plants and other biochemical pesticides. These also include semiochemicals, insect pheromones that disrupt mating behaviour or plant extracts that repel pests, allowing for the management of infestations without toxic effects (Kumar *et al*., 2021).

Biopesticides involve the use of naturally sourced pest control compounds, providing a comparatively safer and target-specific alternative to traditional chemical pesticides (Wattimena and Latumahina, 2021; Huang *et al*., 2021). Of all the microbial biopesticides, bacterial biopesticides have a share of about 74% of the market; 10% is taken up by the fungal biopesticides, viral biopesticides constitute for about 5%; predator biopesticides, 8%; and “other” biopesticides take around 3% share of the total biopesticide market (Thakore, 2006; Tomar *et al*., 2024). They play a vital role in encouraging climate-smart agriculture by enhancing crop quality and yield, minimizing pest resistance, and reducing adverse impacts on human health and the environment (Szewczyk *et al*., 2006; Satish *et al*., 2017; Kumari *et al*., 2022).

The decline in conventional pesticide use, drives the increasing demand for biopesticides, as farmers shift towards climate-smart practices. The shift to biopesticides is driven by their eco-friendly nature, pest-target specificity, resistance management, synergy with chemicals, and compatibility with the Integrated Pest Management (IPM) practices (Kalpana, 2021). Regardless, the effectiveness of biopesticides can differ among pests, as their success depends largely on the target species.

Microbiological biopesticides encompass a wide range of agents that control insects or pathogens, primarily originating from microorganisms such as fungi, bacteria, viruses, protozoa, and nematodes, or their naturally derived products (Adeleke *et al.,* 2022). Many of these biopesticides are economically comparable to traditional pesticides (Ruiu, 2018).

Microbial biopesticides generally have a shorter shelf life than synthetic pesticides and are sensitive to envionemntal conditions such as ultraviolet radiation, temperature changes, and humidity (Matos *et al.,* 2020; Wattimena and Latumahina, 2021). They can retain their effectiveness for about 3 to 6 months when stored at recommended conditions specified on the label (Akutse *et al*., 2020). They can be readily integrated into IPM programs and can substantially boost crop productivity by improving yield (Arora *et al*., 2020). Despite the advantages of biopesticides, their widespread adoption remains a challenge. High production costs, environmental sensitivity, regulatory challenges, market demand constraints, dosage inconsistencies, a lack of standardization, and stability issues are among the challenges (Bharti and Ibrahim, 2020). Although considerable detailed research is required to overcome these limitations, farmers in rural areas can utilize microbial solutions for crop protection to enhance crop quality and farm profitability (Stevenson *et al*., 2017).

METHODOLOGY

The present study followed a structured and systematic research approach to obtain comprehensive information on biopesticides. The existing literature was extensively explored using electronic databases, including PubMed, Google Scholar, Web of Science, Scopus, Academia, Semantic Scholar, and other reliable platforms. The study analyzed more than 150 scientific publications and compiled a detailed collection of relevant studies. The review paper emphasizes the development and utilization of biopesticides for sustainable pest management. The reviewed literature covers classification of biopesticides, formulations of biopesticides, factors affecting efficacy of biopesticides, role of

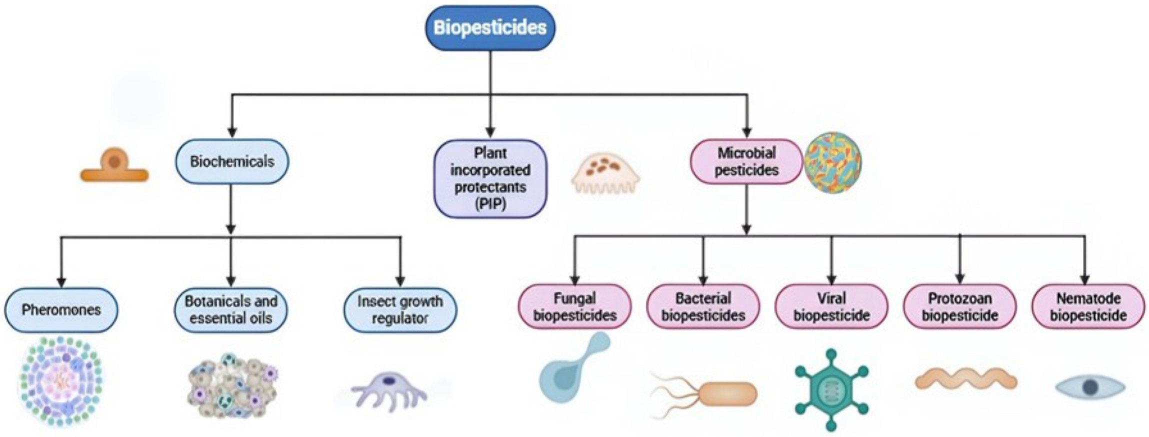

Fig. 1. *Categories of biopesticides (Chakraborty et al., 2023)*

biopesticides in sustainable development and future prospective of biopesticides.

CATEGORIES OF BIOPESTICIDES

The term "biopesticide" broadly refers to substances derived from natural sources, which are typically formulated and applied in a similar manner to traditional pesticides, primarily for short-term pest management (Tadesse *et al*., 2024). There are three major categories of biopesticides, as defined by the US Environmental Protection Agency (EPA, 2023) including: biochemicals, Microbial biopesticides, and Plant-incorporated protectants (Figure 1).

Biochemical biopesticides

Biochemical pesticides are natural substances that manage pests using non-toxic methods, unlike chemical pesticides, which rely on synthetic compounds to eliminate pests directly. These chemicals work by modifying insect's physiology (Magierowicz *et al*., 2020). These pesticides are categorized by their mode of action, such as using pheromones (also known as semiochemicals), plant extracts/botanicals, or insect growth regulators to control pest infestations. Biochemical biopesticides also includes plant growth regulators that inhibit breeding and pheromones that attract or repel pests (Chakraborty *et al*., 2013).

Pheromones are chemicals produced by insects, animals, or plants that are mimicked for use in managing insect populations in IPM programs (Desneux *et al*., 2021). Pheromones interfere with insect mating, ultimately reducing progeny (Singh *et al*., 2023). The target insects become confused by semiochemical flumes diffused in the surrounding area. These chemicals do not kill the insects but has significant effects on the olfactory pathways of insects. The mechanism of pheromone action include their adsorption by insects, transportion via pheromone-binding proteins (PBPs) to chemosensory membranes, and then interaction with receptor proteins to convert chemical signals into amplified electrical signals through a second messenger system (Gurr *et al*., 1999; Ujvary *et al*., 2001; Kumar *et al.,* 2021).

Over the past few years, essential oils and plant extracts have been recognized as sustainable option to synthetic insecticides for achieving effective pest control (Shamsuddeen *et al*., 2024). They contain a wide variety of bioactive chemicals and may behave as attractants, repellents, or antifeedants, impeding host identification by the insect, hindering oviposition, etc. (Tripathi *et al*., 2009; Halder *et al*., 2013; Ali *et al*., 2017). Neem oil, derived from the neem tree, is a widely used botanical insecticide. Its bioactive compounds, solanine and azadirachtin, disrupts insect growth and feeding (Abbey *et al*., 2022). Combining neem oil with the fungal bioagent *Beauveria bassiana* demonstrated significant control of sucking pests on vegetables (Halder *et al*., 2013). The azadirachtin concentration in neem oil must be optimum to avoid harming non-target pests (Mordue *et al*., 2005). Meanwhile, the bioactive compound pyrethrin, extracted from chrysanthemum flower heads, deters herbivores from feeding on them (Tripathi *et al*., 2009; Kojima *et al.,* 2022).

Insect growth regulators (IGRs) disrupt essential biological processes required for sustenance, ultimately leading to insect mortality. These have low toxicity towards non-target organisms (Kumar, 2012). Based on the mechanism of action, these are categorized into insect hormone disruptors and chitin synthesis inhibitors (CSIs) (Chetan *et al*., 2019). IGRs regulate various insects, such as fleas, cockroaches, and mosquitoes, by disrupting reproduction, egg hatching, and moulting, although they are less lethal to adults. When combined with other insecticides, they can enhance adult insect control (Gwinn, 2018).

Plant-incorporated protectants

Plant-incorporated protectants (PIPs) are the compounds produced by the plants from the genetic material introduced into the plant (Parker and Sander 2017).

For instance, scientists can insert a gene responsible for a specific Bt pesticidal protein into a plant's DNA. As a result, the plant produces a protein that kills pests after they ingest that protein. The EPA regulates both the pesticidal protein and the gene that enables its production, but not the plant as a whole (Ghumar *et al*., 2014). PIPs are treated as pesticides and are regulated by the U.S. Environmental Protection Agency. Before a PIP can be approved for use, the EPA evaluates its potential risks to ensure it does not harm human health or the environment. This assessment includes potential impacts on people, non-target plants, animals, and other organisms, as well as strategies to address "insect resistance"—when pests evolve to survive the plant-produced pesticide and the likelihood that PIP genes could transfer to other plants (USEPA, 2024).

In 2023, the EPA revised its regulations. Under the new rules, some PIPs may not require registration or food residue tolerance limits, although they remain under EPA oversight. These exemptions apply to PIPs that pose no greater risk than previously approved ones and that could also be developed through traditional breeding methods (USEPA, 2024).

Microbial biopesticides

Microbial pesticides are the most extensively studied and widely applied group of biopesticides, offering enhanced sustainability compared to chemical pesticides while posing similar levels of risk under approved use guidelines (Shafi *et al*., 2017; Damalas and Koutroubas, 2018). Microbial pesticides employ a range of mechanisms to anatgonise plant pests. Important mechanisms include secretion of volatile compounds and enzymes, production of toxins, colonisation or consumption of the host, competition for nutrients and space, and induction of resistance in crop plants (Freimoser *et al*., 2019). The major difference between microbial and synthetic pesticides is the ability of microbes to persist on crop plants and in the environment after use. This characteristic of microbial pesticides is assumed to be both advantageous and risky. The beneficial aspect of this is that the persistence of microbes enables prolonged pest suppression, as observed in inoculative release strategies, wherein a small microbial population is periodically introduced, allowed to reproduce, and built into a permanent population for long-term pest control. In contrast, favourable conditions may lead to their redundant multiplication and produce toxic metabolites in the environment (Wend *et al*., 2024). However, most microbial species used in biopesticide formulations naturally occur in the environment (Strauch *et al*., 2011). Microbial pesticides account for more than 55% of biopesticides sold worldwide (Wend *et al*., 2024). Their significance is evident and highlights the need to address the challenges and future prospects in evaluating the potential risks associated with these microbial pesticides.

Fungal biopesticides

Fungi were the first type of microorganisms considered for use as biopesticides (Wend *et al*., 2024). The commercially available mycoinsecticides are often derived from species such as *Metarhizium anisopliae, Beauveria bassiana*, *Phytophthora palmivora*, *Isaria fumosorosea*, *Hirsutella thompsonii*, *Alternaria cassia*, and Lecanicillium spp. (Table 1). Unlike bacterial pesticides, which functions primarily via ingestion, fungal pesticides operate through direct contact (Irsad *et al*., 2023). *Beauveria bassiana* and *Metarhizium anisopliae* act against a wide range of pests by penetrating the exoskeleton and growing internally thereafter (Litwin *et al*., 2020). After entering the insect's body, these fungi disrupt physiological functions, which ultimately leads to the insect's death (Bhattacharyya *et al*., 2024).

Entomopathogenic fungi (EPF) are soil-inhabiting microorganisms that infect and kill insects and other arthropods by penetrating their cuticles, making them potent biocontrol agents for managing insect pests (Mantzoukas *et al*., 2022). Several studies have confirmed that EPF, when acting as endophytes, can promot plant growth, suppress plant diseases, and improve rhizosphere health through successful colonization (Jaber and Ownley, 2018; Nelly *et al*., 2019; Bamisile *et al*., 2021; Chang *et al*., 2021). Fungal biopesticides are key elements IPM strategies and ongoing research aims to improve their efficacy through advanced formulations and optimized application methods (Bamisile *et al*., 2021).

Fungal biopesticides plays vital role in endorsing climate-smart agriculture by providing environmentally safe options for pest control. These pesticides are highly selective, and do not harm other beneficial organisms (Tadesse *et al*., 2024). This makes them the perfect candidates for IPM and sustainable agricultural practices, fostering ecological diversity and conserving the environment (Kim and Goettel 2011; Koike *et al*. 2011; Tadesse *et al*., 2024).

Fungal biocontrol agents secrete a number of secondary metabolites that are directly toxic to the pest (Jahan Shaili *et al*., 2025). The fungal bioagent *Trichoderma harzianum* is widely used to manage soil-borne fungi that cause root rot and damping-off diseases in plants (Yao *et al*., 2023). This rhizospheric fungus suppress the growth of pathogenic fungi by secreting antifungal chemicals and competing more effectively for space and nutrients (Harman *et al*., 2004). The oomycete fungus *Pythium oligandrum* exhibits strong mycoparasitic behaviour and can eliminate more than 50 species of fungi and oomycetes (Gabrielová *et al*., 2018). *Gliocladium* species are soil-inhabiting endophytic fungi with strong antagonistic against pathogens and have proven effective in managing potato early blight caused

Table 1. Overview of fungal biopesticides and their mode of action/ use against pests

Fungal-based biopesti-	Mechanism of action /use	References
Beauveria bassiana	The fungus enters the host body through natural openings or wounds, spreading its mycelium throughout the host's body and producing several toxins detrimental to the insect, which eventually cause death. Efficient against a wide variety of pests.	Naqqash *et al.* (2016); Baldiviezo *et al.* (2020)
Metarhizium anisopliae	Targets wide range of insects and is appropriate for use in non-consumable agricultural environments like the nurseries, ornamental greenhouses, residential and institutional areas. It should not be used in areas where water contamination is a significant	Montalva *et al.* (2016); Vivekanandhan *et al.* (2022)
Verticillium lecanii (*Lecanicillium lecanii*)	The spores of this fungus, upon contact with the insect, can germinate its mycelium, infiltrate the cuticle, and spread throughout the host body, ultimately leading to the fatal demise of the insect. It is effective against	Feng *et al.,* (2000); Lee *et al.,* (2006); Ruiu, (2018)
Paecilomyces lilacinus	Effective against plant parasitic nematodes.	Akutse *et al*. (2020)
Isaria fumosorosea	Can control soft-bodied insects like mealy bugs and whiteflies.	Akutse *et al*. (2020)
Trichoderma sp.	Have antagonistic interactions with numerous phytopathogens, including fungi, bacteria, and nematodes. Effective against soil-borne phytopathogens.	Ghayur (2000)
Phytophthora palmivora	The liquid bioherbicide formulation is used	Kachhawa (2017)
Colletotrichum glloeosponoides	A dry powder bioherbicide, used to control Northern joint vetch.	Kachhawa (2017)
Colletotrichum acutatum	A liquid bioherbicide formulation, effective to manage *Hakea sericea* and *H. gibbosa*.	Muir (2023)

by *Alternaria grandis* (da Silva *et al*., 2021). Miastkowska *et al*. (2020) showed that ultrasonically produced nano-emulsions of essential oils—such as cinnamon, thyme, manuka, and tea tree oils—have strong antifungal activity and are inexpensive, safe, and eco-friendly as compared to pure essential oils and traditional macroemulsions. Recent advances have enhanced understanding of host–pathogen interactions and plant defense mechanisms, supporting the development of more targeted and effective fungal applications in agriculture. One such example is integrating EPF with nanotechnology (Nassary, 2015).

Bacterial biopesticides

The use of bacteria against insect pests began with Felix d'Herelle's discovery of entomopathogenic bacteria (F, d'Herelle, 1911). Among the bacterial biopesticides, Bt is the most prevalent, representing 90% of all bacterial biopesticide products (Hubbard *et al*., 2014). Bt produces insecticidal toxins that kill insects either through crystalline inclusions or toxic secretions (Chakroun *et al*., 2016). The first known application of Bt occurred in France during the 1920s, and the first commercial *Bt* product, Sporeine, was launched in 1938. Large-scale production followed in the U.S. in the 1950s.

In India, only 12 biopesticides are officially registered under the Insecticide Act of 1968, with Bt being the most significant (Sinha and Biswas, 2009). Other notable EPBs include *Pseudomonas*, *Chromobacterium*, and *Yersinia* species. Various Bt subspecies are effective against different insect larvae, including Lepidoptera, mosquitoes, and Coleoptera. *Lysinibacillus sphaericus* is specifically used for mosquito control through the production of Bin toxin (Silva *et al*., 2014). Secondary metabolites produced by Streptomyces species are effectively used to control fungal diseases, such as potato scab and rust (Khan *et al*., 2023). Other biocontrol bacteria include *Saccharopolyspora spinosa*, *Pseudomonas aeruginosa*, and *B. popilliae*. *Photorhabdus* and *Xenorhabdus* species also exhibit insecticidal activity and form mutualistic relationships with entomopathogenic nematodes (Vedamurthy *et al*., 2022). *Brevibacillus laterosporus*, first identified in 1912, and *Chromobacterium subtsugae*, tested in the U.S., are additional biocontrol agents. Lastly, the phylum Proteobacteria, classified by Carl Woese in 1980, includes many insecticidal bacteria across its subgroups. Table

Table 2. Overview of bacterial biopesticides and their mode of action/ use against pests

Bacterial-based pesticide	Mechanism of action/use	References
Bacillus thuringiensis (Bt)	Bt primarily targets lepidopteran pests. It secretes toxins inside the gut of the insect, which on mixing with the hemolymph, damages the epithelial cells, causing starvation and death. Effectively used against American bollworm in cotton and rice stem borer.	Ghayur (2000)
Bacillus subtilis	The bacterium produces antibiotics, lipopeptides, and cyclic peptides which prevents the growth of pests. It is shown be effective against *Fusarium, Aspergillus, Pythium*, and *Rhizoctonia.*	Djaenuddin *et al*., (2020)
Bt israelensis	Acts as a bioinsecticide, used to control gnat flies.	Ruiu (2018)
Bt tenebrionsis	Shows antimicrobial activity against Coleopteran adults and larvae	Rajaput *et al*., (2019)
Pseudomonas fluorescens	It invades the rhizosphere and synthesize secondary compounds that inhibit soil-borne diseases. They contribute to phytoremediation and are a key component of microbiome in many plants.	Adesemoye and Kloepper, (2009); Germaine *et al*., (2009); Glick, (2012); Daniel, (2020)
Streptomyces species	This bacterium synthesize antifungal metabolites, which targets different phytopathogens. It is effective in managing *Fusarium* and *Phytophthora* species.	Gonzalez-Franco and Robles-Hernandez (2009); Ara *et al*. (2014); Law *et al*. (2017)

2 presents different bacterial biopesticides, their mechanisms of action, and their applications.

Virus based biopesticides

Virus-based biopesticides offers an environmentally sustainable approach to target pests without harming beneficial organisms, plants, and humans (Harish *et al*., 2021). These biopesticides are sourced from naturally occurring viruses, such as baculoviruses, entomopoxviruses, and ascoviruses, which have naturally adapted to infect and kill specific insect species (Sarwar and Aslam, 2021). The virion particles enter the target pest when ingested during feeding, particularly sap-sucking insect pests. As soon as they enter the insect body, they start replicating and utilizing the pest's machinery to produce multiple copies, which eventually cause the death of the insect within a few days (Kachhawa, 2017). Viral pesticides are highly host-specific, thus being safe for non-target pests and the surrounding environment (Jukes and Merwe, 2020). Since, they take time to degrade, they leave no residue and thus cause no environmental pollution. However, limiting factors, such as a slow mode of action, susceptibility to UV radiation, temperature, and very high specificity, which narrows their host range, pose a significant challenge to using viruses as bioinsecticides. Table 3 presents a list of virus-based biopesticides, their modes of action, and their applications.

Viral formulations utilize viruses, most preferably baculoviruses, which are highly specific to the target pests and safe for the environment. These are incorporated into the IPM, as they serve as a good alternative to chemical pesticides. Baculoviruses have proven to be highly effective due to their ability to infect and kill insect pests without harming non-target pests, making them an ideal candidate for sustainable agriculture (Natra *et al*., 2019; Thapa *et al*., 2020).

The choice of viral formulation depends on the target pest, application method, and environmental factors that can either limit or promote the reduction or persistence of the virus in the field (Quiroga-Cubides *et al*., 2022). Among different types of viral formulations, aqueous suspensions are the most commonly used, wherein virus particles are suspended in water and applied as a foliar spray in the field. Foliar sprays are effective as it causes direct ingestion of viral particles, leading to infection and eventual pest mortality (Monroy-Borrego and Steinmetz, 2022). Also, these can be stored easily for longer duration of time. To control soil- or root-inhabiting pests, granular formulations are applied directly to the soil, ensuring direct exposure to the viral biopesticide (Kergunteuil *et al*., 2016). Bait formulations, often combined with attractants, can be used to target specific insect species while minimizing non-target effects (Behle and Birthisel, 2023).

Baculovirus was first introduced as a pesticide, though it failed to achieve commercial success. However, the successful use of NPV to control the tussock moth in 1984 (Williams, 2023) sparked significant interest in baculoviruses as pest control agents. These viruses are used in biomedical research to better understand virus-host interactions. Additionally, genetic engineering techniques are being used to develop recombinant baculoviruses for insect control (Chambers *et al*., 2018). Most baculovirus-based products are produced in suspension concentrate (SC) form, representing about 88% of the market, whereas solid formulations such as water-dispersible granules (WG) and wettable powders (WP) make up the remaining 12%. Liquid formulations dominate due to their easier handling, higher efficiency, and compatibility with standard spraying systems, for large-scale farming (Martínez-Balerdi *et al*., 2025).

Two commercial *Spodoptera* NPV formulations, Spodopterin™ and SPOD-X™, have been found beneficial for controlling pests of vegetable crops. In Brazil, *S. frugiperda* NPV was once applied to about 20,000 hectares of maize annually (Geisler *et al*., 2024), but its use was discontinued due to technological challenges in producing the virus in the laboratory. Recent studies suggest *S. littoralis'*s gut microbiota may affect its resistance to NPV. Alterations in gut bacteria can boost NPV replication, suggesting that disrupting the microbiome may enhance NPV-based pest control (Li *et al*., 2025).

Nematode biopesticides

Growing efforts to reduce synthetic pesticides have highlighted entomopathogenic nematodes (EPN) as important agents in pest management (Ramakuwela *et al*., 2025). Nematodes, such as *Heterorhabditis* and *Steinernema*, have been successfully employed in managing insect pests (Tarasco *et al*., 2023). These nematodes can exhibit facultative, obligate, necromenic, or phoretic associations with insects. They are cosmopolitan, with their presence observed on all continents except Antarctica (Askary *et al*., 2018). They exhibit a wide range of host preferences and therefore serve as effective biocontrol agents for harmful agricultural pests. Additionally, they are safe for the beneficial insects and are eco-friendly. Twenty-three nematode families are known to be parasites of insects; however, seven families are more effective at controlling pest populations. EPNs are divided into two categories based on their host-searching behaviour: some are cruisers, while others are ambushers. *H. bacterophora* and *S. glaseri* are subterranean cruisers and can more actively find suitable host, whereas ambushers like *S. carpocapsae* are upper surface dwellers and usually wait to attack their suitable host in the soil (Mohan, 2015). EPN formulations, such as gels and alginate beads, protect nematodes from environmental stress, enhance their survival, and improve their field efficacy (Fatimah *et al*., 2025). EPNs serve as effective biological control agents against pests because they can be used for augmentative, conservation, and classical biological control. Similarly, there are nematodes, such as Steinernema nematodes, which have a symbiotic association with entomopathogenic bacteria Xenorhabdus and Photorhabdus, exhibiting significant antimicrobial properties against phytopathogens. Table 4 lists different viral-based biopesticides, their modes of action, and applications.

Protozoa as biopesticides

Protozoans are intracellular parasites that depend on living within host cells for survival. They are widespread in nature and can infect specific insect groups such as lepidopterans and orthopterans, making them valuable agents in IPM programs (Tadesse *et al*., 2024). Their adaptability and diversity make them crucial to many biological processes. Certain protozoans are also effective biopesticides, particularly against grasshopper species. However, in the past decade, *Nosema* spp. has been the only protozoan insecticide registered with the US Environmental Protection Agency (Federici, 1999). *N. pyrausta* infects various insects, including the European corn borer, and can act as a natural control. The infection spreads through contaminated frass and movement of infected larvae between plants (Grushevaya *et al*., 2020). The microsporidium *Nosema locustae* is a commercially available species sold under various brand names for managing grasshopper and cricket populations (Yasin *et al*., 2024). Protozoa infections typically leads to low to moderate mortality in the insects (Sarwar *et al*., 2021). The pathogen penetrates the insect through the gut wall, disseminates to different tissues and organs, and reproduces, occasionally leading to tissue damage and septicemia. Infected insects often become lethargic and smaller than usual, with decreased feeding, reduced reproductive capacity, and difficulties in molting. High levels of infection can result in death. A key advantage of this infection type is that the weakened insects become more vulnerable to environmental stresses and other mortality factors (Han and Weiss, 2017). Despite their pest-specific nature and slow-acting characteristics, protozoa are less effective as biopesticides than other microbial biopesticides. Although they can induce chronic and draining effects on their targets, their efficacy is comparatively lower, which limits their use (Meenatchi and Aditi, 2021). Table 5 represents the different entomopathogenic protozoan and their hosts.

FACTORS AFFECTING EFFICACY OF BIOPESTICIDES

An eco-friendly alternative to synthetic pesticides, biopesticides are formulated from biological materials such as microbes, plants, and other organisms. They tend to be environmental friendly, safer for non-target organisms, and suitable for human consumption. Still, their performance relies on a set of factors that must be

Table 3. Overview of viral biopesticides and their mode of action/ use against pests

Viral biopesti-	**Mechanism of action /use**	**References**
Baculoviruses (Nucleopolyhedrovirus (NPV), Granulovirus (GV))	Upon ingestion, the virus infects gut cells, replicates inside the insect, and kills within 4-10 days. They are commercially formulated as biopesticides such as Helicovex and Cryptex. Its target pests are Caterpillars (e.g., armyworms, cutworms, diamondback moths).	Gelaye and Negash (2023; Martínez-Balerdi *et al*., 2025)
Cytoplasmic polyhedrosis viruses (CPVs)	CPVs primarily target Lepidopteran pests and are widely used in tropical agriculture. The ingested virus disrupts gut cells, causing reduced feeding, digestive issues, and eventual death. Spray application to foliage or crop fields.	Abd-Alla *et al*. (2020)
Iridovirus (IIVs)	IIVs are useful for aquatic pest control and are known for their striking iridescent effect on infected insects. A virus infects tissue cells, leading to lethargy, reduced activity, and ultimately, death. These viruses are effective against mosquito populations in standing water.	Prasad and Srivastava, (2016; Vladimirova *et al*., 2025)
Ascoviruses	Ascoviruses are dsDNA viruses that infect lepidopteran larvae, reducing feeding and causing death. They are well-suited for use in biopesticide formulations due to their host and safety for beneficial insects and humans.	Yu *et al*., (2021)
Densoviruses	Densoviruses, particularly *Aedes aegypti* densovirus (AeDNV), controls mosquito larvae by infecting their gut and organs after ingestion disrupting development and causing death.	Erlandson (2020)
Entomopoxviruses	Entomopoxviruses infect insect’s fat bodies, epithelial cells, and hemolymph. The virus particles are ingested when the insect feeds on foliage that has been treated with the virus. The infected insect exhibits impaired feeding, stunted growth, and lethargy, ultimately leading to death, typically within 4 to 10 days after infection. Its target pests are beetles and caterpillars (e.g., cotton pests). The virus infects epithelial and adipose tissues, disrupting metabolism and leading to cell death. Can be applied as a spray or a bait formulation.	Raj *et al*., (2022)
Reoviruses ((Rice ragged stunt virus (RRSV))	These viruses are double-stranded RNA viruses known for their environmental stability and ability to infect a wide range of insect pests. The virus replicates in insect tissues, reducing mobility, feeding, and reproductive rates. Applied as a spray or vector-mediated delivery, used against rice pests (e.g., brown planthopper).	Ruiu (2018)
Polydnaviruses (*Cotesia congregata* polydnavirus (CcPDV))	These viruses are symbiotic with parasitoid wasps, allowing indirect pest control by ensuring the survival of parasitoid offspring. Its target pests are pests parasitized by specific wasps (e.g., caterpillars). Delivered by parasitoid wasps, weakens the pest's immune system, ensuring wasp larval survival.	Prasad and Srivastava (2016)
Luteoviruses ((Barley yellow dwarf virus (BYDV))	Luteoviruses, unlike direct viral biopesticides (e.g., baculoviruses), do not cause pest mortality through direct infection. Instead, they work indirectly by affecting the interaction between the pest and its host plant. Luteoviruses do not directly kill pests but instead alter the pest’s behavior, physiology, and reproduction. Its target pests are aphids and related sap-feeding insects. Alters pest behaviour or physiology, thereby indirectly reducing crop damage.	Wagemans *et al*. (2022)
Hytrosaviruses ((*Musca domestica* hytrosavirus (MdHV))	Hytrosaviruses are particularly effective for fly management in urban or agricultural settings. By disrupting reproduction, they provide long-term suppression of fly populations. Its target pests are houseflies (*M. domestica*). Its mode of action involves disrupting reproduction by impairing ovarian development, thereby reducing population size.	Petersen *et al*., (2022)
Cydia pomonella granulovirus (CpGV)	A naturally occurring baculovirus called *C. pomonella* granulovirus (CpGV) is employed as a biological control agent against the codling moth (*C. pomonella*). Its target pests is Codling moth larvae, a major pest in apple, pear, and walnut orchards. The virus infects the midgut cells, replicates, and spreads through the insect's body. Applied as a foliar spray to orchard crops.	Olivares *et al*. (2023)

strictly regulated to conduct effective pest management (Tadesse *et al*., 2024).

Nature of the biopesticides

Microorganisms, including bacteria (e.g., *Bacillus, Pseudomonas*), fungi (e.g., Metarrhizium, Beauveria), viruses (e.g., baculoviruses, nucleopolyhedroviruses), and protozoa, exhibit distinct modes of action and varied reactions to environmental conditions, making them examples of biopesticides (Thakur *et al*., 2020); Vermelho *et al*., 2024). Efficiency of Bt, against lepidopteran pests decreases below 15°C (Glare *et al*., 2012). The efficacy of *Bacillus thuringiensis* (Bt) formulations is often compromised by their physicochemical instability and by the photodegradation of pesticidal proteins under ultraviolet (UV) exposure. Furthermore, environmental variability contributes to fluctuations in bioactivity, thereby hindering consistent field performance and complicating large-scale application strategies (Aswathi *et al*., 2024). Certain insect species are targeted by the distinct poisons produced by various *Bt* strains (Santos *et al*., 2022). Few strains of *B. thuringiensis kurstaki* are more suitable for beetles or flies, while others are more powerful against caterpillars (Vimala *et al*., 2020). Formulations such as emulsifiable concentrates, granules, wettable powders, and liquid suspensions have certain applications (Hernandez *et al*., 2022). Encapsulation techniques, including microcapsules or alginate beads, can enhance efficacy and microbial survival under extreme conditions (Singh and Paithankar, 2023).

Environmental factors

Environmental factors are the major driving force behind the proper efficiency of a biopesticide (Jayaseelan, 2024). An optimal temperature range is required for the proper activity of microbial biopesticides, as extreme heat temperatures can kill or reduce their effectiveness (Salimi and Hamedi, 2021). The optimal temperature range for *Metarhizium anisopliae* is 25–30°C (Faria *et al*., 2022). High humidity and leaf wetness are required for fungal and bacterial biopesticides because they favor spore germination and infection (Pathma *et al*., 2021). For fungal biocontrol agents such as *Beauveria bassiana* to be effective in controlling pests, a 10–12-hour dew period is needed (Ghodake *et al*., 2018). Bt is most active at 25℃ under both laboratory and field conditions, but toxic production and spore germination are hindered at temperatures below 15°C and above 35°C (Vero *et al*., 2023). Most biopesticides are broken down by UV light, which reduces their persistence in the field (Thakur *et al*., 2020). For example, exposure to UV light greatly diminishes the effectiveness of granulovirus against codling moth (Wilson *et al*., 2020). Rain may wash biopesticides off plant surfaces, yet, it can also help disperse spores and promote microbial infection (Bharti and Ibrahim, 2020). The effectiveness of biopesticides is influenced by soil properties such as microbial density, organic content, and pH, with soil texture and moisture particularly impacting nematodes such as *S. carpocapsae* (Matuska-Łyżwa *et al*., 2024).

Application factors

The success of pest control depends largely on the proper timing and application of biopesticides (Tadesse *et al*., 2024). The distribution of pesticides and their interactions with pests are influenced by application methods such as spraying, dusting, or soil incorporation. Incorporating biopesticides into the soil is best for soil-dwelling pests, whereas spraying is more effective against foliar pests (García-Espinoza, 2024). Applications must be aligned with the pest's life cycle, the crop’s growth stage, and prevailing environmental conditions (Khursheed *et al*., 2022). Bt is most effective when applied to susceptible insects during their larval stage (Souza *et al*., 2019). The biopesticide will effectively target pests if the spray volume is adequate and the coverage is uniform.

Pest and host-related factors

Factors related to both the insect and the host are important in determining the effectiveness of biopesticides. Based on physiological and behavioural characteristics, pest species vary in their susceptibility; younger stages, such as early instar larvae, are more vulnerable due to their thinner cuticles and weakened immune systems (Kumar *et al*., 2021). Due to their overpowering effect, large insect populations can reduce the efficiency of biopesticides (Arthurs *et al*., 2019). Pest movements and feeding habits are also important; for example, pests that feed on plant surfaces are more likely to come into contact with sprayed biopesticides, whereas pests that burrow into or feed within plant tissues may require systemic treatments (Ramírez *et al*., 2024).

In addition, host plant properties, such as leaf texture, waxy nature, and hairiness, affect the retention and adherence of biopesticides. Smooth leaves tend to have greater deposition than waxy or hairy leaves (Arcot *et al*., 2024). Senescence and leaf exudation are processes that can shorten the persistence of biopesticides or further degrade them. The importance of resistance management practices, such as rotation among products with varying modes of action, is underscored by the emergence of pest resistance, often driven by repeated use of the same biopesticides (Pathma *et al*., 2021).

Compatibility with other inputs

The efficacy of biopesticides may be significantly influenced by their interactions with other agricultural in-

Table 4. Overview of nematodal biopesticides and their use against pests

Nematode based biopesticide	Uses	References
Steinernema pakistanense	Used against *Meloidogyne spp.* (Root -knot nematode)	Ahmed and Javed, (2024)
Heterorhabditis amazonensis	Used against *Agrotis ipsilon* (Black cut worm)	De Oliveira Giannasi *et al.* (2018)
S. carpocapse, S. feltiae, S. riobrave	Used against *Spodoptera frugiperda* (Army worm)	Gozel and Gozel (2021; Meethal Aparna *et al*., 2025)
Heterorhabditis bacteriophora	Used against *Scirpophaga incertulas* (Rice stem borer)	Devi (2020)
S.glaseri, S. carpocapse, S. feltiae	Used against *Cosmopolites sordidus* (Banana root borer)	Prempeh (2019)
H. beicherriana	Used against *Holotrichia parallela* (Peanut grub)	Li *et al*., (2021)
H. indica	Used against *Musca domestica* (Housefly)	Bream *et al*., (2018)
H. amazonensis	Used against *Maconellicoccus hirsutus* (Mango mealybug)	Fuenmayor *et al*., (2020)
S. bicornutum	Used against *Liriomyza* spp. (Leaf miner)	Abbas (2022)
S. carpocapsae, H. bacteriophora	Used against *Pieris rapae* (Larvae of cabbage white butterfly)	Aioub *et al.* (2021)
H. taysearae	Used against *Bactrocera dorsalis* (Oriental fruit fly	Godjo *et al*., (2018)

puts. These factors are responsible for producing effective solutions for biopesticides. Care must be taken when altering pH or introducing certain substances, as the combination of biopesticides with certain agrochemicals, such as copper-based fungicides, can compromise microbial viability (Santos et al., 2021). This may cause phytotoxicity to plants. There should be consistency in the application, or else reduced pest control can occur due to issues such as clumping or precipitation during mixing (Fenibo *et al*., 2022). Proper timing and a gap must be maintained before and after applying a biopesticide and a synthetic pesticide, as this may disrupt the biopesticide's mechanism of action. Some adjuvants alter formulations or degrade active ingredients, while others enhance the performance of biopesticides. Therefore, each element in a formulation must be carefully chosen as the biopesticides are highly sensitive in nature and the same formulation cannot be followed for every biopesticide (Salimi and Hamedi, 2021). Inappropriate timing or mixing can reduce efficacy by 20-30% (Santos *et al*., 2021).

Biopesticides play a crucial role in IPM, to control pests while ensuring environmental and economic sustainability. Therefore, thorough research is needed before applying any biopesticides, as their compatibility varies from organism to organism.

BIOPESTICIDES AND THEIR ROLE IN SUSTAINABLE AGRICULTURE

Climate-smart agriculture represents a sustainable strategy that integrates technological innovations, data-driven decision-making, and flexible farming practices to reduce the negative effects of climate change (Roy *et al*., 2025). Biopesticides are a key component of climate-smart agriculture, offering a sustainable approach for advancing farming (Han *et al*., 2024). Biochemical biopesticides, such as plant extracts, pheromones, and essential oils, target pests broadly while sparing non-target organisms, making them suitable for sustainable pest management (Ody *et al*., 2025). The microbial pesticides naturally carb pest populations, decreasing the reliance on chemical treatments (Sunjka and Mechora, 2022). Collectively, various biopesticide classes reduce the environmental impact of synthetic pesticides and provide a sustainable strategy to manage pest resistance and preserve ecosystem biodiversity (Ullah *et al*., 2025). Combining biopesticides with biostimulants, such as plant growth-promoting rhizobacteria (PGPR) or seaweed extracts, enhances pest resistance, improves stress tolerance, and boosts crop health and yield (Sansinenea, 2021; Matthews et al., 2024). The development of biopesticides has advanced significantly, addressing both pest management and environmental and health concerns. However, their broader adoption in sustainable agriculture remains limited due to factors such as inconsistent knowledge, varying national regulations, and inadequate distribution to farmers. To promote wider use, governments are encouraged to: (1) reduce dependence on chemical pesticides, (2) invest in future-oriented research such as crop system redesign and improved prophylactic measures, (3) support policies and private initiatives that facilitate the transition to pesticide-free agri-food systems, and (4) simplify biopesticide registration by easing requirements for toxicological, environmental, and residue testing (Soetopo and Alouw 2023).

Table 5. Entomopathogenic protozoa and their hosts

Entomopathogenic protozoa	**Host**	**Reference**
Mattesia dispora	*Plodia interpunctella*	Kalen *et al.,* (2022)
Apicystis bombi	*Bumblebees (Bombus spp.)*	Votavova *et al., (*2022)
Gregarina cochlearium	*Phaedon cochleariae*	Barber *et al*., (2024)
Malameba locustae	*Schistocerca*	Bessette *et al*., (2022)
Farinocystis tribolii	*Tribolium castaneum*	Bessette *et al., (*2022)
Vairimorpha plodiae	*Plodia interpunctella*	Saglam *et al., (*2021)
Nosema whitei	*Tribolium castaneum*	Rauf *et al., (*2022)
Mortierella oryzaephilus	*Oryzaephilus surinamensis*	Lord (2007)
Paranosema locustae	*Locusta migratoria*	Zhang *et al. (*2023)

Future prospectives

Biopesticides, which have the potential to fully replace synthetic chemicals in pest management, have recently garnered global interest for several positive reasons. In addition to being environmentally friendly, ongoing research continues to uncover more effective compounds, further enhancing their promise as innovative pest-control solutions. The use of nano-pesticides in agriculture has been shown to enhance controlled release, reduce dosage requirements, deliver genetic material into crops, and facilitate pathogen detection (Manchikanti, 2019). It has a promising future in pest control; however, concerns persist regarding the potential for pests to develop resistance, possible harmful effects on human health, and the risk of manipulating genetic material (Ganguli, 2019). Climate change amplifies the frequency and unpredictability of pest and disease outbreaks and can influence the performance and effectiveness of biopesticides; it is therefore crucial to develop climate-resilient strategies (Narandzic *et al*., 2025). Farmer's adoption of biopesticides is slow due to cost, lack of awareness and familiarity with chemical pesticides, underscoring the need to study their economic viability and role in sustainable farming (Jagadeesan *et al*., 2024). Collaboration among researchers, investors, venture capitalists, manufacturers, and farmers is essential for the widespread adoption of biopesticides (Rezaei *et al*., 2019; Ashaolu *et al*., 2022). Overcoming regulatory challenges is crucial to ensuring an adequate and affordable supply of biopesticides and advancing economic sustainability.

Conclusion

Climate-smart agriculture involves adaptive farming practices designed to anticipate, mitigate, and manage the negative impact of climate change on farming system. Climatic changes expose plants to abiotic and biotic stresses, increasing disease incidence and highlighting the need for effective management to sustain agriculture. In this scenario, biopesticides have emerged as the saviour, offering a more environmentally responsible solution by reducing pollution, preventing pest resistance, and supporting ecological balance by conserving beneficial organisms. This is a fast-growing area of study, with ongoing research expected to yield increasingly innovative microbial pesticides ovel microbial pesticides. High demand could amplify benefits like using waste for biopesticide production and restoring contaminated ecosystems. Similar to antimicrobial management, the strategic and judicious application of biopesticides is essential to maintain their efficacy, and minimize the development of pest resistance or unintended ecological impacts. Adopting agricultural practices that prioritise environmental care, economic feasibility, and social acceptance is fundamental to achieving sustainability in farming and should become the primary goal in agriculture. Such practices are closely associated with the United Nations' 17 Sustainable Development Goals (SDGs) and the principles of Green Chemistry, highlighting a direct connection between sustainable agriculture and at least eight of these goals. IPM strategies based on biopesticides could lead to a future of pesticide-free agriculture, one that supports economic growth, societal well-being, and environmental preservation. The near future demands healthier, safer crop production that does not damage the ecosystem, while maintaining crop productivity and nutritional quality. Promoting education, public awareness, and collaboration among researchers, stakeholders, and regulators can enhance the acceptance and development of biopesticides, thereby supporting sustainable, eco-friendly pest management in agriculture.

Conflict of interest

The authors declare that they have no conflict of interest.

REFERENCES

1. Abbas, W., Javed, N., Haq, I. U. & Ahmed, S. (2022). Virulence potential of two entomopathogenic nematodes, their associated bacteria, and its metabolites to larvae of *Pieris brassicae* L. (Lepidoptera, Pieridae) in cabbage under greenhouse and field bioassays. *Int. J. Trop. Insect Sci.,* 42(1), 557-563. doi:10.1007/s42690-021-00571-y
2. Abbey, L., Abbey, J., Leke-Aladekoba, A., Iheshiulo, E. M. A. & Ijenyo, M. (2019). Biopesticides and biofertilizers: Types, production, benefits, and utilization. *In Byproducts from Agriculture and Fisheries: Adding Value for Food, Feed, Pharma, and Fuels,* Wiley, 479–500
3. Abd-Alla, Adly., Meki, Irene. & Demirbas-Uzel, Güler. (2020). Insect viruses as biocontrol agents: Challenges and opportunities, *Cottage industry of biocontrol agents and their applications,* Springer international publishing, 277-295 doi: 10.1007/978-3-030-33161-0_9
4. Adeleke, B. S., Ayilara, M. S., Akinola, S. A. & Babalola, O. O. (2022). Biocontrol mechanisms of endophytic fungi. *Egypt. J. Biol. Pest Control*, 32, 1–17. doi: 10.1186/s41938-022-00547-1
5. Adesemoye, A, O. & Kloepper, J, W. (2009) Plant-microbes interactions in enhanced fertilizer-use efficiency. *Appl. Microbiol. Biotechnol.,* 85, 1–12. doi: 10.1007/s00253-009-2196-0
6. Ahmed, B. & Javed, S. (2024). Comparative Effects of entomopathogenic nematodes, biopesticides, and plant extracts against agricultural pest *Meloidogyne incognita* (Tylenchida: Heteroderidae). *Pak. J. Nematol*, 42(2), 171-179. https://dx.doi.org/10.17582/journal.pjn/2024/42.2.171.179
7. Aioub, A., El Ashry, R., Hashem, A., Elesawy, A. & El-Sobki, A. (2021). Compatibility of entomopathogenic nematodes with insecticides against the cabbage white butterfly, *Pieris rapae L.* (Lepidoptera: Pieridae), *Egypt. J. Biol. Pest Control.*, 31. doi:10.1186/s41938-021-00498-z
8. Akutse, K. S., Subramanian, S. & Maniania, N. (2020). Entomopathogenic fungus isolates for adult *Tuta absoluta* (Lepidoptera: Gelechiidae) management and their compatibility with *Tuta pheromone*. *J. Appl. Entomol.,* 144, 777–787. https://doi.org/10.1111/jen.12812
9. Ali, M. A., Doaa, S. M., El-Sayed, H. S. & Asmaa, M. E. (2017). Antifeedant activity and some biochemical effects of garlic and lemon essential oils on *Spodoptera littoralis* (Boisduval) (Lepidoptera: Noctuidae). *J. Entomol. Zool.*, 5, 1476–1482
10. Anani, O. A., Mishra, R. R., Mishra, P., Enuneku, A. A., Anani, G. A. & Adetunji, C. O. (2020). "Effects of toxicant from pesticides on food security: current developments" in *Innovations in Food Technology*. Springer, Newyork,313–321. doi:10.1007/978-981-15-6121-4_22
11. Ara, I., Bukhari, N. A. & Aref, N. (2014). Antiviral activities of streptomycetes against tobacco mosaic virus (TMV) in Datura plant: evaluation of different organic compounds in their metabolites. *Afr. J. Biotechnol.*, 11, 2130–2138. doi: 10.5897/AJB11.3388
12. Arcot, Y., Iepure, M., Hao, L., Min, Y., Behmer, S. T. & Akbulut, M. (2024). Interactions of foliar nanopesticides with insect cuticle facilitated through plant cuticle: effects of surface chemistry and roughness-topography-texture. *Plant Nano Biol.*, 7, 100062. doi: org/10.1016/j.plana.2024.100062
13. Arora, N. K., Mishra, J. & Dutta, V. (2020). Biopesticides in India: technology and sustainability linkages. *3 Biotech,* 10, 210–212. DOI:10.1007/s13205-020-02192-7
14. Arthurs, S. & Dara, S. K. (2019). Microbial biopesticides for invertebrate pests and their markets in the United States. *J. Invertebr. Pathol.*, 165, 13-21. doi: 10.1016/j.jip.2018.01.008
15. Ashaolu, C. A., Okonkwo, C. O., Njuguna, E. & Ndolo, D. (2022). Recommendations for effective and sustainable regulation of biopesticides in Nigeria. *Sustainability,* 14, 2846
16. Askary, T., Khalil, A., Nazir, N., Khan, A. & Banday, S. (2018). Nematode parasites of grapevines, *Biocontrol*, Doi:10.1007/978-3-319-94232-2_7
17. Aswathi, N., Balakrishnan, N., Srinivasan, T., Kokiladevi, E. & Raghu, R. (2024). Diversity of Bt toxins and their utility in pest management. *Egypt. J. Biol. Pest Control*, 34, 40
18. Baldiviezo, L. V., Pedrini, N. & Santana, M. (2020). Isolation of *Beauveria bassiana* from the chagas disease vector *Triatoma infestans* in the gran chaco region of argentina: assessment of gene expression during host- pathogen interaction. *J. Fungi*, 6, 219. doi: 10.3390/jof6040219
19. Bamisile, B. S., Siddiqui, J. A., Akutse, K. S., Aguila, L. C. R. & Xu, Y. (2021). General limitations to endophytic entomopathogenic fungi use as plant growth promoters, pests and pathogens biocontrol agents. *Plants,* 10(10), 2119
20. Barber, A., Friedrichs, J. & Müller, C. (2024). Gregarines impact consumption and development but not glucosinolate metabolism in the mustard leaf beetle. *Front. Physiol.*, 15 (01 May 2024). doi: 10.3389/fphys.2024.1394576
21. Behle, R. & Birthisel, T. (2023). Formulations of entomopathogens as bioinsecticides. *In Mass production of beneficial organisms*, Academic press. 407-429. doi:10.1016/B978-0-12-822106-8.00010-5
22. Bessette, E. & Williams, B. (2022). Protists in the insect rearing industry: benign passengers or potential risk? *Insects*, 13(5), 482. doi: 10.3390/insects13050482
23. Bharti, V. & Ibrahim, S. (2020). Biopesticides: Production, formulation and application systems. *Int. J. Curr. Microbiol. App. Sci.,* 9(10), 3931-3946. doi: 10.20546/ijcmas.2020.910.453
24. Bhattacharyya, P. N., Nath, B. C., Sarma, B., Al-Ani, L. K. T., Borgohain, D. J., Garganese, F. & Kumari, R. (2024). Interaction of *Metarhizium anisopliae* against emergent insect pest problems in the North-Eastern tea industry. In *Entomopathogenic Fungi: Prospects and Challenges,* 319–357
25. Boateng, K. O., Dankyi, E., Amponsah, I. K., Awudzi, G. K., Amponsah, E. & Darko, G. (2023). Knowledge, perception, and pesticide application practices among smallholder cocoa farmers in four Ghanaian cocoa-growing regions. *Toxicol Rep.*, 10:46–55. https:// doi. org/ 10. 1016/j. toxrep. 2022. 12. 008
26. Bream, A., Fouda, M. A., Shehata, I. & Ragab, S. (2018). Evaluation of four entomopathogenic nematodes as biological control agents against the housefly, *Musca domestica* L. (Diptera: muscidae). *Egypt. Acad. J. Biol. Sci.* A, *Entomol.*, 11(1), 79-89. doi: 10.21608/eajb.2018.11982
27. Chakraborty, N., Mitra, R., Pal, S., Ganguly, R., Acharya,

K., Minkina, T., Sarkar, A. & Keswani, C. (2023). Biopesticide consumption in India: Insights into the current trends. *Agriculture*, 13, 57. https:// doi.org/10.3390/ agriculture13030557

28. Chakroun, M., Banyuls, N., Bel, Y., Escriche, B. & Ferré, J. (2016). Bacterial vegetative insecticidal proteins (Vip) from Entomopathogenic bacteria. *Microbiol Mol Biol Rev.*, 80(2), 329-50. doi: 10.1128/MMBR.00060-15
29. Chambers, A. C., Aksular, M., Graves, L. P., Irons, S. L., Possee, R. D. & King, L. A. (2018). Overview of the baculovirus expression system. *Current Protocols in Potein Science*, willey, 91(1), 5-4. doi: 10.1002/cpps.47
30. Chang, Y., Xia, X., Sui, L., Kang, Q., Lu, Y., Li, L., Liu, W., Li, Q. & Zhang, Z. (2021). Endophytic colonization of entomopathogenic fungi increases plant disease resistance by changing the endophytic bacterial community. *J. Basic Microbiol*., 61(9), 1098–1112
31. Chen, D., Wang, B., Yang, X., Weng, X. & Chang, Z. (2023). Improving recognition accuracy of pesticides in groundwater by applying TrAdaBoost transfer learning method. *Sensors*, 23(8):3856. https:// doi. org/ 10. 3390/ s2308 3856
32. Chetan, K., Dilnashin, H., Birla, H. & Singh, S. P. (2019). Regulatory barriers to agricultural research commercialization: A case study of biopesticides in India. *Rhizosphere*, 11, 100155. https://doi.org/10.1016/ j.rhisph.2019.100155
33. da Silva, H. A. O., Teixeira, W. D., Borges, Á. V., Silva, Junior. A. L., Alves, K. S., Rodrigues, Junior. O. M. & de Abreu, L. M. (2021). Biocontrol of potato early blight and suppression of *Alternaria grandis* sporulation by *Clonostachys* spp. *Plant Pathol*., 70(7), 1677-1685. https:// doi.org/10.1111/ppa.13402
34. Damalas, C. A. & Koutroubas, S. D. (2018). Current status and recent developments in biopesticide use. *Agriculture,* 8(1), 13
35. Daniel, R. T. (2020). Effect of the Bioherbicide *Pseudomonas fluorescens* D7 on downy brome (*Bromus tectorum*). *Rangel. Ecol. Manag*., 73, 753–755. doi: 10.1016/ j.rama.2019.10.007
36. De Oliveira Giannasi, A., Roque Brambila, C., Zart, M., Guide, B. A. & Alves, V. S. (2018). Assessment of entomopathogenic nematodes in *Agrotis ipsilon* (Lepidoptera: Noctuidae) under laboratory and greenhouse conditions. *Revista Colombiana de Entomología*, 44(1), 25-31. DOI:10.25100/socolen.v44i1.6533
37. Desneux, N., Han, P., Mansour, R., Arnó, J., Brévault, T. & Campos, M. R. (2021). Integrated pest management of *Tuta absoluta*: practical implementations across different world regions. *J. Pest. Sci.*, 1, 1–23. doi: 10.1007/S10340-021-01442-8
38. Devi, G. (2020). Entomopathogenic nematodes against insect pests of rice. *Int. J. Environ. Agric. Biotech*., 5(4), 1143-1150. doi: 10.22161/ijeab.54.34
39. Djaenuddin, N. & Suriani, S., & Muis, A. (2020). Effectiveness of *Bacillus subtilis* TM4 biopesticide formulation as biocontrol agent against maydis leaf blight disease on corn. *International Conference on Sustainable Cereals and Crops Production Systems in the Tropics,* 23-25. doi: 10.1088/1755-1315/484/1/012096
40. EPA (2023). What are Biopesticides? Environmental Protection Agency (EPA)2023. pp. 1-3
41. Erlandson, M. (2020). Advances in the use of entomopathogenic viruses as biopesticides in suppressing crop insect pests. In *Biopesticides for sustainable agriculture*, 167-194. doi: 10.19103/AS.2020.0073.09
42. Felix, d'Herelle (1911). Sur une ´epizootie de nature bact´erienne s´evissant sur les sauterelles au Mexique, C. R. *Acad. Sci.,* 152, 1413–1415
43. Faria, M., Palhares, L. A. M., Souza, D. A. & Lopes, R. B. (2022). What would be representative temperatures for shelf-life studies with biopesticides in tropical countries Estimates through long-term storage of biocontrol fungi and calculation of mean kinetic temperatures. *BioControl*., 67(2), 213-224. doi:10.1007/s10526-021-10126-2
44. Farooq, M. A., Arif, M. J., Gogi, M. D., Nawaz, A. & Atta, B. (2019). Comparative efficacy of different pesticide residue mitigation modules in mango. *Am. J. Biomed. Sci. Res.*, 4, 214–219. doi: 10.34297/AJBSR.2019.04.000801
45. Fatimah, N., Askary, T. H. & Abd-Elgawad, M. M. M. (2025). Factors influencing the performance of entomopathogenic nematodes: From laboratory to field conditions. *Egypt. J. Biol. Pest Control.,* 35, 29
46. Federici, B.A. (1999). A perspective on pathogens as biological control agents for insect pests. In T.S. Bellows & T.W. Fisher (Eds.), *Handbook of biological control: Principles and applications of biological control* (pp. 517–548). Academic Press.
47. Feng, K. C., Liu, B. L. & Tzeng, Y. M. (2000). *Verticillium lecanii* spore production in solid- state and liquid-state fermentations. *Bioprocess Eng.,* 23, 25–29. doi: 10.1007/ s004499900115
48. Fenibo, E. O., Ijoma, G. N., Nurmahomed, W. & Matambo, T. (2022). The potential and green chemistry attributes of biopesticides for sustainable agriculture. *Sustainability,* 14 (21), 14417. doi: 10.3390/su142114417
49. Freimoser, F. M., Rueda-Mejia, M. P., Tilocca, B. & Migheli, Q. (2019). Biocontrol yeasts: Mechanisms and applications. *World Journal of Microbiology and Biotechnology,* 35(10), 154.
50. Fuenmayor, Y., Portillo, E., Bastidas, B., Guerra, M. & San-Blas, E. (2020). Infection parameters of *Heterorhabditis amazonensis* (Nematoda: Heterorhabditidae) in different stages of Hibiscus pink mealybug. *J. Nematol*., 52, 77. doi: 10.21307/jofnem-2020-077
51. Gabrielová, A., Mencl, K., Suchánek, M., Klimeš, R., Hubka, V. & Kolařík, M. (2018). The oomycete *Pythium oligandrum* can suppress and kill the causative agents of dermatophytoses. *Mycopathologia*, 183(5), 751. https:// doi.org/10.1007/s11046-018-0277-2
52. Ganguli, P. (2019) Patenting issues in the development of nanobiopesticides. *In: Nano-Biopesticides today and future perspectives.* Academic Press, 367-395. doi: 10.1016/B978-0-12-815829-6.00017-6
53. García-Espinoza, F. (2024). Multifunctional entomopathogenic ascomycetes for" cotton leafworm" *Spodoptera littoralis* (Boisduval)(Lepidoptera: Noctuidae) control in cucurbits. *Biol. Control*, 92(10), 101-110. doi:10.1016/ j.biocontrol.2015.10.007
54. Geisler, F. C. S., Martins, L. N., Machado, I. E. D. F., Matozo, L. F., Lucena, W. F., Soares, V. N., Pazini, J. d. B.,

Schneid da Rosa, A. P. S. A. & Bernardi, D. (2024). The biological activity of an Sf MNPV-Based biopesticide on a resistant strain of *Spodoptera frugiperda* developing on transgenic corn xpressing Cry1A. 105+ Cry2Ab2+ Cry1F insecticidal protein. *Agronomy*, 14(8), 1632. doi: 10.3390/agronomy14081632

55. Gelaye, Y. & Negash, B. (2023). The role of baculoviruses in controlling insect pests: A review. *COGENT FOOD AGR*, 9(1), 2254139. doi: 10.1080/23311932.2023.2254139
56. Germaine, K. J., Keogh, E. & Ryan, D. (2009). Bacterial endophyte-mediated naphthalene phytoprotection and phytoremediation. *FEMS Microbiol. Lett.*, 296. doi: 10.1111/j.1574-6968.2009.01637.x
57. Ghayur, A. (2000). A study of biopesticides and biofertilisers in Haryana. India: 2000. Gill SS, Cowles PP: Mode of action of Bacillus thuringiensis endotoxins. https://www.iied.org/6348iied
58. Ghodake, V. N., Naik, S. V., Bhukhanwala, K. N., Kande, K. V., Bhor, N. J. & Patravale, V. B. (2018). Nanoengineered systems for biopesticides. *In Handbook of Nanomaterials for Industrial Applications*, Elsevier, 243-259
59. Ghumar, V., Sharma, N., Gavkare, O., Khachi, B. & Singh, D. K. (2014). Biopesticides—for future. *J. Ind. Pollut.Control*., 30, 203–205
60. Glare, T. R., Caradus, J. R., Gelernter, W., Jackson, T., Keyhani, N., Kohl, J., Marrone, P., Morin, L. & Stewart, A. (2012). Have biopesticides come of age, *Trends Biotechnol.*, 35(3), 250-261. doi: 10.1016/j.tibtech.2012.01.003
61. Glick, B. R. (2012). Plant growth-promoting bacteria: mechanisms and applications. *Scientifica (Cairo),* 963401. doi: 10.6064/2012/963401
62. Godjo, T. A. (2018). Entomopathogenic nematodes and their symbiotic bacteria to control fruit flies *(Bactrocera dorsalis)* in mango cultivation in Benin (Doctoral dissertation, Ghent University)
63. Gonzalez-Franco, Ana. & Robles-Hernandez, Loreto. (2009). Actinomycetes as biological control agents of phytopathogenic fungi. *Techno Chih III,* 2, 64-73
64. Gozel, U. & Gozel, C. (2021). Entomopathogenic nematodes in pest management [Internet]. Integrated pest management (IPM): Environmentally sound pest management. https://doi.org/10.5772/63894
65. Grushevaya, I., Ignatieva, A. & Tokarev, Y. (2020). Susceptibility of three species of the genus *Ostrinia* (Lepidoptera: Crambidae) to *Nosema pyrausta* (Microsporidia: Nosematida). *BIO Web of Conferences,* 21, 00040. https://doi.org/10.1051/bioconf/20202100040
66. Gurr, G. M., Thwaite, W. G. & Nicol, H. I. (1999). Field evaluation of the effects of the insect growth regulator (tebufenozide) on entomophagous arthropods and pests of apples. *Austr. J. Entomol.*, 38, 135–140. https://doi.org/10.1046/j.1440-6055.1999.00097.x
67. Gwinn, K. D. (2018). Bioactive natural products in plant disease control. In studies in natural products chemistry; Attaur, R., Ed.; Elsevier Inc.: Amsterdam, The Netherlands, 56, 229–246
68. Halder, J., Rai, A. B. & Kodandaram, M. H. (2013). Compatibility of neem oil and different entomopathogens for the management of major vegetable sucking pests. *Natl. Acad. Sci. Lett*., 36, 19–25. doi:10.1007/s40009-012-0091-1
69. Han, B. & Weiss, L. M. (2017). *Microsporidia: Obligate intracellular pathogens within the fungal kingdom. Microbiology Spectrum,* 5(2), 17
70. Han, H., Zou, K. & Yuan, Z. (2024). Impact of specialized agricultural services on climate-smart agricultural practices: Evidence from biopesticide application in Jiangsu Province, China. *Environ. Impact Assess. Rev.,* 105, 107430
71. Harish, S., Murugan, M., Kannan, M., Parthasarathy, S., Prabhukarthikeyan, S. R. & Elango, K. (2021). Entomopathogenic viruses. Microbial approaches for insect pest management, 1-57. doi: 10.1007/978-981-16-3595-3
72. Harman, G. E., Howell, C. R., Viterbo, A., Chet, I. & Lorito, M. (2004). *Trichoderma* species —Opportunistic, avirulent plant symbionts. *Nat. Rev. Microbiol*., 2(1), 43-56. https://doi.org/10.1038/nrmicro797
73. Hashimi, M. H., Hashimi, R. & Ryan, Q. (2020). Toxic effects of pesticides on humans, plants, animals, pollinators and beneficial organisms. *Asian Plant Res. J.*, 5, 37–47. doi: 10.9734/aprj/2020/v5i430114
74. Hernandez-Tenorio, F., Miranda, A. M., Rodríguez, C. A., Giraldo-Estrada, C.& Sáez, A. A. (2022). Potential strategies in the biopesticide formulations: a bibliometric analysis. *Agronomy*, 12(11), 2665. doi.org/10.3390/agronomy12112665
75. Huang, Y., Zhaoliang, Li., Luo, X. & Liu, D. (2021). Biopesticides extension and rice farmers' adoption behavior: a survey from Rural Hubei Province, *China. Environ. Sci*. 29, 51744–51757. doi:10.21203/rs.3.rs-996808/v1
76. Hubbard, M., Hynes, R. K. & Erlandson, M. (2014). The biochemistry behind biopesticide efficacy. *Sustain. Chem. Process.,* 2, 18. https://doi.org/10.1186/s40508-014-0018-x
77. Irsad, S., Haq, E., Mohamed, A., Rizvi, P. Q. & Kolanthasamy, E. (2023). Entomopathogen-based biopesticides: Insights into unraveling their potential in insect pest management. *Front. Microbiol.,* 14, 1208237
78. Jaber, L. R. & Ownley, B. (2018). Can we use entomopathogenic fungi as endophytes for dual biological control of insect pests and plant pathogens? *Biol. Control,* 116, 36
79. Jagadeesan, Y., Meenakshisundaram, S., Pichaimuthu, S. & Balaiah, A. (2024). A scientific version of understanding "Why did the chickens cross the road"? A guided journey through Bacillus spp. towards sustainable agriculture, circular economy and biofortification. *Environ. Res.,* 244, 117907
80. Jahan Shaili, S., Kabiraj, U. K. & Mahedi, M. (2025). Fungal biocontrol in agriculture: A sustainable alternative to chemical pesticides – A comprehensive review. *World J. Advanced Res. Rev.,* 26(1), 2305–2316
81. Jayaseelan, T. (2024). Sustainable agriculture: Exploring the potential of biopesticides. *Int. J. Entomol. Res.,* 9(12), 44–49
82. Jukes, M. & Van der Merwe, M. (2020). Viruses as biopesticides. *Quest*, *16*(1), 14-15
83. Kachhawa, D. (2017). Microorganisms as a biopesticides. *J. Entomol. Zool. Stud*., 5(3), 468–473
84. Kalen, A., Kara, F. & Öztürk, F. (2022). Characterization, distribution, and virulence of protistan entomopathogen, *Mattesia dispora* (Sporozoa, Gregarina) in the Indian meal moth, *Plodia interpunctella* (Lepidoptera: Pyralidae)

populations in Turkey. *Egypt. J. Biol. Pest Control*, 32, Article 14. doi:10.1186/s41938-022-00583-x

85. Kalpana, A. K. (2021). A review of biopesticides and their plant phytochemicals information. *Ann. Rom. Soc. Cell Biol.*, 3576–3588
86. Kariyanna, B., Senthil-Nathan, S. & Vasantha-Srinivasan, P. (2024). Comprehensive insights into pesticide residue dynamics: unraveling impact and management. *Chem. Biol. Technol. Agric.*, 11, 182. https://doi.org/10.1186/s40538-024-00708-4
87. Kergunteuil, A., Bakhtiari, M., Formenti, L., Xiao, Z., Defossez, E. & Rasmann, S. (2016). Biological control beneath the feet: a review of crop protection against insect root herbivores. *Insects*, 7(4), 70. doi.org/10.3390/insects7040070
88. Khan, M., Anwar, H., Ullah, S. & Iqbal, A. (2023). *Streptomyces* spp. as a potential biocontrol agent against fungal pathogens: Advances and challenges. *Biol. Control*, 185, 105435. doi: https://doi.org/10.55446/hexa.2024.51
89. Khursheed, A., Rather, M. A., Jain, V., Rasool, S., Nazir, R., Malik, N. A. & Majid, S. A. (2022). Plant based natural products as potential ecofriendly and safer biopesticides: A comprehensive overview of their advantages over conventional pesticides, limitations and regulatory aspects. *Microb. Pathog.*, 173, 105854. doi: 10.1016/j.micpath.2022.105854
90. Kim, J. J. & Goettel, M. S. (2011). Evaluation of *Lecanicillium longisporum*, Vertalec against the cotton aphid, *Aphis gossypii*, and cucumber powdery mildew, *Sphaerotheca fuliginea*, in a greenhouse environment. *Crop Prot.*, *29*, 540–544
91. Koike, M., Shinya, R., Aiuchi, D., Mori, M., Ogino, R., Shinomiya, H., Tani, M. & Goettel, M (2011). Future biological control for soybean cyst nematode. In H. A. El-Shemy (Ed.), *Soybean physiology and biochemistry* (pp. 193–208)
92. Kojima, T., Yamato, S. & Kawamura, S. (2022). Natural and synthetic pyrethrins act as feeding deterrents against the black blowfly, *Phormia regina* (Meigen). *Insects*, 13 (8), 678. https://doi.org/10.3390/insects13080678
93. Kumar, J., Ramlal, A., Mallick, D. & Mishra, V. (2021). An overview of some biopesticides and their importance in plant protection for commercial acceptance. *Plants*, 10(6), 1185. doi.org/10.3390/plants10061185
94. Kumar, S. (2012). Biopesticides: A need for food and environmental safety. *J. Biofertil. Biopestic*, 3, 4. doi:10.4172/2155-6202.1000e107
95. Kumar, V. & Kumar, P. (2019). “Pesticides in agriculture and environment: impacts on human health” in *Contaminants in agriculture environment: Health risks remediation, Vol. 1.* eds. V. Kumar, R. Kumar, J. Singh and P. Kumar (India: ture and Environmental Science Academy), 76–95
96. Kumari, I., Hussain, R. & Sharma, S. (2022). Microbial biopesticides for sustainable agricultural practices. *Biopesticides.* Elsevier, 301–317. DOI:10.1016/B978-0-12-823355-9-00024-9
97. Law, J. W., Ser, H. L. & Khan, T. M. (2017). The potential of Streptomyces as biocontrol agents against the rice blast fungus, *Magnaporthe oryzae* (*Pyricularia oryzae*). *Front. Microbiol.*, 8, 3. doi: 10.3389/fmicb.2017.00003
98. Lee, J. Y., Kang, S. W. & Yoon, C. (2006). *Verticillium lecanii* spore formulation using UV protectant and wetting agent and the biocontrol of cotton aphids. *Biotechnol. Lett.*, 28, 1041–1045. Doi: 10.1007/s10529-006-9036-4
99. Li, E. T., Zhang, S., Li, K. B., Nyamwasaa, I., Li, J. Q., Li, X. F., Quin, J. H & Yin, J. (2021). Efficacy of entomopathogenic nematode and *Bacillus thuringiensis* combinations against *Holotrichia parallela* (Coleoptera: Scarabaeidae) larvae. *Biol. Control,* 152, 104469. doi: 10.1016/j.biocontrol.2020.104469
100. Li, T., Jiang, Y., Zhang, Y., Wu, Y., Wilson, K. & Xu, P. (2025). Native mid-gut bacterial community increases resistance to nucleopolyhedrovirus in the cotton leafworm. *Pestic. Biochem. Physio.*, 212, 106462
101. Litwin, A., Monika, N. & Sylwia, R. (2020). Entomopathogenic fungi: Unconventional applications. *Rev. Environ. Sci. Biotechnol.*, 19(1), 23–42
102. Lord, J. C. (2007). Detection of *Mattesia oryzaephili* (Neogregarinorida: Lipotrophidae) in grain beetle laboratory colonies with an enzyme-linked immunosorbent assay. *J. Invertebr. Pathol.*, 94(1), 74–76. doi: 10.1016/j.jip.2006.07.004
103. Lykogianni, M., Bempelou, E., Karamaouna, F. & Aliferis, K. A. (2021). Do pesticides promote or hinder sustainability in agriculture? The challenge of sustainable use of pesticides in modern agriculture. *Sci. Total Environ.*, 795: 148625. https:// doi. org/ 10. 1016/j. scito tenv. 2021. 148625
104. Magierowicz, K., Górska-Drabik, E. & Golan, K. (2020). Effects of plant extracts and essential oils on the Inc.behavior of *Acrobasis advenella* (Zinck.) caterpillars and females. *J. Plant Dis. Prot.*, 127, 63–71. https://doi.org/10.1007/s41348-019-00275-z
105. Manchikanti, P. (2019). Bioavailability and environmental safety of nanobiopesticides. In nano-biopesticides today and future perspectives. *Academic Press*, 207-222. doi:10.1016/B978-0-12-815829-6.00008-5
106. Manfo, F. P. T., Mboe, S. A., Nantia, E. A., Ngoula, F., Telefo, P. B. & Moundipa, P. F. (2020). Evaluation of the effects of agro pesticides use on liver and kidney function in farmers from Buea. *J. Toxicol.*, 2020:2305764. doi: 10.1155/2020/2305764
107. Mantzoukas, S., Kitsiou, F., Natsiopoulos, D. & Eliopoulos, P. A. (2022). Entomopathogenic Fungi: Interactions and applications. *Encyclopedia*, 2(2), 646-656. https://doi.org/10.3390/encyclopedia2020044
108. Martínez-Balerdi, M., Caballero, J., Aguirre, E., Caballero, P., & Beperet, I. (2025). Baculoviruses as Microbial Pesticides: Potential, Challenges, and Market Overview. *Viruses*, 17(7), 917. https://doi.org/10.3390/v17070917
109. Matos, M. P., da Silva, A. M. & El-Din, N. S. (2020). Biopesticides: An overview on the recent developments and perspectives. *Bioorg. Med. Chem.*, 28, 115255
110. Matthews, S., Siddiqui, Y. & Ali, A. (2024). Unleashing the power of bio-stimulants for enhanced crop growth, productivity, and quality: A comprehensive review. *J. Plant Nutr.*, 1–23
111. Matuska-Łyżwa, J., Duda, S., Nowak, D. & Kaca, W. (2024). Impact of abiotic and biotic environmental conditions on the development and infectivity of entomopathogenic nematodes in agricultural soils. *Insects,* 15(6), 421
112. Meenatchi, R. & Aditi, N. (2021). Biopesticides for pest

management. Sustainable bioeconomy: pathways to sustainable development goals, 239-266. Doi: 10.1007/978-981-15-7321-7_11

113. Meethal Aparna, T., Siddhapara, M. R. & Kumari, S. (2025). Entomopathogenic nematode: A sustainable option for IPM. IntechOpen. doi: 10.5772/intechopen.1010919
114. Miastkowska, M., Michalczyk, A., Figacz, K. & Sikora, E. (2020). Nanoformulations as a modern form of biofungicide. *J. Environ. Health Sci. Eng*,18(1), 119-128. https://doi.org/10.1007/s40201-020-00445-4
115. Mohan, Sharad. (2015). Entomopathogenic nematodes and their bacterial symbionts as lethal bioagents of lepidopteran pests. 273-288. doi:10.1007/978-3-319-14499-3_13
116. Monroy-Borrego, A. G. & Steinmetz, N. F. (2022). Three methods for inoculation of viral vectors into plants. *Front. Plant Sci*., 13, 963756. doi.org/10.3389/fpls.2022.963756
117. Montalva, C., Rocha, L. F. N., Fernandes, É. K. K., Luz, C. & Humber, R.A. (2016). *Conidiobolus macrosporus* (Entomophthorales), a mosquito pathogen in Central Brazil. *J Invertebr Pathol*., 139, 102-108. doi: 10.1016/j.jip.2016.08.003
118. Mordue, A. J., Morgan, E. D. & Nisbet, A. J. (2005). Azadirachtin, a natural product in insect control. *In Comprehensive Molecular Insect Science*; Gilbert, L.I., Ed, Elsevier, 117–135. DOI:10.1016/B0-44-451924-6/00077-6
119. Muir, D. (2023). Environmental programmes pesticide policy. Department of Forestry, Fisheries and the Environment, 13, 1071. doi: 10.12688/f1000research.154392.2
120. Naqqash, M. N., Gökçe, A. & Bakhsh, A. (2016). Insecticide resistance and its molecular basis in urban insect pests. *Parasitol. Res*., 115, 1363–1373. doi: 10.1007/s00436-015-4898-9
121. Narandzic, T., Sarac, V., Rodic, V., Vukelic, N., Lukac-Bulatovic, M., Bijelic, S. & Ljubojevic, M. (2025). Exploring the known and mapping future directions in biopesticides research: A bibliometric analysis. *Horticulturae*, 11(1), 97. https://doi.org/10.3390/horticulturae11010097
122. Nassary, E. K. (2025). Fungal biocontrol agents in the management of soil-borne pathogens, insect pests, and nematodes: Mechanisms and implications for sustainable agriculture. *The Microbe.,* 7, 100391
123. Natra, N. T., Kumar, M., Apurva, K. & Thakur, V. V. (2019). Viral biopesticides: An effective and environment-friendly approach to control insects. *In Biofertilizers and Biopesticides in Sustainable Agriculture*, Apple Academic Press, 71-90. doi: 10.1201/9780429059384-4
124. Nelly, N., Syahrawati, M., Hamid, H., Habazar, T. & Gusnia, D. N. (2019). Diversity and characterization of entomopathogenic fungi from the rhizosphere of maize plants as potential biological control agents. *Biodivers. J. Biol. Divers*., 20, 1435–144
125. Ody, L. P., Santos, M. S. N., Lopes, A. M., Mazutti, M. A., Tres, M. V. & Zabot, G. L. (2025). Review on biological and biochemical pesticides as a sustainable alternative in organic agriculture. *Biocatal. Agric. Biotechnol*., *67*, 103655.
126. Olivares, J., Siegwart, M., Gautier, M., Maugin, S., Gingueneau, L. & Gauffre, B. (2023). Genetic basis of codling moth (*Cydia pomonella*) resistance to the original isolate of *C. pomonella Granulovirus* (CpGV-M). *Entomol. Gen.*, 43(3), 649-658. doi: 10.1127/entomologia/2023/2052
127. Parker, K. M. & Sander, M. (2017). Environmental fate of insecticidal plant-incorporated protectants from genetically modified crops: Knowledge gaps and research opportunities. *Environ. Sci. Technol*., *51*(21), 12049–12057. https://doi.org/10.1021/acs.est.7b03456
128. Pathma, J., Kennedy, R. K., Bhushan, L. S., Shankar, B. K. & Thakur, K. (2021). Microbial biofertilizers and biopesticides: nature's assets fostering sustainable agriculture. Recent developments in microbial technologies, 39-69. doi: 10.1007/978-981-15-4439-2_2
129. Pelosi, C., Bertrand, C., Daniele, G., Coeurdassier, M., Benoit & P., Nélieu, S. (2021). Residues of currently used pesticides in soils and earthworms: a silent threat? *Agric. Ecosyst. Environ.,* 305, 107167. doi: 10.1016/j.agee.2020.107167
130. Pertile, M., Antunes, J. E. L., Araujo, F. F., Mendes, L. W., Van den Brink, P. J. & Araujo, A. S. F. (2020). Responses of soil microbial biomass and enzyme activity to herbicides imazethapyr and flumioxazin. *Sci. Rep*., 10, 1–9. doi: 10.1038/s41598-020-64648-3
131. Petersen, J. M., Bézier, A., Drezen, J. M. & van Oers, M. M. (2022). The naked truth: An updated review on nudiviruses and their relationship to bracoviruses and baculoviruses. *J. Invertebr. Pathol*., *189*, 107718. https://doi.org/10.1016/j.jip.2022.107718
132. Prasad, V. & Srivastava, S. (2016). Insect viruses. *In Eco-friendly pest management for food security* Academic Press, 411-442
133. Prempeh, C. (2019). Process optimization and techno-economics assessment of nematode biopesticide production (Doctoral dissertation, Stellenbosch: Stellenbosch University)
134. Quiroga-Cubides, G., Araque-Echeverry, G., Ruíz Moreno, C., Barrera Cubillos, G. P., Gómez-Valderrama, J., Cuartas-Otálora, P. E., Gómez Álvarez, M. I. & Cortés-Rojas, D. (2022). Formulation process analysis of a virus-based biopesticide to control the tomato leafminer *Tuta absoluta*. *Braz. Arch. Biol. Technol*., 65, e22210342
135. Raj, M. N., Samal, I., Paschapur, A. & Subbanna, A. R. N. S. (2022). Entomopathogenic viruses and their potential role in sustainable pest management. *In New and Future Developments in Microbial Biotechnology and Bioengineering*, Elsevier, 47-72. doi:10.1016/B978-0-323-85579-2.00015-0
136. Rajaput J., Rao, M. S. L. & Hegde, R. V. (2019). Biopriming: a novel seed treatment options to manage the seed-borne fungal infection of tomato. *J. Pharmacogn. Phytochem*., 6, 659-661
137. Rakhimol, K., Thomas, S., Volova, T. & Jayachandran, K. (2020). *Controlled release of pesticides for sustainable agriculture*. New York, NY: Springer. doi: 10.1007/978-3-030-23396-9
138. Ramakuwela, T., Tarasco, E., Chavarría-Hernández, N. & Toepfer, S. (2025). Entomopathogenic nematodes: Commercial use and future perspectives. *J. Invertebr. Pathol*., 212, 108388
139. Ramírez-Ordorica, A., Adame-Garnica, S. G., Ramos-

Aboites, H. E., Winkler, R. & Macías-Rodríguez, L. (2024). Volatile semiochemicals emitted by Beauveria bassiana modulate larval feeding behavior and food choice preference in *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *J. Fungi.*, *10*(6), 438. doi.org/10.3390/jof10060438

140.Rauf, A. & Wilkins, R. M. (2022). Malathion-resistant *Tribolium castaneum* has enhanced response to oxidative stress, immunity, and fitness. *Pestic. Biochem. Physiol.*, 184, 105128. doi: 10.1016/j.pestbp.2022.105128.

141.Reddy, A. A.; Reddy, M. & Mathur, V. (2024). Pesticide use, regulation, and policies in Indian agriculture. *Sustainability*, 16, 7839. doi.org/10.3390/su16177839

142.Rezaei, R., Safa, L. & Damalas, C. A. (2019). Drivers of farmers' intention to use integrated pest management: integrating theory of planned behavior and norm activation model. *J. Environ. Manage.*, 236: 328–339. doi: 10.1016/j.jenvman.2019.01.097

143. Ruiu, L. (2018). Microbial biopesticides in agroecosystems. *Agron.* 8, 235. 8235. https://doi.org/10.3390/agronomy8110235

144.Sabarwal, A., Kumar, K. & Singh, R. P. (2018). Hazardous effects of chemical pesticides on human health–cancer and other associated disorders. *Environ. Toxicol. Pharmacol.*, 63, 103–114. doi: 10.1016/j.etap.2018.08.018

145.F, d'Herelle., T., Yaman, M. & Erturk, O. (2021). Distribution and occurrence of *Vairimorpha plodiae* (Opisthokonta: Microspora) in the Indian meal moth, *Plodia interpunctella* (Lepidoptera: Pyralidae) populations: an extensive field study. *Acta Protozool.*, 60, 31–36. doi: 10.4467/16890027AP.21.004.14064.

146.Al-Rawashdeh microbiomes for sustainable agriculture: Functional annotation, 471-501. doi:10.1007/978-3-030-73507-4_15

147.Sansinenea, E. (2021). Application of biofertilizers: Current worldwide status. In *Biofertilizers*, 183–190

148.Santos, E. N., Menezes, L. P., Dolabella, S. S., Santini, A., Severino, P., Capasso, R., Zielinska, A., Souto, E. B. & Jain, S. (2022). Bacillus thuringiensis: From biopesticides to anticancer agents. *Biochimie.*, 192, 83-90. doi: 10.1016/j.biochi.2021.10.003

149.Santos, M. S., Rodrigues, T. F., Nogueira, M. A. & Hungria, M. (2021). The challenge of combining high yields with environmentally friendly bioproducts: A review on the compatibility of pesticides with microbial inoculants. *Agronomy*, 11(5), 870. https://doi.org/10.3390/agronomy11050870

150.Sarwar, M. & Aslam, R. (2021). Usage of entomopathogenic viruses for insect pest control. in biopesticides in organic farming, CRC Press, 99-108

151.Satish, G., Ashokrao, D. M. & Arun, S. K. (2017). Microbial degradation of pesticide: a review. *Afr. J. Microbiol. Res.*, 11, 992–1012. DOI:10.5897/AJMR2016.8402

152.Shafi, J., Tian, H., & Ji, M. (2017). *Bacillus* species as versatile weapons for plant pathogens: A review. *Biotechnol. Biotechnol. Equip.,* 31(3), 446–459

153.Shamsuddeen, R., Mathew, T. S., Haladu, M., Ahmad, K. B., Adam, A. B. & Abubakar, M. Y. (2024). Recent advances in biopesticides: A review of efficacy and environmental impact. *Afr. J. Biochem. Mol. Biol. Res.*, 1(1), 706-725. https://doi.org/10.58578/ajbmbr.v1i1.3706

154.Silva, F., Maria, H. N. L., Berry, C. & Regis, L. (2014). *Lysinibacillus sphaericus:* Toxins and mode of action, applications for mosquito control and resistance management. Dhadialla, Tarlochan S. and Gill, Sarjeet S, eds. *Advances in Insect Physiology*, *Insect Midgut and Insecticidal Proteins*, Elsevier, 47, 89-176. Doi: 10.1016/B978-0-12-800197-4.00003-8

155.Singh, A., Kumawat, M. M., Dangi, N. L. & Yadav, S. (2023). Role of insect pheromones in integrated pest management. *J. Agric. Environ. Sci.*, 2(11). E-ISSN 2583-1755

156.Singh, G. & Paithankar, I. (2023). Encapsulation of biofertilizers, biopesticides and biocontrol agents. In *Sustainable Agriculture Reviews 60: Microbial Processes in Agriculture* Cham: Springer Nature Switzerland, 121-150. DOI:10.1007/978-3-031-24181-9_6

157.Sinha, B. & Biswas, I. (2009). Potential of bio-pesticides in Indian agriculture vis-a-vis rural development. *India Science and Technology*, http://dx.doi.org/10.2139/ssrn.1472371

158.Soetopo, D. & Alouw, J. C. (2023*)*. Innovation on biopesticides to support sustainable agriculture development. *IOP Conference Series: Earth Environ. Sci*., 1179, 012003. https://doi.org/10.1088/1755-1315/1179/1/012003

159.Souza, C. S. F., Silveira, L. C. P., Pitta, R. M., Waquil, J. M., Pereira, E. J. G. & Mendes, S. M. (2019). Response of field populations and Cry-resistant strains of fall armyworm to Bt maize hybrids and Bt-based bioinsecticides. *Crop Prot.*, *120*, 1-6. https://doi.org/10.1016/j.cropro.2019.01.001

160.Steiner, M., Falquet, L., Fragnière, A. L., Brown, A. & Bacher, S. (2024). Effects of pesticides on soil bacterial, fungal and protist communities, soil functions and grape quality in vineyards. *Ecol. Solut. Evii.,* 5(2). https://doi.org/10.1002/2688-8319.12327

161.Stevenson, P. C., Isman, M. B. & Belmain, S. R. (2017). Pesticidal plants in Africa: a global vision of new biological control products from local uses. *Ind. Crop. Prod*., 110, 2–9. https://doi.org/10.1016/j.indcrop.2017.08.034

162.Strauch, O., Strasser, H., Hauschild, R. & Ehlers, R. U. (2011). Proposals for bacterial and fungal biocontrol agents. In R. U. Ehlers (Ed.), *Regulation of biological control agents* (pp. 267–288). Springer Netherlands

163.Sunjka, D. & Mechora, S. (2022). An alternative source of biopesticides and improvement in their formulation—Recent advances. *Plants,* 11(22), 3172

164.Syromyatnikov, M. Y., Isuwa, M. M., Savinkova, O. V., Derevshchikova, M. I. & Popov, V. N. (2020). The effect of pesticides on the microbiome of animals. *Agriculture*, 10, 1–14. doi: 10.3390/agriculture10030079

165.Szewczyk, B., Hoyos-Carvajal, L. & Paluszek, M., (2006). Baculoviruses—reemerging biopesticides. *Biotechnol.*, 24, 143–160. doi: 10.1016/j.biotechadv.2005.09.001

166.Tadesse, M. K., Malinga, L., Muir, D Ge, J. & Ndolo, D. (2024). Recent advances in biopesticide research and development with a focus on microbials. *F1000Res.*, 11 (13), 1071. doi: 10.12688/f1000research.154392.2

167.Tarasco, E., Fanelli, E., Salvemini, C., El-Khoury, Y., Troccoli, A., Vovlas, A. & De Luca, F. (2023) Entomopathogenic nematodes and their symbiotic bacteria: from genes to field uses. *Front. Insect Sci.*, 3:1195254. doi: 10.3389/finsc.2023.1195254

168.Thakore, Y. (2006). The biopesticide market for global agricultural use. *Ind. Biotechnol*., 2(3), 194-208. doi:10.1089/ind.2006.2.194

169.Thakur, N., Kaur, S., Tomar, P., Thakur, S. & Yadav, A. N. (2020). Microbial biopesticides: current status and advancement for sustainable agriculture and environment. *In New and future developments in microbial biotechnology and bioengineering*. Elsevier. https://doi.org/10.1016/B978-0-12-820526-6.00016-6

170.Thapa, A., Tamang, J. & Rai, M. (2020). Viral insecticides in sustainable agriculture: A. TTPP, 329. Doi: 10.1007/s12010-023-04765-7

171.Tomar, P., Thakur, N., Jhamta, S, Chowdhury, S., Kapoor, M., Singh, S., Shreaz, S., Rustagi, S., Rai, P. K., Rai, A. K. & Yadav, A.N. (2024). Bacterial biopesticides: Biodiversity, role in pest management and beneficial impact on agricultural and environmental sustainability. *Heliyon*, 10 (11), e31550

172.Tripathi, A. K., Upadhyay, S., Bhuiyan, M. & Bhattacharya, P. R. (2009). A review on prospects of essential oils as biopesticide in insect-pest management. *J. Pharmacogn. Phytother*.,, 1, 52–63

173.Ujvary, I. (2001). Chapter 3—Pest control agents from natural products. *In Handbook of Pesticide Toxicology,* 2nd ed.; Krieger, R.I., Krieger, W.C., Eds.; Academic Press: San Diego, 109–179. https://doi.org/10.1002/047126363X.agr170

174.Ullah, Q., Haider, W., Waqar, M., Athiqah, M. Y. N., Maysaroh, U., Sajjad, N., Khomphet, T. & Ageru, T. A. (2025). Innovative biotechnological approaches in agriculture: From biopesticides against insect pests to flavor enhancement in crops. *J. Agric. Food Res.,* 24, 102369

175.USEPA. (2024). Overview of Plant Incorporated Protectants.

176.Vedamurthy, A. B., Jogaiah, S. & Shruthi, S. D. (2022).Chapter 15 - Insights into the genomes of microbial biopesticides, *In Advances in Bio-inoculant Science, Biopesticides,* Woodhead Publishing, 225-236, https://doi.org/10.1016/B978-0-12-823355-9.00026-2

177.Vermelho, A. B., Moreira, J. V., Akamine, I. T., Cardoso, V. S. & Mansoldo, F. R. P. (2024). Agricultural pest management: The role of microorganisms in biopesticides and soil bioremediation. *Plants*, 13(19), 2762. https://doi.org/10.3390/plants13192762

178.Vero, S., Garmendia, G., Allori, E., Sanz, J. M., Gonda, M., Alconada, T., Cavello, I., Dib, J. R., Diaz, M. A., Nally, C., Pimenta, R. S., da Silva, J. F. M., Vargas, M., Zaccari, F. & Wisniewski, M. (2023). Microbial biopesticides: Diversity, scope, and mechanisms involved in plant disease control. *Diversity*, 15(3), 457. https://doi.org/10.3390/d15030457

179.Vimala Devi, P. S., Duraimurugan, P., Poorna Chandrika, K. S. V., Vineela, V. & Hari, P. P. (2020). Novel formulations of Bacillus thuringiensis var. kurstaki: an eco-friendly approach for management of lepidopteran pests. *World J. Microbiol. Biotechnol*., 36, 1-14. doi: 10.1007/s11274-020-02849-8

180.Vivekanandhan, P., Swathy, K. & Murugan, A. C. (2022). Insecticidal efficacy of metarhizium anisopliae derived chemical constituents against disease-vector mosquitoes. *J. Fungi*., 8: 300. doi: 10.3390/jof8030300

181.Vladimirova, D., Kunecova, D., Nascimento, M., Kim, J. Y., Kunec, D. & Trimpert, J. (2025). Engineering iridoviruses: Development of reverse genetics and virus rescue systems. *J. Virol*., 99(5), e01852-24

182.Votavova, A., Trneny, O., Stavenikova, J., Dybova, M., Brus, J. & Komzakova, O. (2022). Prevalence and distribution of three bumblebee pathogens from the Czech Republic. *Insects*, 13(12), 1121. doi: 10.3390/insects13121121

183.Wagemans, J., Holtappels, D., Vainio, E., Rabiey, M., Marzachì, C., Herrero, S., Ravanbakhsh, M., Tebbe, C. C., Ogliastro, M., Ayllón, M. A. & Turina, M. (2022). Going viral: virus-based biological control agents for plant protection. *Annu. Rev. Phytopathol.*, 60(1), 21-42. doi: 10.1146/annurev-phyto-021621-114208

184.Wan, N. F., Fu, L. & Dainese, M. (2025). Pesticides have negative effects on non-target organisms. *Nat. Commun.* 16, 1360. https://doi.org/10.1038/s41467-025-56732-x

185.Wattimena, C. M. A & Latumahina, F. S. (2021). Effectiveness of botanical biopesticides with different concentrations of termite mortality. *J. Belantara.*, 4, 66–74. Doi: 0.29303/jbl.v4i1.630

186.Wend, K., Zorrilla, L., Freimoser, F. M. & Gallet, A. (2024). Microbial pesticides: Challenges and future perspectives for testing and safety assessment with respect to human health. *Environ. Health,* 23(1), 49

187.Williams, T. (2023). Soil as an environmental reservoir for baculoviruses: Persistence, dispersal and role in pest control. *Soil Syst*., 7(1), 29. https://doi.org/10.3390/soilsystems7010029

188.Wilson, K., Grzywacz, D., Curcic, I., Scoates, F., Harper, K., Rice, A., Paul. N. & Dillon, A. (2020). A novel formulation technology for baculoviruses protects biopesticide from degradation by ultraviolet radiation. *Scientific Reports*, 10(1), 13301. https://doi.org/10.1038/s41598-020-70293-7

189.Yao, R., Zheng, X., Hu, L. & Wang, Q. (2023). *Trichoderma* spp. in biocontrol and biofertilization applications. *J. Appl. Microbiol*., 134(6), 2189-2201. doi: 10.3389/fmicb.2023

190. Yasin, M., Khan, A., Qayyum, M. A., Yousuf, H. M. B., Mehfooz, A. & Hunter, D. (2024) Biological control of locusts and grasshoppers: A review. *J. Orthopt. Res.*, 33(2): 289–304. doi.org/10.3897/jor.33.114472

191.Yu, H., Yang, C. J., Li, N., Zhao, Y., Chen, Z. M., Yi, S. J., Li, Z. Q., Adang, M. J. & Huang, G. H. (2021). Novel strategies for the biocontrol of noctuid pests (Lepidoptera) based on improving ascovirus infectivity using Bacillus thuringiensis. *Insect Sci*., 28(5), 1452-1467. doi: 10.1111/1744-7917.12875

192.Zanchi, M. M., Marins, K. & Zamoner, A. (2023). Could pesticide exposure be implicated in the high incidence rates of depression, anxiety and suicide in farmers? A systematic review. *Environ. Pollut.* 15(331)121888. https://doi. org/ 10. 1016/j. envpol. 2023. 121888

193.Zhang, H., Yang, K., Wang, H., Liu, H., Shi, W., Kabak, I., Ji, R. & Hu, H. (2023). Molecular and biochemical changes in *Locusta migratoria* (Orthoptera: Acrididae) infected with *Paranosema locustae. J. Insect Sci.,* 23(5), 1