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Advances in Bio-Insecticides: Mechanisms, Efficacy, and Field Applications

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ABSTRACT

The harmful impacts of the traditional chemical pesticides on environment, creatures that coexist, and human health have made a huge demand for sustainable farming techniques worldwide. Bio-insecticides, which offer targeted pest control from natural sources such as plants and microbes and their bioactive metabolites have emerged as eco-friendly and effective solutions in this regard. These biologically based medicines offer selective toxicity against a variety of insect pest through a variety of mechanisms, including neurotoxicity, digestive inhibition, pathogenic infection, hormone disruption, and behavioral alteration. Their physiological and biochemical means of actions are better known due to the recent research developments that have also enhanced the formulation methods and tactics of field application. Their stability, persistence and effectiveness under a variety of environmental conditions has been further improved through modern delivery techniques, such as microencapsulation, nano biopesticides and synergistic combinations with other biological or cultural practices. Despite problems with short shelf life, sensitivity to the environment, and regulatory restrictions, bio-insecticides have shown great potential in the integrated pest management (IPM) systems, which reduce the dependence on conventional pesticides and promote ecological balance and crop yield. The ways, efficiency, formulation, and applications in the field of bio-insecticides are summarized in this review together with possible future directions, such as genetic improvements, advances in technology, and sustainable deployment strategies. All of these developments make bio-insecticides an important tool for modern crop protection that reduces the use of chemicals, ensures food security, and achieves environmentally sustainable agriculture.

1. INTRODUCTION

Worldwide, insect pests pose a serious threat to agricultural production, resulting in massive crop losses and financial losses. Chemical pesticides have always been the mainstay of pest control. However, their unthoughtful use has led to environmental pollution, residual toxicity and insecticide resistance, as well as adverse effects on biodiversity, human health and beneficial creatures. Eco-friendly alternatives that can ensure effective pest management without any damage to the environment are, therefore, in desperate need. Bio-insecticides, also called biopesticides, are a broad category of products, which are derived from living things, or their naturally occurring metabolites. These include naturally occurring biochemical molecules, plant extracts (botanicals) and microbiological agents (bacteria, fungus and viruses). In contrast to chemical pesticides, bio-insecticides are bio-degradable, are selectively toxic to the pest to be controlled, and are often minimally disruptive to the environment.

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Extensive study during the past 20 years has resulted in a greater understanding of their mechanisms of action, formulation techniques, and the uses of these products in the real world and increase in their acceptance and efficacy in agricultural systems (Badavath et al., 2025).

This review is aimed to present an overview of the development in bio-insecticides with an emphasis on the mechanism of action, efficacy, formulation techniques, field application and incorporation in sustainable pest management programs. Challenges and future perspectives are also discussed to lay the road for future research and commercialization (Mounika et al., 2022).

2. TYPES OF BIO INSECTICIDES

Bio-insecticides consisting of microbial agents, plant-based chemicals, and naturally occurring biochemical metabolites can be broadly classified based on their origin and their mode of action (Zaki & Ismail 2021). Microbial pesticides are those that are prepared from viruses, fungi, or bacteria specific to insect pests. The most widely used bacterial agent is Bacillus thuringiensis (Bt) which produces crystal proteins (Cry otoxin) that are specific to the midgut cells of lepidopteran, coleopteran and dipteran larvae, resulting in their death. Fungal bio-insecticides (entomopathogenic fungi such as Beauveria bassiana and Metarhizium anisopliae) are a natural and eco-friendly control means that infect insects by penetrating the cuticle, multiplying in the insect's body and killing the insect. High host specificity is displayed by viral pesticides, particularly granuloviruses and nucleopolyhedroviruses (NPVs) which infect target pests fatally without having any impact on the environment and beneficial organisms. Conversely, substances derived from plants and that have insecticidal, repellant, or antifeedant properties are called botanical insecticides. Alkaloids, terpenoids, flavonoids, and essential oils are some of the different bioactive components present in the aforementioned products that interfere with the physiology and behavior of pests (Chakraborty et al., 2023). Among the most notable examples is Azadirachta indica, also called neem, which produces azadirachtin, an effective growth regulator that functions as an antifeedant and a developmental disruptor by preventing molting and avoiding oviposition. Pyrethrins [a neurotoxic substance present in Chrysanthemum cinerariifolium (pyrethrum)] rapidly paralyses the insect by interfering with the neurological system. Furthermore, popular plant powders and extracts from cloves, turmeric and garlic have poisonous or repellant properties against a variety of field and storage pests and provide a secure and environmentally responsible replacement for chemical pesticides. Finally, by interfering with the insect hormone regulation, eating behavior, and reproductive activities, bioactive biochemicals and secondary metabolites which can be generated from either plants or microorganisms play an important role in natural pest management. These substances are an important component in integrated pest control programs because they exert selective toxicity to the target pest and minimize adverse effects on non-target organisms. Microbial agents, botanical extracts and natural metabolites work with one another to deliver a wide array of bio-insecticides which are increasingly being adopted for the support of ecologically conscious and sustainable farming practices (Mounika et al., 2025).

2.1. Mechanisms of Action of Bio-Insecticides

The different and often specialized modes of action that distinguish bio-insecticides from the traditional chemical pesticides are what give them efficacy. Bacillus thuringiensis (Bt) and other microbial bio-insecticides have their mode of action based on the production of protein toxins that cause damage to the epithelium of the insect's midgut and cause gut paralysis, cessation of feeding, and eventual death (Talukdar & Yadav 2019). Through the process of enzymatic degradation, the entomopathogenic fungi such as Beauveria bassiana and Metarhizium anisopliae permeate the cuticle of the insect, multiply internally and excrete toxins that inhibit physiological and metabolic activities leading to death of the insect. Viral bio-insecticides, e.g. granuloviruses and nucleopolyhedroviruses (NPVs) have impressive host specificity without harming beneficial organisms. (Vardhan et al., 2021).

They specifically infect the target insect cells, multiply within the insect host and ultimately lead to systemic infection and subsequent death. There are various physiological and behavioral mechanisms of action of botanical pesticides. (Vardhan et al., 2022). Neem contains compounds such as azadirachtin that interferes with the molting, metamorphosis and reproduction processes by interfering with the insect's endocrine system. It is also an oviposition inhibitor and a feeding deterrent. By changing the activity of sodium channels, pyrethrins of Chrysanthemum cinerariifolium impact the neurological system and lead to hyperexcitability, paralysis and sudden death. Other metabolites from plants, like essential oils and secondary compounds from cloves, garlic and turmeric, are growth inhibitors, anti-feedants or repellents, which reduce the number of insects and reduce the damage to plants. By modifying insect physiology, biochemical metabolites found naturally in plants or microbes, also expand the repertoire of bio-insecticides. Reduced fecundity, stunted development or mortality can occur as a result of the inhibition of digestive enzymes by these substances, impairment of nutritional absorption, modification of reproductive behavior, or induction of hormonal imbalances. When multiple bioactive substances are applied at once, these benefits are often synergistic where multiple benefits are obtained at reduced environmental hazard. Bio-insecticides provide highly targeted, environmentally benign and sustainable control of pests by exploiting these diverse processes which vary from physical infection and toxin production to hormone disruption, neurotoxicity and behavioural change. They are key components of integrated pest control systems designed to reduce the use of chemical pesticides and enable sustainable agricultural practices due to their selective modes of action, biodegradability and low non-target toxicity (Mounika, 2023).

2.2. Efficacy of Bio Insecticides

Laboratory and field environments have a significant influence on the effectiveness of bio-insecticides which display remarkable variation depending on the pest species, the stage of development, the environmental parameters and the type of formulation. Laboratory studies provide controlled environments to test the toxicity and ability to kill bio-insecticides to some pests. Such experiments have proven, again and again, that entomopathogenic fungi and microbial agents such as Bacillus thuringiensis (Bt) induce great mortality rates within their target insects, in particular, if administered at the correct dosages and life stages (Copping et al., 2023). Similar to this, under controlled conditions, botanical pesticides such as pyrethrum, neem and other extracts from plants exhibit powerful antifeedant and growth inhibitory properties (Mounika et al., 2025).

Thus, lab investigations provide a proper evaluation of their efficacy, and are also helpful in determining the optimal dosages, exposure durations and application methods for some pests. However, several environmental factors that are introduced by field studies such as temperature, humidity, rainfall and sunlight may impact on the activity and persistence of the bio-insecticides. Their effectiveness in agriculture is often dependent on how they are complemented by cultural practices, e.g., crop rotation, pruning, sanitation, application at times of vulnerability to pest infestation and infection (Vardhan et al., 2022). In order to gain reliable suppression, bio-insecticides are also widely used along with other pest management methods such as natural enemies, resistant cultivars, or selective chemical insecticides. These combined strategies ensure the better usefulness of bio-insecticides and contribute to environmental friendly control of pests. Microbial agents are useful for targeted interventions without affecting the non-target organisms because they often exhibit high selectivity towards target pests, and longer persistence in the field as compared to botanical bio-insecticides. On the other hand, under field conditions, botanical insecticides often have wider-spectrum activity and rapid degradation which requires repeated application for any efficacy. Optimizing pest control strategies and developing integrated management plans that are appropriate for specific crop-pest systems requires an understanding of these distinctions (Mounika et al., 2023).

2.3. Bio-Insecticides Formulation and Delivery

The formulation and delivery methods of bio-insecticides that influence stability, usability, and persistence are as vital to the success of bio-insecticides in the field as the inherent toxicity (Ahmad et al., 2021). Because of the simplicity and ease of use and compatibility with standard application equipment, more traditional formulations such as powders, granules and suspensions are often used. With minimal training, farmers can apply these formulations to directly to crops or stored goods to administer bio-insecticides. The effectiveness of bio-insecticides has also been enhanced in recent years with the formulation technology, such as microencapsulation and nanotechnology (Vardhan et al., 2022). While nano-formulations enhance bioavailability and penetrationas, enhancing the effectiveness of the microbial and botanical agents under differing field circumstances, microencapsulation protects active compounds from environmental degradation, ensures regulated and sustained release and extends shelf life.

There is a lot of potential in the synergistic mixtures of botanical and microbial bio-insecticides. These formulations can be used to increase pest mortality, reduce application frequency, and delay the appearance of pest resistance by using drugs with complimentary modes of action. For example, using a combination of entomopathogenic fungi and Bt formulations or neem extracts can provide short and long term pest management, achieving greater overall efficacy while maintaining environmental safety. Bio-insecticides are indispensable components of current integrated pest management programs due to possible better administration potential, persistence in field situations and consistent suppression effects thanks to smart formulation and delivery. (Mounika et al., 2022).

3. INTEGRATION INTO PEST MANAGEMENT PROGRAMS

In Integrated Pest Management (IPM), in which a multi-pronged approach that coordinates various pest control methods in order to achieve sustainability in crop protection as well as less reliance on chemical insecticides, bio-insecticides are indispensable. Bio-insecticides are often used in IPM programs along with cultural practices, which reduce the pest environment and prevent their infestation, such as crop rotation, intercropping and sanitation practices (Vardhan et al., 2025). The use of resistant or tolerant crop cultivars increases the efficacy of bio-insecticides by lowering the reproduction and damage done by pests. Furthermore, microbial or botanical agents can be used in conjunction with natural predators and parasitoids to keep pest populations below economic thresholds. In order to contain outbreaks, selective chemical insecticides may sometimes be added in small amounts and the effectiveness of bio-insecticides and the preservation of beneficial organisms are maintained. There are several benefits to the use of bio-insecticides in IPM (Vardhan et al., 2022). By reducing the use of artificial chemicals, they reduce the risks to human health, the environment and the rise of pest resistance (Bhutia et al., 2024).

By targeting specific pests while preserving pollinators, beneficial insects and soil microbes, they also foster ecological balance. This eventually leads to higher crop yields, more resistant agroecosystems and sustainable pest suppression. The wide application of bio-insecticides for IPM programs is limited, however. Their persistence and field activity could be reduced by environmental factors such as temperature, humidity and UV exposure which often influence how effective they are. Compared to chemical insecticides, which may not immediately get rid of pests, bio-insecticides are often slower acting. Furthermore, problems relating to shelf-life and storage, in particular, for microbial agents, can affect their accessibility and effectiveness at remote or resource-limited sites. Despite these limitations, the benefits of bio-insecticides in IPM frameworks can be maximized through careful planning, timing, and integration with other complementary control techniques (Mounika et al., 2024).

4. CHALLENGES AND FUTURE PROSPECTS

Despite its potential, there are a number of obstacles to preventing bio-insecticides from being widely used. The efficiency of many microbial and botanical formulations may be reduced during storage or transportation because of their short shelf-life and/or varying stability in the field. Environmental factors such as moisture, UV rays and extreme temperatures also come into play for bio-insecticides to work well, especially when applied in open fields. Furthermore, new bio-insecticides might take a longer time to reach the market, due to regulatory barriers and the high cost of commercialization, which would limit the availability of these environment-friendly instruments to farmers (Vardhan et al., 2025). As the technologies of biotechnology and formulation science continue to advance, the future for bio-insecticides is bright. Improved stability, controlled release, enhanced effectiveness under various environmental conditions are some of the benefits given by the development of nano biopesticides. More virulence and a higher variety of target pests could be achieved through the genetic engineering of microbial agents and therefore more precise and effective pest control is possible. The time, dose and location of the application of bio-insecticides may be optimised by coupling with precision agriculture technology, such as sensor-guided application and use of drones for spraying, which will reduce waste and maximise impact.

The successful adoption and administration of bio-insecticides requires awareness campaigns and capacity building projects for farmers, which ensure that producers can successfully use these products in a safe and effective manner, ensuring that sustainable pest management techniques are followed. Bio-insecticides are poised to become key building blocks of a sustainable agriculture system through additional research, technological innovation and education, reducing chemical dependency, promoting ecological balance and enhancing food security across the world (Mounika et al., 2021).

5. CONCLUSION

Bio-insecticides as alternatives to traditional chemical insecticides, as they offer selective, efficient and environmentally friendly alternatives, have become an important part of sustainable pest control. These agents which are derived from microorganisms, plants and naturally occurring metabolites offer targeted control over a variety of insect pests, through a variety of mechanisms including neurotoxicity, digestive interference, hormonal disruption, pathogenic infection, and behavioral modification. Their effectiveness has been demonstrated in both laboratory and field research especially when combined with natural predators, resistant crop varieties, cultural practices and selective chemical interventions in Integrated Pest Management (IPM) programs. The stability, persistence and field performance of bio-insecticides has been improved through the development of formulation technologies such as microencapsulation, nanobiopesticides and synergistic combinations of microbial and botanical. As a result, these products are becoming more feasible to be used in large-scale agricultural applications. Even though there are issues such as environmental sensitivity, storage, action slower than synthetic chemicals and restrictions in regulations, these problems are being overcome due to continuous research and innovation. In order to ensure uptake and use, the future of the use of bio-insecticides relies on the development of better formulations, microbial agent genetic engineering, coupling with precision agriculture technologies and efficient farmer training initiatives. In conclusion, bio-insecticides are a crucial tool for achieving sustainable agriculture, reducing dependence on chemical pesticides, preserving the environment, and enhancing food security. Developing and promoting ecologically aware crop production systems and integrating ecologically strong agroecosystems worldwide requires the continued development and integration into modern pest management methods (Barman et al., 2023).

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