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BIOPESTICIDES: A POTENTIAL SOLUTION FOR THE MANAGEMENT OF INSECT PESTS

Maida Shahid[1], Fiza Shaukat[2]*, Aniqa Shahid[3], Aqsa Sohail[4] and Mawra Nadeem[5]

[1]Department of Zoology, Wildlife and Fisheries, University of Agriculture, Faisalabad, Pakistan
[2]Centre of Agricultural Biochemistry and Biotechnology (CABB), University of Agriculture, Faisalabad, Pakistan
[3]Department of Biochemistry, University of Agriculture, Faisalabad, Pakistan
[4]Department of Plant Pathology, University of Agriculture, Faisalabad, Pakistan
[5]Faculty of Medicine, Chulalongkorn University, 1873 Rama 4 Road, Pathumwan, Bangkok 10330, Thailand

**Corresponding author*: fizaali.3855@gmail.com

ABSTRACT

Biopesticides have gained significant attention as an environmentally friendly and sustainable approach for managing insect pests. These pest control agents are derived from natural sources such as plants, microbes, and insects themselves, offering several advantages over conventional chemical pesticides. Biopesticides offer target specificity, minimal environmental impact, and reduced risks to human health. They can be classified into three main categories: microbial biopesticides, bio-derived chemicals, and plant-incorporated protectants. Microbial biopesticides utilize microorganisms, such as bacteria, fungi, and viruses, to control pests through various mechanisms, including direct pathogenicity or the production of toxins. Bio-derived chemicals are derived from natural compounds, such as botanical extracts or pheromones, and act as repellents, attractants, or disruptors of pest behavior. Plant-incorporated protectants involve genetic modification of plants to produce insecticidal proteins, providing continuous pest control. The efficacy of biopesticides can be influenced by factors such as formulation, application methods, and environmental conditions. Integrated Pest Management (IPM) strategies that combine multiple pest control methods, including biopesticides, have shown great potential in achieving sustainable pest management. Despite their advantages, challenges remain in the development and commercialization of biopesticides, including limited availability of effective strains or compounds, regulatory barriers, and market acceptance. Future research should focus on optimizing biopesticide formulations, improving efficacy, expanding the target pest range, and addressing concerns related to persistence, non-target effects, and resistance development. Overall, biopesticides present a promising alternative for insect pest management, offering effective and sustainable solutions for crop protection and public health.

Keywords: Biopesticides, Nano-Biotechnology, Insect Pest Management

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1. INTRODUCTION

Pesticides play a crucial role in pest control and disease prevention, but their usage poses significant challenges and concerns. The commonly used active ingredients in pesticides, such as organophosphates, chlorinated hydrocarbons, carbamates, and carbamide derivatives, have the potential to harm humans, animals, and the environment. Absorption through the skin, inhalation, and dietary intake are the main routes of exposure, leading to the contamination of both living organisms and their surroundings. Furthermore, improper pesticide use in agriculture can disrupt the balance of antioxidant and oxidant enzymes in the human body, resulting in oxidative stress-related diseases (Ren et al., 2019). Conventional pesticide formulations have inherent limitations, including high organic solvent content, susceptibility to dust drift, low dispersibility, and prolonged persistence in the soil. These factors contribute to environmental pollution as a significant portion of the applied pesticides is lost to the air, with only a small fraction remaining on target surfaces. This inefficiency leads to environmental contamination and results in pesticide waste, increased manufacturing costs, and the need for repeated applications. Therefore, minimizing pesticide waste, reducing manufacturing costs, mitigating environmental emissions, and extending pesticide activity on crops (Zafar et al., 2022). In modern agriculture, the effective management of pests and diseases is essential for maintaining crop health, maximizing productivity, and ensuring food security. Traditionally, synthetic pesticides have been the primary tools used to control pests. However, concerns over their environmental impact, human health risks,

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and the development of pesticide resistance have prompted the search for safer and more sustainable alternatives. This has led to the emergence of biopesticides as a promising solution (Razzaq et al., 2021).

Biopesticides are a type of pesticide derived from natural sources such as plants, microorganisms, and certain minerals. They are designed to control pests through non-toxic mechanisms, targeting specific pests while minimizing adverse effects on the environment, beneficial organisms, and human health. Unlike synthetic pesticides, biopesticides adhere to the principles of green chemistry, emphasizing the use of renewable resources, waste reduction, and the production of harmless end products. The use of biopesticides in agriculture is not a new concept. Throughout history, farmers have employed various natural substances to combat pests and diseases. However, recent advancements in technology, scientific understanding, and regulatory frameworks have propelled biopesticides into the forefront of modern pest management strategies (Razzaq et al., 2023). There are several categories of biopesticides, each with its unique characteristics and modes of action (Fig. 1). Microbial pesticides, for example, utilize naturally occurring microorganisms such as bacteria, fungi, and viruses to control pests. These microorganisms can infect or parasitize pests, inhibit their growth, or produce toxins that are specific to certain pest species. Plant-based biopesticides, on the other hand, harness the insecticidal, fungicidal, or herbicidal properties of botanical extracts, essential oils, or plant-derived compounds (Akbar et al., 2023).

The advantages of biopesticides are numerous. Firstly, they have a favorable environmental profile, as they typically have lower toxicity levels compared to synthetic pesticides. This makes them safer for beneficial insects, pollinators, wildlife, and human health. Secondly, biopesticides have minimal residual effects, meaning they break down more rapidly in the environment, reducing their impact on non-target organisms and reducing the risk of pesticide accumulation. Thirdly, biopesticides can be an integral component of integrated pest management (IPM) systems, which aim to combine multiple strategies for effective and sustainable pest control (Ramzan et al., 2023). Moreover, biopesticides offer potential solutions to the challenges posed by pesticide resistance. Since they often employ multiple modes of action, pests are less likely to develop resistance, making biopesticides valuable tools for long-term pest management strategies. Additionally, the use of biopesticides can contribute to the conservation of biodiversity, support organic farming practices, and address consumer demands for pesticide-free produce (do Nascimento et al., 2022). In recent years, the development and commercial availability of biopesticides has seen significant growth. Researchers and industry experts continue to explore new sources, improve formulations, and optimize application methods to enhance the efficacy, stability, and cost-effectiveness of biopesticides. Furthermore, the integration of emerging technologies such as nanotechnology, genetic engineering, and omics approaches holds promise for expanding the scope and potential of biopesticides in pest management.

2. Various Classes of Biopesticides

2.1. Microbial Biopesticides

Microbial biopesticides, also known as biological control agents (BCAs), are a type of biopesticide that utilizes microorganisms as the active ingredient for pest management. These microorganisms can occur naturally in the environment or be genetically modified for enhanced pest control properties. Microbial biopesticides offer several advantages over conventional chemical pesticides, including higher selectivity, lower toxicity to non-target organisms, and reduced environmental impact. Various microorganisms are used as microbial biopesticides, including bacteria, fungi, viruses, protozoa, algae, rickettsia, Mycoplasma, and nematodes (Fig. 1). Each type of microorganism has its own mode of action to suppress or control pests, making them effective against a wide range of target organisms (Ayilara et al., 2023).

Bacteria: Bacterial biopesticides are among the most commonly used microbial pesticides. Bacillus spp., such as *bacillus thuringiensis* (Bt), are extensively utilized. Bacteria can produce toxins, called endotoxins, that are specific to certain pests. These endotoxins disrupt the digestive system of the target pests, leading to their death. Bacterial biopesticides are often used to control insect pests, such as moths, butterflies, beetles, flies, and mosquitoes. They can be applied as sprays or incorporated into formulations that pests ingest (Zafar et al., 2020).

Fungi: Fungal biopesticides use naturally occurring fungi or their spores to control pests. Fungal pathogens, such as *Beauveria bassiana* and *Metarhizium anisopliae*, are commonly employed. Fungi infects pests through direct contact or by entering their bodies. Once inside, the fungi grow and spread, causing diseases that eventually lead to pest mortality. Fungal biopesticides are effective against a wide range of pests, including insects, mites, and nematodes (Ayilara et al., 2023).

Viruses: Viral biopesticides utilize insect-specific viruses, known as entomopathogenic viruses, to control pest populations. These viruses infect and replicate within the pests, causing disease and mortality. Baculoviruses, such as the nucleopolyhedrovirus (NPV), are commonly used. Viral biopesticides are highly specific to particular pest species and have minimal impact on non-target organisms (Ayilara et al., 2023).

Protozoa and Nematodes: Certain protozoa and nematodes are also used as microbial biopesticides. For example, the protozoan Nosema locustae are used to control locust and grasshopper populations, while entomopathogenic nematodes, such as Steinernema and Heterorhabditis species, are effective against soil-dwelling insects. These

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microorganisms invade the pest's body, releasing symbiotic bacteria that kill the host and provide nutrients for the microorganism's growth and reproduction (Ayilara et al., 2023).

Microbial biopesticides offer several benefits in pest management. Firstly, they are highly selective, targeting specific pests while sparing beneficial organisms, such as pollinators and natural enemies. They also have low toxicity to humans, wildlife, and the environment, reducing the risk of adverse effects. Additionally, microbial biopesticides do not persist in the environment for extended periods, minimizing the accumulation of harmful residues. They can be integrated into integrated pest management (IPM) programs, promoting sustainable and environmentally friendly pest control practices. Furthermore, microbial biopesticides are valuable tools for managing pesticide resistance. Due to their unique modes of action, pests are less likely to develop resistance against microbial biopesticides compared to chemical pesticides. This helps to prolong the effectiveness of pest control strategies and reduce reliance on conventional pesticides (Sabbahi et al., 2022).

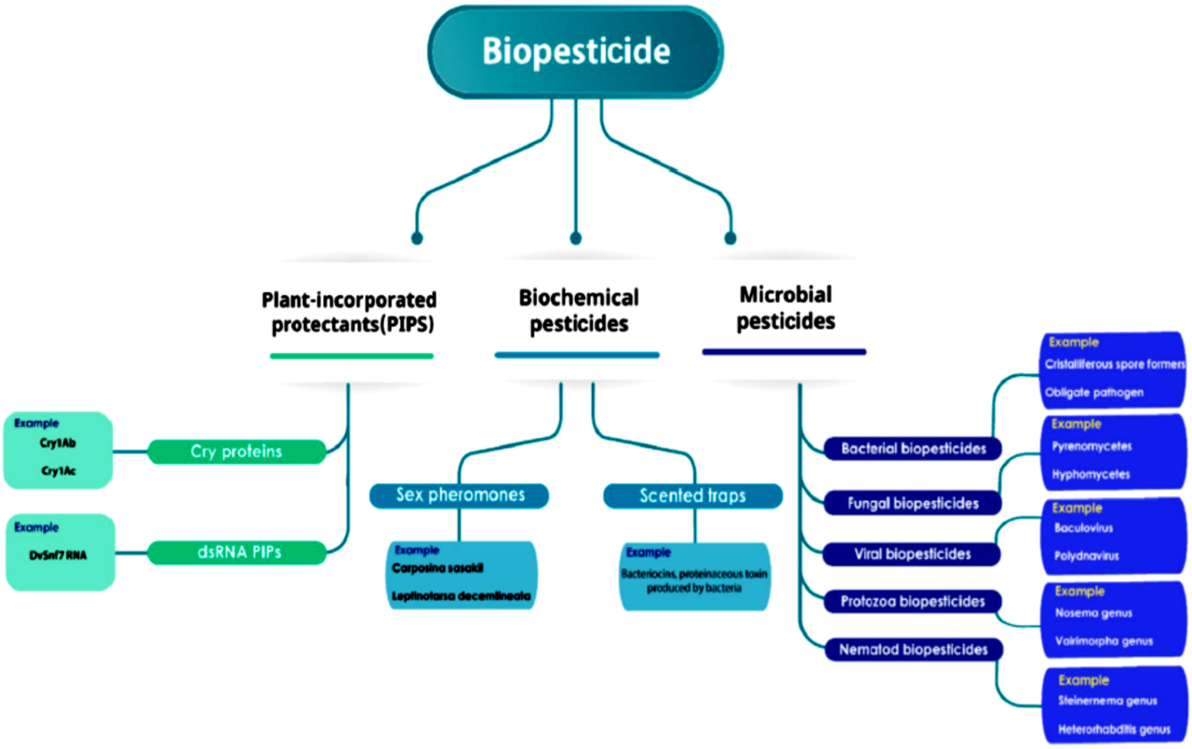

Fig. 1: Classification of biopesticides with examples (Abdollahdokht et al., 2022).

2.2. Biochemical Pesticides

Biochemical pesticides, also known as biopesticides, are a class of pest control agents derived from natural sources or produced through biological processes. These substances offer an alternative to conventional chemical pesticides, as they are generally considered safer for human health and the environment. Biochemical pesticides work by utilizing naturally occurring compounds or biochemical processes to control pests and diseases. There are several types of biochemical pesticides, including microbial pesticides, plant-incorporated protectants (PIPs), and biochemical-based products derived from plants or other natural sources (Fig. 2). Each type has its unique characteristics and mechanisms of action (Zafar et al., 2020).

Biochemical-Based Products: Biochemical-based pesticides are derived from natural sources such as plants, minerals, or animal byproducts. These substances include various compounds like essential oils, plant extracts, pheromones, and insect growth regulators. Essential oils obtained from plants, such as neem, garlic, or citrus, have demonstrated insecticidal, repellent, or antifeedant properties. Pheromones, which are chemical signals released by insects, can be used to disrupt their mating behavior and control population levels. Insect growth regulators are substances that interfere with the growth, development, or reproduction of insect pests (Zafar et al., 2022).

The advantages of biochemical pesticides include their selective toxicity, minimal impact on non-target organisms, biodegradability, and reduced risk of resistance development in pests. They are also compatible with integrated pest management (IPM) strategies, which aim to combine multiple pest control methods for sustainable and environmentally friendly pest management (Fig. 2). However, it is essential to consider certain factors when using biochemical pesticides. The efficacy of biopesticides can be influenced by environmental conditions, target pest

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species, and proper application techniques. Regulatory authorities ensure the safety and effectiveness of these products through rigorous testing and evaluation processes.

2.3. Plant-Incorporated Pesticides

Plant-incorporated pesticides, also known as plant-produced pesticides or genetically modified (GM) crops with pesticidal traits, are a type of biopesticide that involves genetically engineering crops to produce their own pesticides. This approach combines genetic material from a pest control agent, such as a bacterium or a toxin-producing gene, with the genetic makeup of the target crop (Fig. 2). As a result, the crop itself produces proteins or compounds that exhibit pesticidal properties, providing built-in protection against specific pests. The development of plant-incorporated pesticides has been driven by the need for effective and sustainable pest control strategies. By incorporating the ability to produce pesticides within the plant, farmers can reduce reliance on external pesticide applications, thereby minimizing environmental impact and potential health risks associated with chemical pesticides (Zafar et al., 2020). The most well-known and widely cultivated example of plant-incorporated pesticides is *Bacillus thuringiensis* (Bt) crops. Bt crops have been genetically modified to express a gene derived from the bacterium *B. thuringiensis*, which produces a protein toxic to certain pests. When pests feed on Bt crops, they ingest the Bt toxin, which binds to receptors in their digestive system, leading to paralysis and death. Bt crops have been developed to target specific pests, such as corn borer, cotton bollworm, and potato beetle, among others (Fig. 2). One of the main advantages of plant-incorporated pesticides is their specificity. The pesticidal proteins produced by the modified crops typically target specific pests while being harmless to beneficial organisms and humans. This characteristic allows for precise pest control and reduces the risk of non-target effects associated with broad-spectrum chemical pesticides (Razzaq et al., 2021). Furthermore, plant-incorporated pesticides can provide continuous protection throughout the growing season, as the pesticidal traits are present in every part of the plant, including leaves, stems, and roots. This feature can be particularly advantageous in regions with high pest pressure, where frequent pesticide applications may be required otherwise (Haroon et al., 2022).

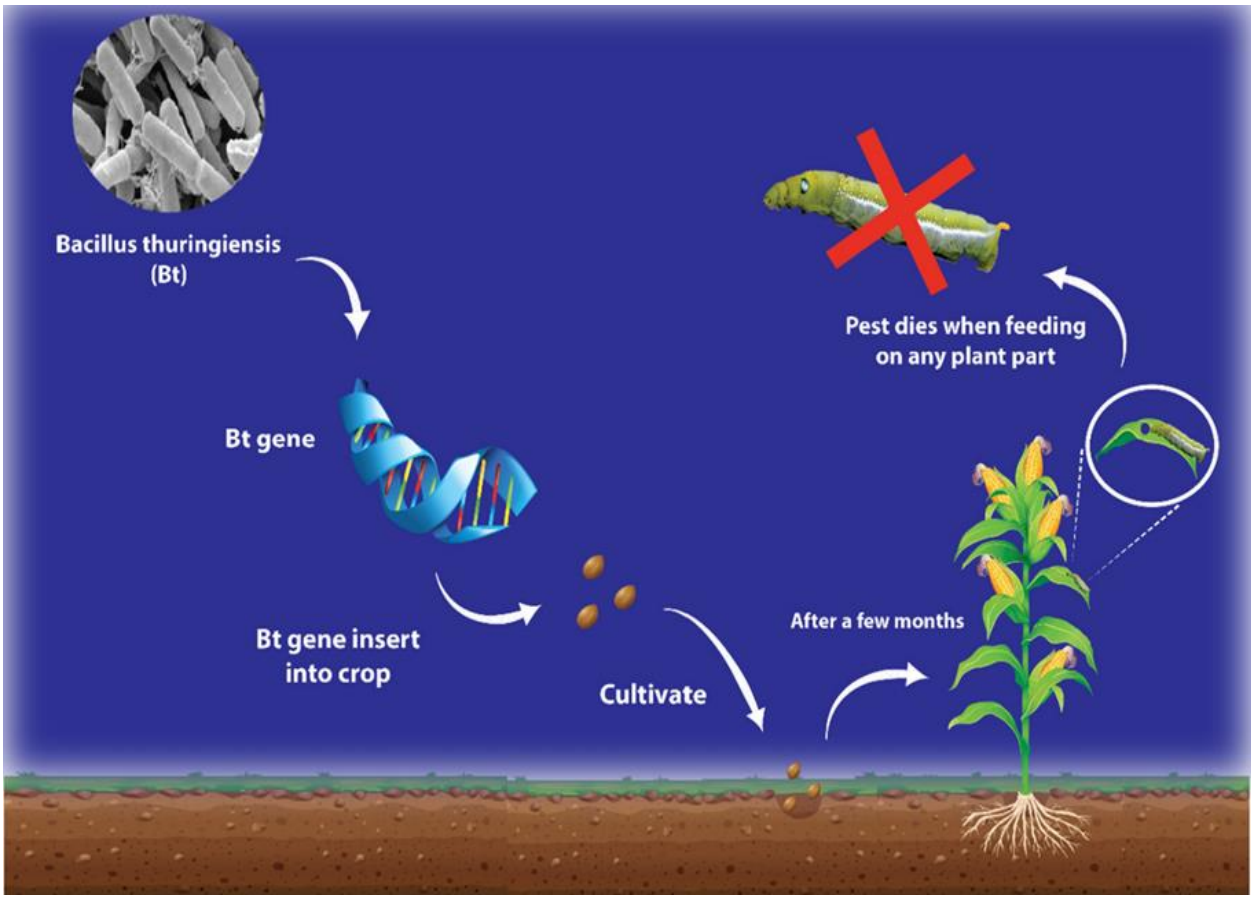

Fig. 2: The naturally existing bacterium possesses the ability to produce a toxic protein that specifically affects certain types of insects. By transferring the Bt gene responsible for producing this toxin from the bacterium into crops, the crops acquire increased resistance against the targeted insect species (Abdollahdokht et al., 2022).

The use of plant-incorporated pesticides has shown numerous benefits in agricultural practices. It can lead to increased crop yields, reduced crop losses due to pest damage, decreased reliance on external pesticide applications, and improved overall productivity. Additionally, the reduced need for chemical pesticides can contribute to lower pesticide residues in food and reduced environmental contamination. However, the use of plant-incorporated esticides also raise concerns and challenges. There are potential risks associated with the development of pest resistance to the pesticidal traits present in GM crops. To mitigate this risk, it is crucial to employ proper stewardship practices, such as planting refuge areas with non-Bt crops to maintain susceptible pest populations and delay the emergence of resistant individuals (Haroon et al., 2023). Additionally, the introduction of GM crops and their associated pesticidal traits requires rigorous safety assessments to ensure they do not pose risks to human health, the environment, or non-target organisms. Regulatory frameworks vary across countries, with many implementing strict regulations and extensive testing procedures before approving the cultivation and commercialization of GM crops.

2.4. Nano-Biopesticides for Insect Pest Management

In recent years, there has been growing interest in using engineered nanoparticles as carriers for pesticide delivery. These nanoparticles have the potential to revolutionize the field of pest management by improving the efficacy of existing pesticides and enhancing their environmental safety profiles. Various formulation types, including nano-emulsions, nano-encapsulations, nano-vesicles, nano-gels, nanofibers, and more, have been suggested for this purpose. Nano-emulsions are formulations where the pesticide active ingredients are dispersed as nanoscale droplets in an aqueous solution. These droplets have a high surface area and can provide improved pesticide coverage and absorption on the target organisms. Nano-emulsions are particularly useful for enhancing the efficacy of hydrophobic pesticides, which otherwise tend to form large droplets and exhibit poor stability in water (Ahmed et al., 2023).
Nano-biopesticides, a combination of nanotechnology and biotechnology, have emerged as a promising approach for managing insect pests. These innovative formulations utilize nanoparticles and bioactive compounds derived from biological sources to control insect populations (Fig. 3; Fig. 4). Nano-biopesticides offer several advantages over conventional pesticides, including enhanced efficacy, reduced environmental impact, and increased target specificity. They represent a significant advancement in the field of insect pest management (Fig. 4). The development of nano-biopesticides involves the incorporation of nanoparticles into biological agents such as microbial pathogens, botanical extracts, or pheromones. The nanoparticles used can be metallic, metal oxide, carbon-based, or polymeric in nature. These nanoparticles serve as carriers or delivery systems for the bioactive compounds, ensuring their targeted delivery to the pests (Kannan et al., 2023).

One of the key advantages of nano-biopesticides is their improved efficacy. The nanoparticles help to enhance the stability and bioavailability of the active ingredients, enabling better penetration and adhesion to the target pests. The small size and large surface area of nanoparticles allow for increased contact with the pests, leading to improved insecticidal activity. This increased efficacy often results in lower application rates, reducing the overall pesticide load in the environment.

Nano-biopesticides also offer increased target specificity. By incorporating specific pheromones or attractants into the nanoparticles, it is possible to develop formulations that selectively target a particular pest species while minimizing the impact on beneficial organisms. This targeted approach reduces the risk of non-target effects and promotes sustainable pest management practices (Jasrotia et al., 2022).

Furthermore, nano-biopesticides exhibit reduced environmental impact compared to conventional pesticides. The use of nanoparticles helps to minimize off-target drift and leaching, decreasing the potential for water and soil contamination. Additionally, the controlled release properties of nanoparticles allow for prolonged and sustained release of bioactive compounds, reducing the need for frequent reapplication (Jasrotia et al., 2022). The mode of action of nano-biopesticides can vary depending on the specific formulation and active ingredients. Some nano-biopesticides exert their effects by disrupting the insect's physiology, such as interfering with its metabolism or development. Others may target specific biochemical pathways, enzymes, or receptors crucial for the insect's survival. The nanoparticles can also enhance the penetration of bioactive compounds through the insect cuticle, improving their efficacy (Deka et al., 2021).

Nano-encapsulations involve encapsulating pesticide AIs within nanoscale shells or matrices. These shells can be made from materials such as polymers, lipids, or inorganic substances. The encapsulation process provides several advantages, including controlled release of the pesticide over time, protection against degradation or volatilization, and targeted delivery to the pests. Nano-encapsulated pesticides can have improved stability, reduced off-target effects, and prolonged residual activity. Nano-vesicles, such as liposomes or niosomes, are bilayer structures that can entrap pesticide AIs within their aqueous compartments. These vesicles can enhance the solubility and stability of pesticides, improve their bioavailability, and enable targeted delivery to pests. Liposomes, in particular, have been extensively studied for their potential in pesticide delivery due to their biocompatibility and ability to encapsulate both hydrophilic and hydrophobic pesticides (Jasrotia et al., 2022).

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Nano-gels are three-dimensional networks of cross-linked polymer chains that can absorb and release pesticides. These gels can provide controlled and sustained release of pesticides, ensuring a prolonged and effective exposure to the target pests. Nano-gels can be formulated with various polymers and can be designed to respond to specific environmental triggers, such as pH or temperature changes, to release the pesticide at the desired time and location (Manna et al., 2023).

Nanofibers are long, thin fibers with a nanoscale diameter that can be loaded with pesticide AIs. These fibers can be made from natural or synthetic materials and can be designed to have a high surface area for improved contact with pests. Nanofibers can be incorporated into different materials, such as textiles or coatings, to create pesticide-treated surfaces with enhanced efficacy and durability (Manna et al., 2023). The use of engineered nanoparticles as carriers for pesticide delivery offers several benefits. Firstly, it allows for the efficient delivery of pesticide AIs, ensuring their optimal concentration and coverage on the target pests. This can result in improved pest control and reduced pesticide usage (Fig. 3). Secondly, these formulations can enhance the environmental safety profiles of pesticides by minimizing off-target effects, reducing the risk of water and soil contamination, and improving the selectivity towards pests while minimizing impacts on beneficial organisms. However, it is important to consider the potential risks associated with the use of engineered nanoparticles in pesticide formulations. These include the potential for nanoparticle toxicity, environmental persistence, and unintended effects on non-target organisms. Therefore, rigorous testing and evaluation of the safety and efficacy of these formulations are necessary before their widespread application.

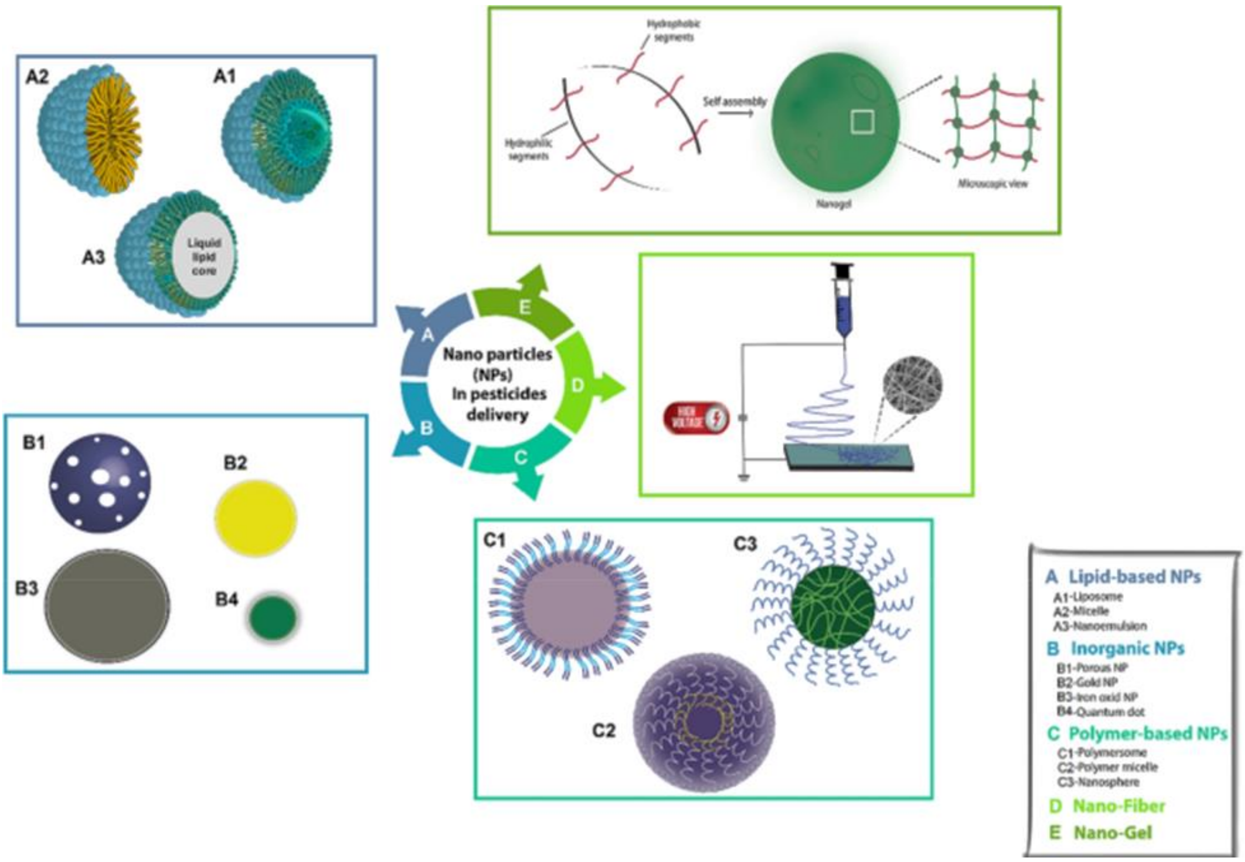

Fig. 3: Nanoparticles in pesticide delivery: A Lipid-based nanoparticles. B Inorganic nanoparticles. C Polymer-based nanoparticles. D Nanofibers. E Nano-gels (Abdollahdokht et al., 2022).

Despite their significant potential, there are still challenges associated with developing and commercializing nano-biopesticides. These include concerns about the potential toxicity of nanoparticles to non-target organisms, the stability and persistence of nanoparticles in the environment, and regulatory considerations. The mode of action of nano-biopesticides for insect pest management can vary depending on the specific formulation and active ingredients used. However, there are some common mechanisms through which these nano-biopesticides exert their effects on insects (Jasrotia et al., 2022). Here are a few examples:

Physical Interaction and Disruption: Nanoparticles can physically interact with insects, leading to their immobilization, suffocation, or dehydration. For example, nanoparticles may adhere to the insect cuticle, disrupting its integrity and causing water loss through increased permeability. This dehydration can eventually lead to the mortality of the pest (Bhan, Mohan, & Srivastava, 2018).

Enhanced Delivery of Bioactive Compounds: Nanoparticles act as carriers or delivery systems for bioactive compounds, facilitating their targeted delivery to pests. The small size and large surface area of nanoparticles allow for better penetration through the insect cuticle or ingestion by the pests. Once inside the insect, the bioactive compounds can disrupt vital physiological processes, such as metabolism, reproduction, or development (Ahmed et al., 2023).

Disruption of Biochemical Pathways: Nano-biopesticides can target specific biochemical pathways in insects, interfering with their normal functioning. For instance, nanoparticles may inhibit key enzymes or receptors necessary for essential processes in pests, such as digestion, nervous system function, or hormone regulation. This disruption can result in the death or dysfunction of the insect (Ahmed et al., 2023).

Toxicity and Oxidative Stress: Some nano-biopesticides affect insects by inducing toxicity or oxidative stress. Nanoparticles or bioactive compounds may generate reactive oxygen species (ROS) inside the pests, overwhelming their antioxidant defense mechanisms and causing cellular damage or death. This oxidative stress can disrupt cellular functions and lead to insect mortality (Manna et al., 2023).

Interference with Reproduction: Nano-biopesticides can also target the reproductive processes of insects, affecting their fertility and population growth. By disrupting reproductive hormones, enzymes, or signaling pathways, nanoparticles can impair mating, egg development, or embryo viability. This interference can lead to reduced pest populations and control of insect pests (Kannan et al., 2023).

It's important to note that the specific mode of action may vary depending on the type of nano-biopesticide and the target pest species. Additionally, the choice of nanoparticles and bioactive compounds can be tailored to target specific pests while minimizing impacts on non-target organisms and the environment (Ahmed et al., 2023). Overall, nano-biopesticides offer a range of mechanisms through which they can effectively manage insect pests. Their targeted delivery, enhanced efficacy, and potential for specific modes of action make them a promising tool for sustainable and environmentally friendly pest management practices. However, further research and testing are necessary to fully understand the mode of action of nano-biopesticides and their potential impacts in different ecosystems.

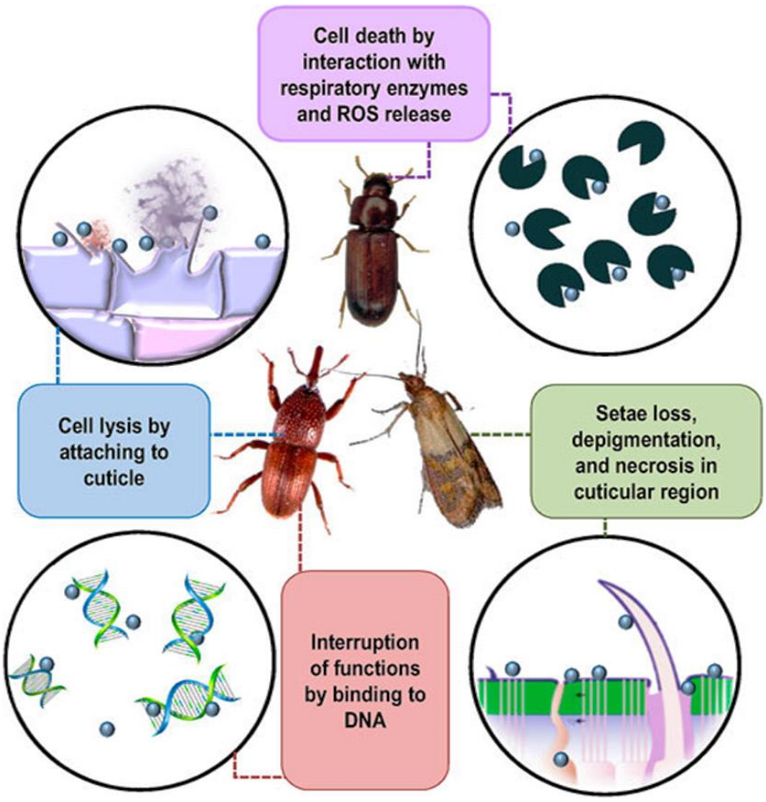

Fig. 4: Some modes of action of nanoparticles against storage insect pests (Jasrotia et al., 2022).

3. Conclusion

Biopesticides have emerged as a promising and environmentally friendly approach for managing insect pests. These pest control agents, derived from natural sources such as plants, microbes, and insects, offer several advantages over conventional chemical pesticides. Biopesticides promote target specificity, reduce environmental impact, and pose fewer risks to human health. Microbial biopesticides, bio-derived chemicals, and plant-incorporated protectants are the three main categories of biopesticides. Microbial biopesticides utilize microorganisms to control pests through various mechanisms, while bio-derived chemicals are derived from natural compounds and disrupt pest behavior. Plant-incorporated protectants involve genetically modifying plants to produce insecticidal proteins. The efficacy of biopesticides can be influenced by factors such as formulation, application methods, and environmental conditions. Integrated Pest Management (IPM) strategies that combine multiple pest control methods, including biopesticides, have shown promise in achieving sustainable pest management. Although biopesticides offer numerous benefits, there are challenges in their development and commercialization. Limited availability of effective strains or compounds, regulatory barriers, and market acceptance are among the hurdles that need to be overcome. Future research should focus on optimizing biopesticide formulations, improving efficacy, expanding the range of target pests, and addressing concerns related to persistence, non-target effects, and resistance development. This will contribute to the continued advancement and adoption of biopesticides in insect pest management. Overall, biopesticides provide effective and sustainable solutions for the management of insect pests, offering a viable alternative to conventional chemical pesticides. Their use not only protects crops but also promotes the preservation of ecosystems and human well-being. As the demand for environmentally friendly pest control continues to grow, biopesticides are poised to play a crucial role in the future of pest management practices.

ORCID

Mawra Nadeem https://orcid.org/0000-0001-8854-6064
Fiza Shaukat https://orcid.org/0000-0001-6148-7631

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