

Review Article

Recent Advances in Biopesticide Formulations for Targeted Insect Pest Management – A Review.

Abstract

The increasing environmental and health concerns associated with the use of synthetic chemical pesticides have driven the need for alternative, eco-friendly pest management solutions. Biopesticides, derived from natural sources such as plants and microorganisms, offer a promising solution, as they are less toxic, decompose quickly, and target specific pests with minimal impact on non-target organisms. Recent advancements in biopesticide formulations, including nano pesticides, controlled release formulations (CRFs), hydrogels, polymer-coated granules, and tablets, are enhancing the effectiveness, stability, and environmental safety of these products. The integration of nanotechnology and controlled release systems in biopesticides is opening new avenues for sustainable agriculture. This review discusses the various biopesticide formulation technologies, highlighting their advantages, disadvantages, and future prospects.

Key words: Biopesticides, controlled release formulations, nano-technology, tablet

1. Introduction

The damaging actions of many pests, such as bacteria, fungi, weeds, and insects, which drastically lower crop yields, have long been a problem for agriculture [1]. Synthetic organic pesticides have been the predominant approach of pest management since the 1960s. Organophosphate and carbamate pesticides followed the introduction of dichloro-diphenyl-trichloroethane (DDT) in the 1940s, which signaled the start of a new era in pest management[2]. The successful implementation of Green Revolution technology, which heavily relied on synthetic pesticides, led to increased agricultural production. Unfortunately, an over-reliance on these chemical pesticides has led to a number of negative environmental effects, including pesticide resistance, insect resurgence, and the buildup of pesticide residues in soil, water, and the air, which poses a risk to human health and disturbs ecological equilibrium[3,4].

Recognizing these harmful impacts, there is an increasing need for alternative, environmentally safe methods of pest control [5]. The application of biopesticides, which are made from naturally occurring materials like plants and microbes, is one of the more promising approaches. Because they frequently target particular pests, are less toxic than chemical pesticides, and have a lower negative impact on non-target animals including beneficial insects, mammals, and birds, biopesticides are seen as being more environmentally friendly. Additionally, biopesticides decompose quickly, reducing the risk of environmental pollution[6].

Biopesticides encompass various forms, including viruses, microorganisms, plant-derived products, and genetically modified organisms. Their appeal lies in their environmental safety, target specificity, and efficacy, which has driven their increasing adoption in sustainable agriculture[7,8] . With the growing demand for safe, healthy, and organic food, the biopesticide market is expanding, and many biopesticides, such as *Bacillus thuringiensis* (Bt)

and neem-based products, have already been registered and are widely used in countries like India[9] .

In recent years, there has been a notable shift in pesticide formulations from traditional wettable powder (WP) formulations to more advanced options like water-dispersible granules (WG) and emulsions in water (EW). Suspension concentrates (SCs) have also gained popularity due to their environmental benefits, being water-based, easy to apply, and dispersing quickly when diluted in water[10] . These advancements reflect the industry's commitment to creating safer, more efficient, and environmentally friendly pest control solutions [11].

In light of these developments, it is crucial to explore the classification and formulation of biopesticides to better understand their role in pest management and their potential to replace hazardous chemical pesticides.

Newer Trends in Formulations An extensive work is being carried out worldwide, for developing new formulation technologies which would serve the objectives of easier application, labour saving, improved safety, reduced toxicity, minimization of environmental pollution, higher efficacy and reduced cost. The areas of development include **Nano pesticide, Controlled Release Formulation**, microemulsions, microgranules, water dispersible granules, concentrated emulsions, controlled release, gels, and tablets etc[12].

Nano pesticide

Nanotechnology is rapidly emerging as a promising tool in agriculture, offering innovative solutions to enhance the effectiveness of biopesticides and reduce their environmental impact. Nanoscale particles, measuring between 1 and 100 nanometers, exhibit unique properties that differ from larger particles of the same material, making them particularly effective in various applications, including plant protection [13]. Nano pesticides utilize these tiny particles to improve the delivery and efficacy of pesticides while mitigating their harmful effects on the environment (Table -1). By enabling the slow release of active ingredients, nano pesticides contribute to safer and more sustainable pest management [14].

Several types of nano delivery systems have been developed for use in agriculture, including nanoemulsions, nanoencapsulates, nanocontainers, and nanocages, each offering different mechanisms for controlled release and targeted delivery [15]. These nano-based systems have been applied to various biopesticides such as nucleopolyhedrovirus (NPV), *Bacillus thuringiensis* (Bt), and entomopathogenic fungi (EPF), which are known for their environmentally friendly and target-specific pest control properties [16]. The integration of nanotechnology with these biopesticides enhances their performance and longevity, contributing to the development of sustainable pest management strategies. There are two main ways to create nanoparticles: the top-down method, which uses physical methods like laser ablation to break down larger materials into nanoparticles, and the bottom-up method, which uses chemical processes like chemical reduction to assemble nanoparticles from atoms and molecules.[17]. Although physical and chemical methods are commonly used for nanoparticle production, they often require complex and expensive processes. In contrast, biological methods, which utilize organisms such as fungi, bacteria, or plants to produce nanoparticles, offer a cost-effective and environmentally friendly alternative[18].

The application of nanotechnology in biopesticides has shown promise in improving the stability, delivery, and efficacy of these natural pest control agents. For instance, nanoparticles can protect NPV, a virus that targets insect larvae, thereby extending its shelf life and enhancing its insecticidal activity. Similarly, the effectiveness of Bt, which produces insecticidal toxins, and EPF, fungi that parasitize insects, can be significantly improved with nano-based formulations[19]. These nano pesticides offer controlled release, better penetration, and precise targeting of pests, reducing the need for conventional chemical pesticides and promoting more sustainable agricultural practices [20].

The advantages of nanomaterial-based formulations are primarily due to their increased surface area, smaller particle size, and enhanced mobility, which result in improved efficacy. Additionally, the use of nanoparticles eliminates the need for harmful organic solvents typically used in conventional pesticide formulations, thereby reducing unwanted toxicity [21]. Nanoscale particles, defined as ultrafine particles with dimensions ranging from 1 to 100 nanometers, develop unique properties at this critical length scale, setting them apart from bulk materials of the same composition [22]. These particles can be engineered using both top-down and bottom-up approaches, as well as naturally occurring processes[23].

Controlled Release Formulation (CRF) technologies for insect biopesticides represent a major innovation in pest control, allowing for the precise and sustained delivery of active biological agents to control insect populations[24,25,26]. These technologies are especially beneficial for biopesticides based on living organisms like bacteria, fungi, viruses, and naturally occurring substances that target specific insect pests[27].

Types of Control Release Formulations

Encapsulanon

Formulated matrices offer organisms some protection from environmental conditions, and the distinct skin around capsules offers more, as well as greater, opportunities of improving suspendability in water (Table -1). [28] made two types of capsule: (1) by stirring a mixture of *B. thuringiensis* ssp. *israelensis* and dried yeast or yeast extract in a solution of low density polyethylene in cyclohexane, and (2) by stirring the bacteria into a slowly cooling, fine emulsion of a fatty acid (decanoic, palmitic or stearic). The capsules were filtered and dried. Both types increased the flotation coefficient and improved the insecticidal activity against *Culex* and *Aedes* larvae in glass containers with mud on the bottom[29].

The increasing demand for microbial BCAs due to their eco-friendly nature and the need for novel formulation methods, particularly bioencapsulation, to enhance their effectiveness. Encapsulation offers numerous advantages, such as extended shelf life, improved handling, reduced doses, and targeted delivery of microbial BCAs[30]. The article categorizes encapsulation methods based on droplet formation techniques, such as dripping and emulsification, and discusses the role of gelation and membrane formation in solidifying the droplets into particles[31,32]. Encapsulation within a matrix protects microbial BCAs from various environmental stressors like temperature, UV light, and mechanical stress, ultimately leading to increased persistence and efficiency in pest control applications[33]. The potential for co-encapsulation of multiple active ingredients, such as semiochemicals and chemical pesticides, to enhance the performance of microbial BCAs[34,35].

Hydrogels:

Hydrogels are water-absorbing polymers that can hold and slowly release biopesticides. These materials provide moisture to the biopesticides, maintaining their viability and activity, especially in dry environments[36]. Hydrogels are often used with entomopathogenic fungi, which require specific moisture conditions to infect and kill insect pests. The controlled release ensures that the fungi remain active over a prolonged period (Table -1).

Polymer-Coated Granules:

Polymer-coated granules are another form of controlled release where biopesticides are coated with a polymer layer that slowly degrades, releasing the active ingredients over time. This method is used with various insect biopesticides, including microbial agents, to provide a steady release into the soil or onto plant surfaces, where pests are present[37].

Emulsion-Based CRF:

Emulsions involve suspending biopesticides in oil-in-water or water-in-oil systems that slowly release the active ingredients. These formulations help protect the biopesticides from environmental degradation while allowing a controlled and sustained release. Bt, NPV, and EPF can all be formulated as emulsions, helping to extend their effectiveness against target insect pests over time[38].

Tablets

Biopesticide tablets are eco-friendly pest control solutions that contain natural agents like *Bacillus thuringiensis* (Bt), nucleopolyhedroviruses (NPV), or entomopathogenic fungi. These tablets are designed for long-term control of specific pests by slowly releasing active ingredients, reducing the need for chemical pesticides and minimizing preparation time[39,40]. Tailored to suit the target pest's feeding habits, the tablets can be made to float, suspend, or sink, with release rates ranging from rapid to slow. For example, rapid-release effervescent tablets can float on water surfaces, dispersing active ingredients effectively to control insect populations in small water bodies [41,42]. The addition of gustatory stimulants can enhance their effectiveness by encouraging insect feeding. Preformed solids of uniform shape and dimensions, usually circular, with either flat or convex faces, the distance between faces being less than the diameter" is the definition of biopesticide tablets (Table -1). These tablets are composed of adjuvants and active ingredients (AIs) that have been optimized and compacted into a solid mass with a uniform size and shape[43].

Microemulsions (ME): Microemulsions are transparent dispersions of two immiscible liquids that exhibit thermodynamic stability and are stable throughout a broad temperature range [44]. Their droplet size is minuscule, measuring less than 0.05 microns, or 50 nanometers. Compared to a standard o/w emulsion, which has a surfactant concentration of around 5%, a microemulsion can have a total surfactant concentration of as much as 10–30% or more (Table -1). Despite the comparatively modest quantities of active ingredients in microemulsions, the high surfactant content and solubilization of the active ingredient may result in increased biological activity.

Water-dispersible granules

Water-dispersible granules (WDGs), also called dry flowables, are a newer type of pesticide formulation[45,46,]. They are becoming more popular as safer and more convenient alternatives to wettable powders and suspension concentrates. WDGs are non-dusty, easy-to-handle granules that quickly disperse when mixed with water in a spray tank[47]. They combine the ease of use found in liquid formulations with the safety and stability benefits of dry formulations. Additionally, WDGs minimize packaging waste, making them environmentally friendly[48].

WDGs can also include biological agents like bacteria, fungi, or viruses that target specific pests, such as insects. These granules protect the biological agents during storage and transport while ensuring they work effectively once applied[49]. Due to these advantages, WDGs are increasingly used in integrated pest management (IPM) and sustainable agriculture.

For example, WDG formulations like VectoLex® (containing *Bacillus sphaericus*) and VectoBac® (containing *Bacillus thuringiensis israelensis*) are used to control mosquito

larvae. Similarly, formulations like Dipel WG and Xentari WG, containing *Btkurstaki*, are used to manage caterpillar pests (Table -1) [50,51].

Table 1. Formulations of Biopesticides and Their Target Insect Pests

Sl .no	Formulation	Biopesticide	Target Insect Pest	References
1	ZnO NPs	<i>B. thuringiensis</i>	<i>Callosobruchus maculatus</i> (F)	[52]
2	Au NPs	<i>B. thuringiensis</i>	<i>Aedes aegypti</i> (Linnaeus) and <i>Anopheles subpictus</i> Grassi	[53]
3	Chitosan Nanoparticles	<i>Metarhizium anisopliae</i> (Metchnikoff) Sorokin	<i>Plutellaxylostella</i> (Linnaeus)	[54]
4	Titanium Dioxide Nanoparticle	<i>Trichoderma Viride</i> Pers	<i>Helicoverpa Armigera</i> (Hub.)	[55]
5	Ag	<i>Penecillium verucosum</i> Dierckx	<i>Culex quinquefasciatus</i> Say	[56]
6	Nanosilver	<i>Beauveria bassiana</i> (Balsamo-Crivelli) Vuillemin	Aedes larvae	[57]
7	Iron nanoparticles	<i>Isaria fumosorosea</i> Wize	<i>Bemisiatabaci</i> (Gennadius)	[58]
8	Zinc nanoparticles	<i>B. bassiana</i>	<i>Trialeurodes vaporariorum</i> Westwood	[59]
9	Microcapsules	<i>B. thuringiensis</i>	<i>Trichoplusiani</i> (Hubner)	[60]
10	Microcapsules	<i>B. thuringiensis</i> sorovar. <i>israelensis</i>	<i>A. aegypti</i>	[61]
11	CMC-encapsulated	<i>B. thuringiensis</i> sorovar. <i>israelensis</i>	<i>A. aegypti</i>	[62]
12	Sodium alginate, (HPMC) and chitosan	<i>M. anisopliae</i>	Aphids	[63]
13	Selffloating slow release	<i>B. thuringiensis</i> var. <i>israelensis</i>	<i>C. quinquefasciatus</i>	[64]
14	Screen bag formulation granules	<i>Beauveria</i> and <i>Metarhizium</i>	<i>Riptortus pedestris</i> (Fabricius)	[65]
15	Gelatin (GE) and gum arabic (GA)	<i>M. anisopliae</i>	<i>Solenopsis Invicta</i> (Buren)	[66]
16	Alginate	<i>B. bassiana</i>	<i>Triatoma infestans</i> (Klug)	[67]
17	Spray drying	<i>B. thuringiensis</i>	<i>Spodoptera exigua</i> (Hübner)	[68]

	Vectobac® DT	<i>B. thuringiensis var israeliensis</i>	Mosquitos	[69]
	Invert emulsion	<i>M. anisopliae</i>	<i>Sitophilus oryzae</i> (Linnaeus,) and <i>Rhizophorthadominica</i> (Fabricius)	[70]
	Oil-Emulsion	<i>M. anisopliae</i>	<i>Rhynchophorusferrugineus</i> (Olivier)	[71]
	Oil-Emulsion	<i>B.bassiana</i> and <i>M. anisopliae</i>	<i>Diatraeasaccharalis</i> (Fabricius)	[72]
	Inverted emulsion	<i>B.bassiana</i>	<i>Aedes albopictus</i> (Skuse) and <i>Culex pipiens</i> (Linnaeus)	[73]
	Water dispersible granule DuPel	<i>B. thuringiensis kurstaki</i>	Caterpillar pests on vegetables, fruits	[74]
	Water-dispersible powder	<i>B.popilliae</i>	Japanese beetle grubs	[75]
	Water-dispersible granule (WG)	<i>B.bassiana</i>	<i>Hypothenemushampeii</i> (Ferrari)	[76]
	Capsule formulation of	<i>B.bassiana</i>	<i>Odoiporuslongicollis</i> (Olivier)	[77]
	Hydrogel	<i>M. rileyi</i>	<i>Spodoptera litura</i> (Fab.)	[78]
	Encapsulation	<i>M. anisopliae</i>	<i>Rhipicephalus microplus</i> (Canestrini)	[79]
	Encapsulation	<i>B. bassiana</i>	<i>Spodoptera cosmioides</i> (Walker)	[80]
	Hydrogel	<i>B. bassiana</i>	<i>Leptinotarsa decemlineata</i> Say	[81]
	Microemulsion	<i>M. anisopliae</i>	<i>Rhynchophorusferrugineus</i> Olivier	[82]
	Nanoemulsion	<i>M. anisopliae</i>	<i>R.ferrugineus</i>	[83]
	Micro-encapsulated	<i>S.littoralisnucleopolyhedrovirus (SpliNPV)</i>	<i>Spodopteralittoralis</i> (Boisduval)	[84]
	Tablet	<i>B. thuringiensis</i>	<i>A. aegypti</i>	[85]
	Oil-Emulsion	<i>M. anisopliae</i>	<i>R.ferrugineus</i>	[86]

Advantages:

Environmental Safety: Biopesticides are less harmful to the environment as they are biodegradable and target specific pests, reducing collateral damage to beneficial organisms.

Reduced Chemical Use: The use of biopesticides can decrease reliance on synthetic chemical pesticides, minimizing pesticide residues in soil, water, and food.

Target Specificity: Many biopesticides are highly specific, targeting particular pests without affecting non-target species such as beneficial insects or mammals.

Nanotechnology Benefits: Nano pesticides improve the delivery, stability, and controlled release of active ingredients, reducing environmental impact and enhancing efficacy.

Improved Formulations: Advances such as water-dispersible granules, hydrogels, and polymer-coated granules ensure easier application, better pest targeting, and extended efficacy in the field.

Disadvantages:

Cost: Biopesticides, especially those utilizing advanced technologies like nanotechnology and controlled release formulations, can be more expensive than traditional pesticides.

Short Shelf Life: Some biopesticides have shorter shelf lives compared to chemical pesticides, making storage and distribution more challenging.

Limited Pest Range: Biopesticides are often highly specific, which can limit their application to only certain pests, requiring the use of multiple products to cover a broader range of pests.

Environmental Sensitivity: Biopesticides, especially those based on living organisms, may be sensitive to environmental conditions such as temperature and humidity, which can affect their efficacy.

Regulatory Hurdles: Biopesticides must undergo stringent regulatory approval processes, which can delay their entry into the market.

Conclusion:

Biopesticides represent a sustainable and environmentally friendly alternative to synthetic chemical pesticides, offering targeted pest control with minimal ecological impact. Recent innovations in formulation technologies, such as nano pesticides, controlled release systems, and advanced granules, have significantly improved the effectiveness and practicality of biopesticides in modern agriculture. However, challenges such as higher costs, shorter shelf lives, and regulatory barriers need to be addressed to ensure broader adoption.

Future Prospects:

The future of biopesticides lies in the continued advancement of formulation technologies, particularly in the areas of nanotechnology and controlled release systems. Research efforts should focus on improving the stability, cost-effectiveness, and scalability of these products, as well as expanding their applicability to a wider range of pests. Additionally, regulatory frameworks must evolve to facilitate the approval and commercialization of biopesticides, ensuring they can compete with traditional chemical pesticides in the market. With increasing global demand for organic and sustainable agricultural products, biopesticides are poised to play a pivotal role in the future of pest management.

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