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Review

Microbial Insecticides in Sustainable Agriculture: Mechanisms, Applications, and Future Prospects

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Abstract

The current research work examines microbial insecticides as potential and sustainable alternatives to chemical pesticides for agricultural pest management. The development, mechanisms, and use of bacterial, fungal, viral, and protozoan pesticides are studied with particular attention to mode of action and specificity. The review explains that toxins produced by important bacteria, such as *Bacillus thuringiensis* (Bt), damage cells, and toxins from fungi, such as *Beauveria bassiana*, penetrate and colonise insects, rendering them ineffective. Microbial pesticides have many advantages, including negligible pollution, safety to non-target organisms, and a low likelihood of pest resistance development. Microbial insecticides are complex in nature but degrade rapidly. The review also covers production methods, application techniques, and quality control measures needed for effective use in integrated pest management. Although microbial pesticides can be an environmentally sound solution for sustainable agriculture, their use must be designed taking into consideration the formulation, application, and environmental conditions.

Keywords: Bioinsecticides, *Bacillus thuringiensis*, Integrated pest management, Pest control, *Beauveria bassiana*

1. Introduction

Pest management comprises preventive and control measures to reduce or prevent pests from causing significant harm to humans and the environment (Pijnakker *et al*., 2020). This is intended to achieve the desired result with reduced cost and the least risk to man and the environment. Pest management involves managing the environmental components that enhance the invasive species' ability to reproduce, survive, and thrive. Pests can inhabit food substances and water and thrive and reproduce within their habitat under favourable conditions, which is detrimental to human beings and the environment (Savary *et al*., 2019; Westwood *et al*., 2023). A pest may be defined as any organism (insects, bacteria, fungi, nematodes, weeds, viruses, or a vertebrate animal) that damages, devalues, and destroys crops, food stores, lawns, gardens, human structures, clothing, and furniture (Kumar and Rathor, 2020). They have a negative impact on terrestrial and aquatic ecosystems. Moreover, pests affect the health of human beings and other animals living in the vicinity. These species might have harmful effects by invading and displacing native plant species. Besides, they also change environmental factors, including soil health, nutrient and moisture availability, that further harm native plant species as well as microbial life and wildlife as a whole. Beneficial species may become pests if their actions or impacts become problematic or if populations escalate and expand into areas where conflicts arise (Savary *et al*., 2019). Pest infestation can occur nearly everywhere and may affect living organisms to varying degrees (Kumar and Rathor, 2020).

A variety of methods exist to manage pests, including natural, biological, chemical, cultural, genetic, mechanical, physical, and regulatory controls. Natural controls (weather or topography) are environmental factors that limit the number and distribution of pests. Biological controls utilise natural enemies to harm or consume target pests, thereby managing their population sizes. Cultural practices influence pest infestations directly or indirectly by making the surroundings less suitable for pests but more suitable for desirable species such as humans, crops, and animals (Kumar and Rathor, 2020). Mechanical and physical controls include the use of tools to directly impact populations or limit/alter access to environmental factors necessary to support pest populations (Savary *et al*., 2019). Natural or synthetic chemicals are also commonly used to manage pests.

Organisms such as bacteria and fungi are typically associated with the production of toxins. However, it is worth noting that not all species of bacteria and fungi produce toxins. Bacteria such as *Staphylococcus* species produce enterotoxins, while *Penicillium expansum* and other fungi produce mycotoxins such as aflatoxin, ochratoxin, and patulin (Cetin *et al*., 2020). The bacterial pesticide from *Bacillus thuringiensis* (Bt) is well known and has been made into products available for commercial purposes (Ruiu *et al*., 2018). *Bacillus thuringiensis* is a Gram-positive bacterium that acts as an insecticide by producing exudates, such as poisonous parasporal crystals and endospores, which, when consumed by insects, are dissolved in their midgut by the alkaline environment and release delta-endotoxin, a protein that has a lethal effect on insects (Cetin *et al*., 2020). *Bacillus thuringiensis* is used to reduce pest infestation in plants such as cabbage and potato and is capable of controlling lepidopterans in different plants (Ragasruthi *et al*., 2024). *Beauveria bassiana* is an example of an entomopathogenic fungus that has been widely used as a biopesticide because it is highly efficacious against a lot of arthropod hosts (Emaru *et al*., 2024). This review discussed microbial insecticides in sustainable agriculture, looking into their mechanisms, applications, and future.

2. Biopesticides

Synthetic chemical pesticides are resistant and harmful, and cannot be decomposed easily. Over the years, biopesticides have raised much concern in pest control and serve as an alternative to the synthetic pesticides used along with post- and pre-harvest management of diseases and crop pests (Ayilara et al., 2023). Biopesticides are not harmful to humans and are also target-specific, affecting the targeted pests (Manda et al., 2025). There has been improved durability of biopesticides and reduced pollution levels caused by synthetic pesticides because of innovations in research and development (Cetin et al., 2020). The production of pure biopesticides is often problematic as a result of the variability of active and integrated ingredients.

2.1 The use of microbes in the production of pesticides

Microbial pesticides or biopesticides are pesticides obtained from microbes. These have attracted a lot of attention over the years. Microbial pesticides use bacteria, fungi, viruses, or protozoa to control pests. Due to target specificity, environmental persistence, and non-target risk that are low and far less than their respective chemicals, they are seen as organic alternatives to chemical pesticides.

There are different types of microbial pesticides. Different bacterial species are utilised to target plant pathogens and parasitic nematodes, and the most widespread is *Bacillus thuringiensis* (Bt). *Bacillus thuringiensis* is a bacterium that makes some protein toxins lethal to insects, and fatally affects specific larvae upon ingestion (Ragasruthi *et al*., 2025). An example of a fungal pesticide is the entomopathogenic fungus *Beauveria bassiana*, which infects and kills the target insects. The fungus usually does this by producing spores or toxins that disrupt the insect's cellular processes. Baculoviruses, such as nucleopolyhedrosis viruses (NPVs) and granuloviruses (GVs), are widely used as insect-specific biopesticides, especially against plant-chewing insects. They are generally safe for vertebrates but can be slow-acting and unstable under UV radiation. Protozoan and nematode pesticides include organisms such as protozoa and entomopathogenic nematodes. Nematodes are microscopic roundworms that can infect insect larvae, while protozoa such as *Nosema* species can be used as biological control (Hailu and Hailu, 2020; Zhang and Lecoq, 2021). Bacteria, bacteriophage, fungi, viruses, and nematodes are used to make microbial pesticides, which are used to kill various pests in food crops worldwide (Yadav *et al*., 2017). They are applied through spraying or drenching or directly applied to the roots in the form of a tablet, coating of seeds or treatment of the root before sowing and by different insects (Hailu and Hailu, 2020).

In sustainable farming, microbial pesticides are the most favoured method, as the excessive chemical use leads to the degeneration of the structure and deteriorates the health of the soil. Microbial pesticides are nontoxic, eco-friendly, and user-friendly. Biopesticides from bacteria, fungi, viruses, and nematodes contain metabolites that act as the primary pest-control agents (Hailu and Hailu, 2020).

2.2 Mechanism of Action of Microbial Insecticides

The biological control of pests is an essential part of integrated pest management. This component uses live organisms (microbes) to reduce insect numbers (Hailu and Hailu, 2020). Among these natural enemies, viruses, fungi, and bacteria are very important in controlling pest populations and provide eco-friendly alternatives to conventional insecticides (Hailu and Hailu, 2020). To attack, cripple, and eventually kill pests, these microbes use unique mechanisms of action that support sustainable farming methods.

2.2.1 Mechanism of Action of Microbial Insecticides

Numerous bacterial species are harmful to pests, especially insects. *Bacillus thuringiensis* is the most common species of bacteria employed in pest management (Ruiu *et al*., 2015). This bacterium has unique modes of action against pests, as do others like *Serratia*, *Pseudomonas*, and *Bacillus cereus* (Ruiu *et al*., 2015). The mode of action of *Bacillus thuringiensis* is shown in Figure 1.

The toxin of *Bacillus thuringensis* is lodged in a large structure known as parasporal structure. The parasporal structure is produced during sporulation; however, it is not the toxin, but a protoxin is released from it once it is solubilised. It is safe to humans and higher animals and most insects because the parasporal structure is highly insoluble at a pH less than 9.5. The pH of the intestines of humans, higher animals and most insects is less than 9.5. The pH in the midgut of lepidopteran larvae is higher than 9.5. The insect eats the bacterial spores or crystal toxins. When the pest consumes the organism, the protoxin is cleaved by gut proteases to form an active toxin. The pest's midgut epithelial cells possess specific receptors that bind the activated toxins (López-Molina *et al*., 2025). The binding of toxin molecules forms pores in the gut cell membranes, causing lysis of cells and rupturing of the gut (Liu *et al*., 2021). The interruption in the gut impairs digestion and permits the development and spread of bacteria throughout the insect's body, eventually leading to death (Liu *et al*., 2021).

Bacteria like *Serratia* spp. and *Pseudomonas* spp. infect pests by causing wounds or natural holes. This is done by releasing toxins or enzymes that break down the pest's tissues and suppress the immune system (Ruiu *et al*., 2015). The infection that follows causes septicaemia, or blood poisoning, paralysis, and finally death. Some bacterial strains also hinder insects' digestive tracts. They do this by generating protease inhibitors or enzymes that act by disrupting gastrointestinal processes (Pijnakker *et al*., 2020). Over time, this leads to famine and death.

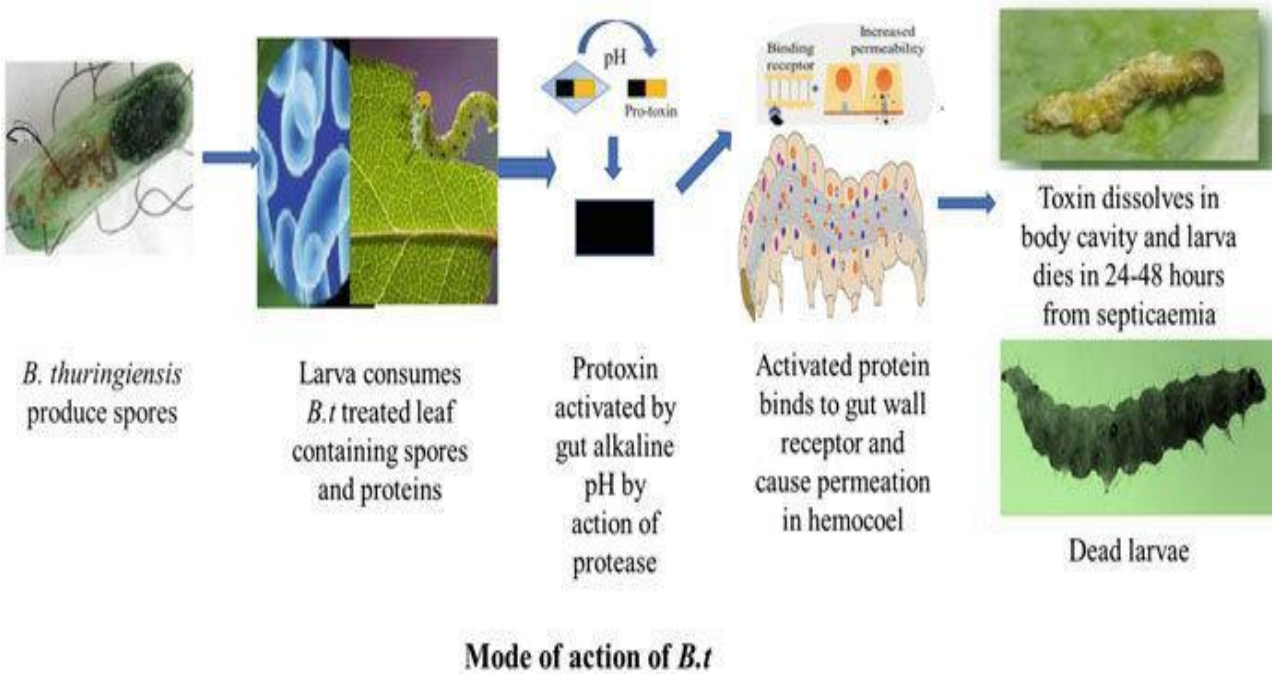

Figure 1: Mode of action of *Bacillus thuringiensis* (Rajamani and Negi, 2020)

2.2.2 Mechanism of some fungi as a biological agent

It has been shown that a wide variety of pests, such as nematodes, weeds, and insects, can be managed with the help of fungi (Zhang *et al*., 2020). Some fungi act as biological agents for controlling pests through several modes of action, such as competition, production of antibiotics or enzymes, induction of the host's defences (in this case, plants), and mycoparasitism (Zhang *et al*., 2020). Among fungi that have been used as biological agents are *Beauveria bassiana*, *Metarhizium anisopliae*, *Lecanicillium lecanii*, *Trichoderma* spp. and *Paecilomyces lilacinus* (Liu *et al*., 2022; Nassary, 2025). The simplified process of fungal infection of insect hosts is shown in Figure 2. Fungal infection in pests begins with the attachment of conidia (asexual spores) to the host's cuticle (Mora *et al*., 2017). The process can be described as spore attachment and germination. The fungal spores attach themselves to the pest's body surface by hydrophobic interactions or specific structures (Mora *et al*., 2017). Under favourable conditions, the spores then germinate, producing a filamentous growth called hyphae (Mora *et al.*, 2017). The hyphae then penetrate the pest's cuticle. After germination, the fungal hyphae extend into the insect's body, where the enzymes they secrete break away the protective layers of the cuticle (Mora *et al*., 2017). This makes it possible for the fungus to enter the pest's interior tissues directly.

Once inside the pest's body, the fungus proliferates, spreading throughout the internal organs and tissues (Mora *et al*., 2017). During this process, the fungus consumes the pest's body fluids and tissues. Some fungi also create mycotoxins that impair a pest's immune system or interfere with physiological functions (Zhang *et al*., 2024). After fungal invasion of the pest cell for a few days, the infected pest eventually dies because the fungus eats away at the host from the inside and outside (Zhang *et al.*, 2024). The infection cycle is completed when the fungus emerges from the dead pest and sporulates, releasing conidia that can infect new hosts (Zhang *et al*., 2024). Fungi are beneficial in pest management because they do not need to be ingested by the insect before they can cause infection (Maina *et al*., 2018). They are especially effective against pests that only come into contact with treated surfaces occasionally or that feed by puncturing plant tissues.

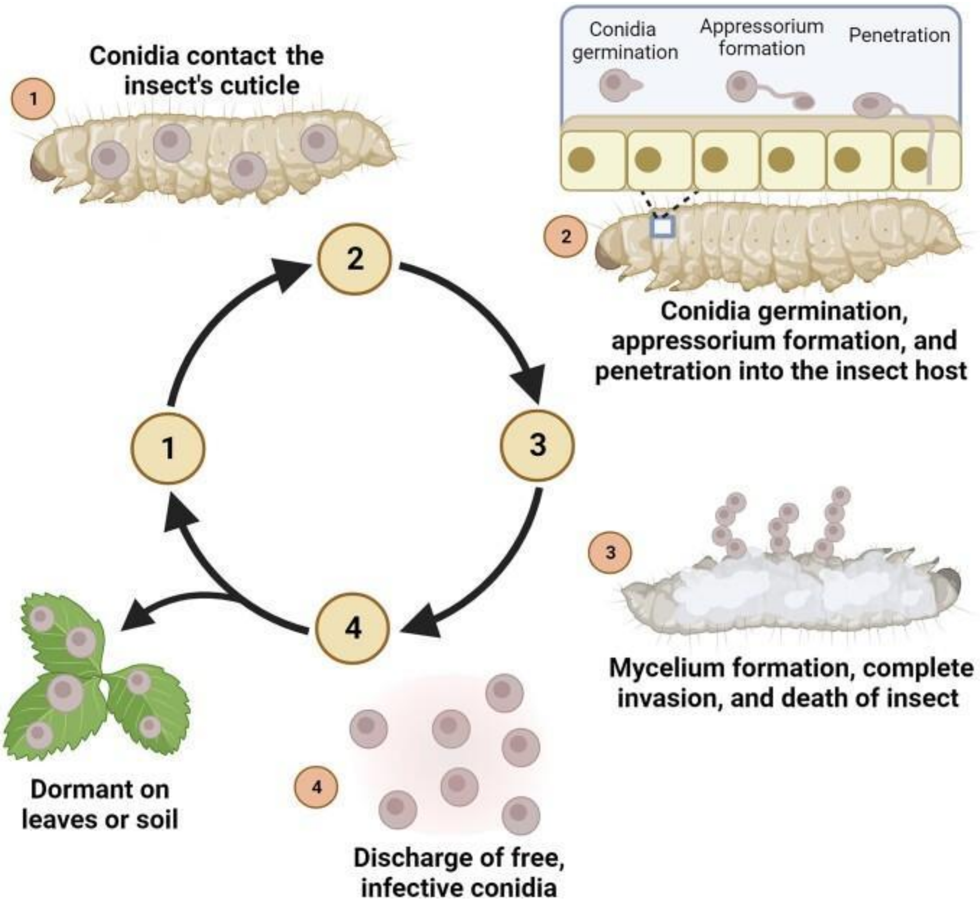

Figure 2: Simplified process of fungal infection of insect hosts (Zhang *et al.*, 2024)

2.2.3 Mechanism of action of some viruses as a biological agent

The principal microbial agents employed in pest management are insect-pathogenic viruses, with notable emphasis on those from the families Baculoviridae and Iridoviridae (Maina *et al.*, 2018). Among these, baculoviruses such as nucleopolyhedroviruses (NPVs) and granuloviruses (GVs) exhibit a high degree of host specificity and are considered safe for non-target organisms, including beneficial insects and vertebrates (Gelaye and Negash, 2023). The mechanism of action of a virus against a pest is shown in Figure 3. Infection typically begins when a susceptible insect pest, most often a larva, consumes viral occlusion bodies present on contaminated plant surfaces. These occlusion bodies are proteinaceous structures that protect the enclosed virions in the environment (Gelaye and Negash, 2023). After the insect ingests the occlusion body, it rapidly dissolves in the midgut. The disassembly of viral progeny from the viral capsid helps its infectious virions get in contact with and infect the gut epithelium cells (Gelaye and Negash, 2023). After penetrating the midgut, the viruses breach the gut wall and enter the body cavity. Once produced, they are distributed throughout the insect's body within the hemolymph, which is the equivalent of blood (Terra *et al.*, 2023). As the virus spreads through various tissues and organs, it continues to replicate, gradually producing many new viruses.

Replication of the viruses leads to severe damage in the internal tissues and vital organs of pests. This effect results in damage to the midgut and the release of new virions into the hemolymph that disrupt essential physiological processes (Terra *et al.*, 2023). The insect succumbs eventually due to multiple causes, including organ failure or septicemia, or they stop feeding. Upon the death of the host, the skin of the host ruptures and the new occlusion bodies are released into the environment. These occlusion bodies are very stable and can remain on leaves and in soil, making them sources of infection for other individuals of the pest population, thus continuing the control (Vallad *et al.*, 2018). The viruses like NPVs and GVs have a very narrow host range, usually limited to one or a few related insect species, and this is an important safety feature. As a result, beneficial insects, like pollinators, remain free from harm, which makes these viruses suitable for low-impact pest management in integrated pest management (IPM) programmes (Vallad *et al*., 2018).

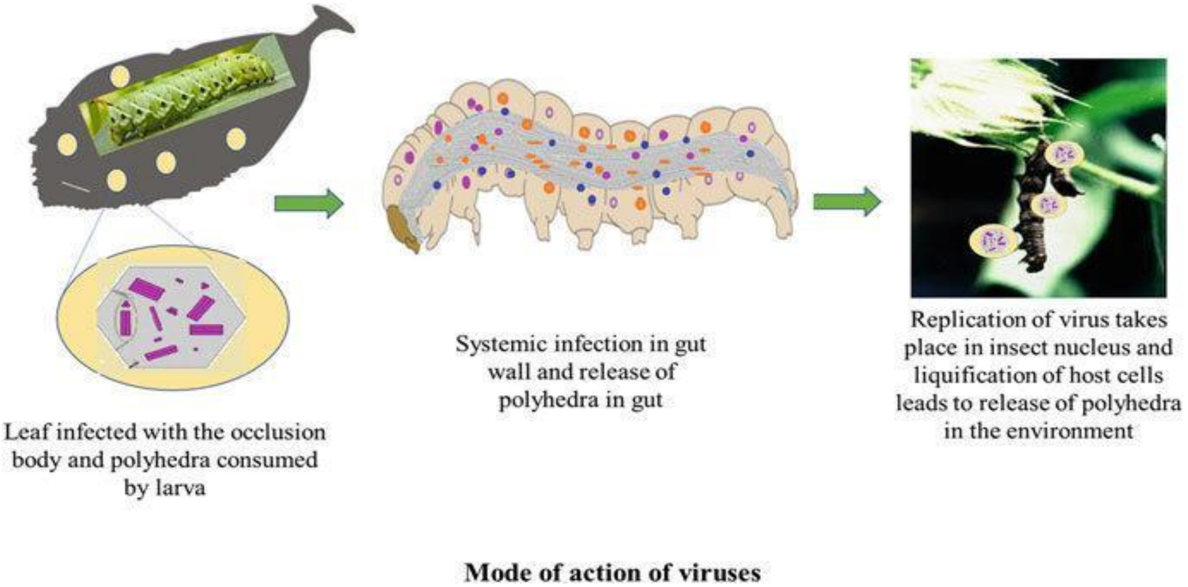

Figure 3: Mechanism of action of Virus (Rajamani and Negi, 2020)

3. Safety and Target Specificity of Microbial Insecticides

Microbial insecticides could be a valuable substitute for chemical ones. Microorganisms like bacteria, fungi, viruses, and protozoa provide insect pest control agents (Sawangproh *et al*., 2025). The use of microbial pesticides is ecologically safe and target-specific, which is essential for the development of an ecologically sustainable pest management system. Microbial insecticides are safe (Sarwar, 2015).

Microbial insecticides are being progressively assigned greater roles in modern-day pest management programmes, owing to their good safety profile. Many synthetic chemical pesticides can act on other creatures besides the intended pest, including human and animal life. Bees can also be negatively impacted by these harmful insects. Microbial insecticides were thought of as posing a risk to human health and the environment, and were believed to be extremely poisonous for any animal or human species, but are not (Sarwar, 2015). Some experts agreed that the negative impact of pesticide use is far worse than that of biopesticides (Sahoo *et al*., 2024; Wend *et al*., 2024). According to their views, use of biopesticides is safe for humans and does not cause pesticide-related poisoning, which is often fatal. One great example of this is the bacterial insecticide of *Bacillus thuringiensis* (Bt). *Bacillus thuringiensis* produces crystals (cry) that, when ingested, severely affect the midgut epithelial cells of the larvae of certain insects (Bravo *et al*., 2011). Vertebrates exhibit variations in their digestive physiologies, preventing the activation of these protein toxins (Karasov *et al*., 2013), thus averting harm to vertebrates.

Regular pesticides harm many categories of insects and cause considerable collateral damage to many beneficial insects, including pollinators such as bees and natural enemies such as predators and parasites. Microbial insecticides are extremely specific and usually affect only the pest organism for which they are designed. Generally, other creatures are not killed by microbial insecticides. The conservation of beneficial insects will ensure the perpetuation of essential ecosystem services (Karasov *et al*., 2013). Microbial insecticides are specific in their action, unlike broad-spectrum chemicals. This was indicated in a study published by Bhatt *et al*. (2019), which showed that microbial pesticides did not affect the environment or beneficial organisms. Several insect pathogens attack an insect of their own species. Each strain of *Bacillus thuringiensis* is active against different groups of insects. For example, the Kursk strain works against caterpillars (Lepidoptera), while Israeli's strain works against mosquito and black fly larvae (Diptera) (Mashtoly *et al*., 2011). This specificity helps control the pest without causing any harm to other insects.

Microbial insecticides are unlikely to affect non-target species via mechanisms of action that operate in different ways. For *Bacillus thuringiensis* toxins to work, they must bind to some receptors of the gut cells of these insects. *Bacillus thuringiensis* (Bt) can be safely consumed by other species, as non-target organisms do not have these receptors (Bravo *et al*., 2011). Similarly, nucleopolyhedrovirus (NPV) must infect specific cells in its host insect to multiply and cause disease, just as bacteria do. Because of their strong specificity for particular species of hosts, they are used to control caterpillar insect pests in forests and crops. Microbial insecticide product processes involve the cultivation of microorganisms used in the manufacture and application of the product on the target pest, which also ensures maximum efficiency and minimum damage to the environment (Bravo *et al*., 2011).

The initial step in the preparation and cultivation of microbes is the isolation and identification of the microbes with insecticidal activity. The microorganisms are then grown under controlled conditions to ensure the consistency and effectiveness of the final product. The large-scale fermentation systems are the microbial insecticides. The bacterium called *Bacillus thuringiensis* (Bt) is an example of growing bacterial cultures in bioreactors with nutrient medium. In controlled environments, the bacterium rapidly multiplies, producing insecticidal toxins as a byproduct. Likewise, the bacterium *Bacillus thuringiensis* is cultivated in a solid or liquid medium. Microbial insecticide-producing fungi are cultivated on a solid substrate like grains or other organic matter and liquid nutrients (Bravo *et al*., 2011). Nucleopolyhedrovirus, like other viruses, is grown by infection of its insect host, from which purified viral particles are extracted after the host dies.

After growing microbial cultures, it is formulated into a product that can be used effectively in the field. The long-sought ability to concentrate and deliver microbes in a form suitable for crop application is finally being realised (Bravo *et al*., 2011). The ability of microbes to concentrate into a powder, liquid suspension, or granule form, depending on the intended mode of application. At this stage or step, substances such as stabilisers or UV protection are added to improve the product's shelf life and in-field performance (De La Cruz Quiroz *et al*., 2019). In comparison to powder or granule formulations, dry formulations are easier to store and transport. However, liquid formulations are better at allowing for precise dosing and application (De La Cruz Quiroz *et al*., 2019). A formulation is selected based on the parasite attacked, environmental conditions, and the crop to be treated.

It is important to execute thorough inspections and conduct tests to produce an efficient microbial insecticide. This involves testing for microbial strength and impurities. The aim is to create a consistent and reliable product that will perform in real-life situations. Certain species of microbial insecticides have a restricted number of hosts. It mostly contains one species or a few related species. For example, *Bacillus thuringiensis* var. tenebrionis primarily targets larvae of beetles (Coleoptera) (Domínguez-Arrizabalaga *et al*., 2020). Because it has a narrow host range, it is probable that it will be able to improve the accuracy of pest control activities and lessen the off-target impacts, such as population control of non-target species.

The biological mechanisms that characterise incompatible non-target organisms do not permit the application of microbial insecticides. For instance, *Bacillus thuringiensis* toxins need to bind to certain receptors in the gut cells of susceptible insects in order to be successful (Bravo *et al*., 2011). Non-target animals do not have these receptors, so they are safe from *Bacillus thuringiensis*. For viral insecticides, such as nucleopolyhedrovirus, to be replicated and cause disease, they must first infect specific insect cells like any other virus (Bravo *et al*., 2011). Because of their high species specificity, they are frequently exploited against caterpillar pests in forests and crops. The processes of growing microorganisms, formulating products, and application techniques for target pests are controlled to achieve the desired results. The production consists of many steps, which include the isolation and identification of insecticidal microorganisms. The strategy could help reduce the total pesticide load in the system (Bravo *et al*., 2011).

There are various techniques for the application of microbial insecticides. The effectiveness of the chemical varies with the nature of the pest, the type of crop, and the formulation of the chemical. These techniques are used to ensure that a microorganism reaches its target pest (Ramanujam *et al*., 2014).

Microbial insecticides may be applied as a soil drench to pests that live in the soil; these are root-feeding insects or soil-borne pathogens (Ramanujam *et al*., 2014). This means that a liquid or granule formulation is applied to the soil, wherein the microbes infect the pest or inoculate themselves (Preininger *et al*., 2018). Soil drenching could be an effective way to control certain pests that cannot be reached by foliar applications, as the microbial insecticide will reach the pest habitat. Microbial insecticides can also be applied via seed treatments. The coating of a microbial product on the seed allows the microorganisms to help the plant get rid of the pest when it grows. This strategy shields the plant when it is most defenceless and may prevent the use of extra pesticides later in the growing season (Preininger *et al*. 2018).

4. Advantages and Limitations of microbial insecticides

4.1 Advantages of microbial insecticides

The use of microbial insecticides, which are derived from microorganisms (bacteria, fungi, viruses, and protozoa) is gaining attention. Bioinsecticides have multiple advantages, such as a lower risk to environmental safety and a lower risk of pest resistance. Safety of the environment is one of the key merits of these microbial insecticides. They have a relatively lesser effect on the environment than synthetic chemical pesticides (Ayilara *et al*., 2023). Microbial insecticides are natural and target-specific pesticides, which enable them to have a number of environmental benefits.

Microbial insecticides are often highly selective of the target insect species, and usually, non-target organisms, including beneficial insects, wildlife, and plants, are not harmed (Ayilara *et al*., 2023). For example, *Bacillus thuringiensis* produces toxins that affect the gut cells of caterpillars but do not harm animals and other organisms. Beneficial species such as pollinators (bees, butterflies) and the natural enemies of pests (ladybugs, parasitic wasps) are unharmed in this way, and therefore the bioecological balance is ensured. (Ayilara *et al*., 2023).

Microbial insecticides involve the application of existing natural organisms designed to control pest populations (Sarwar, 2015). Many synthetic chemical pesticides are in sharp contrast. They can remain in soil, water, and air for long periods of time, leading to contamination and collateral impacts on ecosystems. This microbial insecticide is degradable and non-accumulating in the environment, thus reducing the risk of soil and water pollution. Using microbial insecticides, the hazards of contamination in soil and aquatic ecosystems have been lowered. Overuse of chemical pesticides generally leads to leaching into the water systems, which pollutes water, affecting aquatic life and water quality (AbuQamar *et al*., 2024). Microbial insecticides are less likely to leach and cause runoff, making them safer for use around water bodies. This environmental safety is largely useful in enhancing and sustaining the organisms and ecosystems that are dependent on clean water.

One more important benefit is that microbial insecticides are less likely to cause pest resistance compared to the normal insecticides. The pest population becoming less susceptible over time to a certain control measure leads to the ineffectiveness of the control measure (Choquenot and Parkes, 2001). Microbial insecticides have complex and multiple modes of action, developing resistance to the insecticide by pathogens will become more difficult (Choquenot and Parkes, 2001). One example is the Bt toxin, which must be ingested by the insect, activated by enzymes in the insect gut, and bound to specific receptors on gut cells. The insect is not killed if any of these steps are disrupted (Perkin *et al*., 2016). There are multiple biological mechanisms involved in the killing of pests, so pest resistance is much less likely than with chemical insecticides, which usually have a single mode of action.

Beauveria bassiana and Metarhizium anisopliae are fungal insecticides that kill insects by penetrating their exoskeleton and growing inside their bodies (Zhang *et al*., 2024). The infection is a complicated process that depends on factors such as the release of enzymes and toxins, and also invasion of the insect's body (Zhang *et al*., 2024). The complexity leaves pests less able to develop resistance since they would have to evolve against multiple infection pathways at once (Hawkins *et al*., 2019). Chemical insecticides are so strong that they create more selection pressure on the pest populations which leads to long evolution of strains. Pesticides mainly target a single enzyme or a particular physiological process

(Hawkins *et al*., 2019). The pesticide-resistant individuals that survive pass on their resistance to the next generation. Ultimately, this can lead to whole populations of pests resisting it (Hawkins *et al*., 2019).

4.2 Limitation of biopesticides

It is often too expensive to manufacture these insecticides compared to synthetic chemical pesticides. Microbial insecticides are expensive to produce for various reasons. Microbial insecticides can be produced on a laboratory scale, however, their scaling up is difficult for commercial production. The fermentation or cultivation of microorganisms on a large scale may be complex. The production process has to undergo stringent quality control for the microbial agents to be effective and viable, and this drives up costs even more. The process of turning microbial insecticides into effective and practical products for the market is called formulation. The extra requirements of drying, stabilisation, and packaging of microorganisms add to the cost.

Another problem with microbial insecticides is that they have a short shelf life. Microbial insecticides are basically biological agents or living forms that lose viability easily, as compared to synthetic pesticides, which can retain their efficacy for a longer duration of time (Ayilara *et al*., 2023). Environmental factors like temperature, humidity, and light can affect microbial pesticides. Under extreme conditions, microorganisms are either degraded or killed, limiting their effectiveness (Banu *et al*., 2024). This kind of storage can harm bacterial spores or fungal spores, making them ineffective in the field if they are exposed to high temperatures or direct sunlight (Banu *et al*., 2024). Distribution of microbial insecticides may be complicated by the requirement of certain storage conditions (Banu *et al.,* 2024). In some regions, refrigeration or special handling procedures may be necessary to ensure the viability of these products, which requires farmers to do so. Consequently, microbial insecticides may not be as effective or easy to use as chemical pesticides, which are usually more robust and have specific shelf life and storage requirements.

Acceptance and use of these microbial insecticides can be impacted by public perception. Microbial insecticides are natural substances, and people often have misconceptions regarding their safety and effectiveness in use. Some consumers and advocacy groups have recently expressed scepticism since farmers have been adopting increased biotechnology use in agriculture. Worries about Genetically Modified Organisms (GMO) and unforeseen issues may lead to opposition to microbial insecticides, even if they are safe and effective. A misunderstanding or misinformation regarding the science behind the microbial insecticides may drive this scepticism.

5. Upcoming Expectations

The field of microbial insecticides is evolving on a continuous basis. There are some promising developments. One of the applications of microbial biotechnology is strain improvement, which refers to the enhancement of microbial strains to improve their performance as well as their resistance to environmental stresses. Genetic modification or selective breeding may produce more robust strains with enhanced pest-targeting capabilities and improved resilience to storage and application conditions. Novel formulation methods can help in enhancing the effectiveness and stability of the microbial insecticide by nano-encapsulation. Farmers may find these innovations appealing, as they have the potential to improve product shelf life and usability.

The use of drones and precision agriculture technology can improve the delivery of beneficial substances to targeted pests. Recent research indicates that technological advances can improve delivery mechanisms (Ezike *et al*., 2023). Using these targeted approaches can enhance efficacy while reducing their impact on the environment.

Incorporating microbial insecticides into integrated pest management strategies has great potential for sustainable agriculture. The integration can be achieved through some cultural practices. Microbial insecticides could be integrated into cultural practices like crop rotation, intercropping, and habitat management to improve pest management practices (Akter *et al*., 2019). Farmers can disrupt pest life cycles and reduce pest outbreak chances by creating more diverse agricultural surroundings.

Training and education of farmers on the use of microbial insecticides and their role in integrated pest management can enhance acceptability and understanding (Toepfer *et al*., 2020). One of the ways to help farmers realise the benefits of microbial insecticides in pest management and for the environment in the long term is through extension services and outreach programmes (Toepfer *et al*., 2020).

6. Conclusion

Microbial insecticides use natural mechanisms to safely reduce insect pests while ensuring environmental safety and continued agricultural productivity. These biological control agents are obtained from bacteria, fungi, viruses, and protozoa. They have distinct advantages due to target specificity, low persistence in the environment, and compatibility with integrated pest management. Microbial insecticides are an essential tool for pest control because of their diverse modes of action that can disrupt the gut of insect pests (e.g. *Bacillus thuringiensis* toxin), penetrate and colonise their cuticle (e.g. *Beauveria bassiana*), thereby providing effective pest control with minimal or no impact on non-target organisms. Despite the production costs and shelf life issues, as well as consumer perception challenges, continued scientific investigation into strain improvement, formulation technology, and application method is improving these products' efficiency and practicality. With greater emphasis on sustainability in global agriculture, one expects that microbial insecticides will be proven to be essential to reduce the dependency of agriculture on chemical pesticides and pollution and facilitate sustainable food production. In order to fully realise their potential in creating resilient and ecologically balanced agricultural systems, they require continued innovation, farmer education, and supportive policies. Microbial insecticides can help achieve sustainable agriculture, thus ensuring food security in the future. This will be possible by overcoming challenges and harnessing new opportunities in agriculture.

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