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

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Review Article

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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

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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.

Keywords: 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].

The formulation of biological agents used for pest control, such as insect-pathogenic bacteria, fungi, viruses, and entomophilic nematodes, is highly dependent on both the biological characteristics of the organisms and the environments in which they are applied [7]. A key factor in determining the formulation requirements is the mode of action of the organisms [8]. For example, insect-pathogenic bacteria and viruses often act through ingestion by the pest, while fungi and nematodes may rely on direct contact or mobility to find and infect their targets [9]. Formulators must consider how to encourage pests to ingest these agents or facilitate contact between the organism and the pest's external surfaces [10]. Additionally, for mobile organisms like entomophilic nematodes, the preservation of their search behavior is crucial for effective pest control [11]. The formulation must also provide a suitable environment for the organisms to proliferate once they are in their new surroundings. Different environments, such as foliage, soil, water, or food storage commodities, present unique challenges. Therefore, the formulator must tailor the biological agents' formulations to ensure they are effective in the specific conditions and for the specific purposes for which they are intended [10,12].

Formulation technology plays a critical role throughout the entire lifecycle of biological control agents, from their production to their eventual action on the target [13]. The method of production often influences formulation activities, which may necessitate adjustments in the production process [14]. The organisms involved, as detailed in Table 1. require formulation to fulfill four essential functions: stabilizing the organism during production, distribution, and storage; facilitating handling and application so the product can be effectively delivered to the target in the appropriate form; protecting the agent from harmful environmental conditions at the target site to enhance persistence; and enhancing the organism's activity at the target site by promoting its reproduction, contact, and interaction with the pest or disease organism Table 2 [15].

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 [16,17]. 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 [18].

Table 1. Main types of formulated organism and environments to which they are applied

Organism	Distributed life stage	Mode of action	Main environment
Spore-forming bacterial insecticide	Crystal toxin, durable spore	Stomach poison, infection	Plant surfaces, water, soil
Protozoan insecticide	Durable spore	Infects via gut	Plant surfaces
Insect viruses	Durable inclusion body	Infects via gut	Plant surfaces
Mycoinsecticide	Relatively delicate ordurable spore	Infects on contact	Soil, plant surfaces, water, insect cuticle
Entomophilic nematodes	Infective stage (and associated bacteria) delicate	Infects after search	Soil, water

Table 2. Problems faced by a formulator [10]

Stage	Function
Harvest	Reduction of material bulk. Division into particles able to pass spray nozzles
Stabilization	Prevent growth of agent and contaminant microorganisms. Prevent proteases denaturing active agent
Storage	Avoid powders caking due to moisture uptake. Control viscosity of liquids to keep particles in suspension without aggregation so that they flow. Retain viability
Application	Ensure good performance in applicators for dusts/powders/granules. Maintain appropriate viscosity of liquids to form spray droplets. Ensure good performance of sprayers without making foam
Post-application	Ensure good coverage of target and good product retention. Reduce physical loss by rain or other means. Protect agents from inactivating factors, e.g. sun. Ensure deposit is palatable and preferably attractive to target pest

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 [19]. These advancements reflect the industry's commitment to creating safer, more efficient, and environmentally friendly pest control solutions [20]. 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 [21].

2. NANO BIOPESTICIDE

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 [22]. Nano pesticides utilize these tiny particles to improve the delivery and efficacy of pesticides while mitigating their harmful effects on the environment (Table 3). By enabling the slow release of active ingredients, nano pesticides contribute to safer and more sustainable pest management [23].

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 [24]. 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 [25]. 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 [26]. 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 [27].

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 [28]. 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 [29].

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 [30]. 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 [31]. These particles can be engineered using both top-down and bottom-up approaches, as well as naturally occurring processes [32].

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 [33,34,35]. These technologies are especially beneficial for biopesticides based on living organisms like bacteria, fungi, viruses, and naturally occurring substances that target specific insect pests [36].

3. TYPES OF CONTROL RELEASE FORMULATIONS

3.1 Encapsulanon

Microcapsules, containing organisms, are typically made from encapsulating materials such as gelatin, starch, cellulose, and various polymers. These capsules offer effective protection against environmental factors like sunlight and leaf-surface chemicals. Dyes can be incorporated into the capsule walls to enhance UV protection, while stickers and wetters can be adsorbed to their surfaces to improve retention on the target [37].

Depending on the encapsulating material, the capsule wall can be broken to release the organisms through crushing, pressure, dissolution, or hydrolysis—though diffusion is not used. Fine products made by spray-drying can be sprayed in any volume, as the protective matrix holds the pathogen close to additives like sunscreens, ensuring optimal positioning and minimizing waste [38].

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). [39] 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 [40].

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 [41]. 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 [41,42]. 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 [43]. the potential for co-encapsulation of multiple active ingredients, such as semiochemicals and chemical pesticides, to enhance the performance of microbial BCAs [44,45].

3.2 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 [46]. 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 3).

3.3 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 [47].

3.4 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 [48].

4. 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 [49,50]. 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 [51,52]. 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 3). 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 [53].

Microemulsions (ME): Microemulsions are transparent dispersions of two immiscible liquids that exhibit thermodynamic stability and are stable throughout a broad temperature range [54]. 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.

5. WATER-DISPERSIBLE GRANULES

Mixing problems in pest control formulations can often be resolved by dry blending a powder with a binder to create water-dispersible granules [55]. These granules break surface tension more easily than powders, allowing for higher concentrations of organisms while flowing freely with minimal dust [56]. They can be accurately measured by volume, similar to liquids. However, despite their advantages, such as ease of measurement and effectiveness, production costs for water-dispersible granules are high, and additional agitation may be required for dispersion in cold water within spray tanks [57]. Achieving small particle sizes can also be challenging. Despite these challenges, water-dispersible granules are gaining popularity, with a new range of 'Altox' wetting and dispersing agents developed for their use [58].

When mixed with water to form a spray, these granules dissolve solutes such as enzymes, bacterial nutrients, and additives like surfactants and sugars, which can stimulate the germination of some microbes [59]. However, care must be taken not to allow the spray to stand for too long, as deterioration may occur within 1-2 days, especially in the presence of surfactants that may harm the organisms. The rapid settling of particles in these products can be mitigated by using tanks with agitators or by minimizing particle size and adding thickeners to increase the viscosity of the spray tank mix. During storage, Bacillus thuringiensis and baculoviruses offer the advantage of being among the most stable biocontrol agents, with shelf lives for water-dispersible granules—provided they have satisfactory moisture content—exceeding 18 months, which is essential for successful commercialization [10].

Water-dispersible granules (WDGs), also called dry flowables, are a newer type of pesticide formulation [60,61]. 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 [62]. 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 [63].

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 [64]. 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 *Bt kurstaki*, are used to manage caterpillar pests (Table 1) [65,64].

Table 3. Formulations of biopesticides and their target insect pests

Sl .no	Formulation	Biopesticide	Target Insect Pest	References
1.	ZnO NPs	*B. thuringiensis*	*Callosobruchus maculatus* (F)	[66]
2.	Au NPs	*B. thuringiensis*	*Aedes aegypti* (Linnaeus) and *Anopheles subpictus* Grassi	[67]
3.	Chitosan Nanoparticles	*Metarhizium anisopliae* (Metchnikoff) Sorokin	*Plutella xylostella* (Linnaeus)	[68]
4.	Titanium Dioxide Nanoparticle	*Trichoderma Viride* Pers	*Helicoverpa Armigera* (Hub.)	[69]
5.	Ag	*Penecillium verucosum Dierckx*	*Culex quinquefasciatus* Say	[70]
6.	Nanosilver	*Beauveria bassiana (Balsamo-Crivelli) Vuillemin*	Aedes larvae	[71]
7.	Iron nanoparticles	*Isaria fumosorosea Wize*	*Bemisia tabaci* (Gennadius)	[72]
8.	Zinc nanoparticles	*B. bassiana*	*Trialeurodes vaporariorum* Westwood	[73]
9.	Microcapsules	*B. thurigiensis*	*Trichoplusia ni* (Hubner)	[74]
10.	Microcapsules	*B.thuringiensis sorovar. israelensis*	*A. aegypti*	[75]
11.	CMC-encapsulated	*B.thuringiensis sorovar. israelensis*	*A. aegypti*	[76]
12.	Sodium alginate, (HPMC)and chitosan	*M. anisopliae*	Aphids	[77]
13.	Self floating slow release	*B. thuringiensis var. israelensis*	*C. quinquefasiatus*	[78]
14.	Screen bag formulation granules	*Beauveria and Metarhizium*	*Riptortus pedestris* (Fabricius)	[79]
15.	Gelatin (GE) and gum arabic (GA)	*M. anisopliae*	*Solenopsis Invicta* (Buren)	[80]
16.	Alginate	*B. bassiana*	*Triatoma infestans* (Klug)	[81]
17.	Spray drying	*B. thuringiensis*	*Spodoptera exigua* (Hübner)	[82]
18.	Vectobac® DT	*B. thuringiensis var israeliensis*	Mosquitos	[83]
19.	Invert emulsion	*M. anisopliae*	*Sitophilus oryzae* (Linnaeus,) and *Rhyzopertha dominica* (Fabricius)	[84]
20.	Oil-Emulsion	*M. anisopliae*	*Rhynchophorus ferrugineus* (Olivier)	[85]
21.	Oil-Emulsion	*B. bassiana* and *M. anisopliae*	*Diatraea saccharalis* (Fabricius)	[86]
22.	Inverted emulsion	*B. bassiana*	*Aedes albopictus* (Skuse) and *Culex pipiens*(Linnaeus)	[87]
23.	Water dispersible granule DuPel	*B. thuringiensis kurstaki*	Caterpillar pests on vegetables, fruits	[88]
24.	Water-dispersible powder	*B. popilliae*	Japanese beetle grubs	[89]
25.	Water-dispersible granule (WG)	*B. bassiana*	*Hypothenemus hampei* (Ferrari)	[90]
26.	Capsule formulation of	*B. bassiana*	*Odoiporus longicollis* (Olivier)	[91]
27.	Hydrogel	*M. rileyi*	*Spodoptera litura* (Fab.)	[92]

Sl .no	Formulation	Biopesticide	Target Insect Pest	References
28.	Encapsulation	*M. anisopliae*	*Rhipicephalus microplus* (Canestrini)	[93]
29.	Encapsulation	*B. bassiana*	*Spodoptera cosmioides*(Walker)	[94]
30.	Hydrogel	*B. bassiana*	*Leptinotarsa decemlineata* Say	[95]
31.	Microemulsion	*M. anisopliae*	*Rhynchophorus ferrugineus* Olivier	[96]
32.	Nanoemulsion	*M. anisopliae*	*R. ferrugineus*	[97]
33.	Micro-encapsulated	*S.littoralis nucleopolyhedrovirus (SpliNPV)*	*Spodoptera littoralis* (Boisduval)	[98]
34.	Tablet	*B. thuringiensis*	*A. aegypti*	[99]
35.	Oil-Emulsion	*M. anisopliae*	*R. ferrugineus*	[100]

6. 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.

7. DISADVANTAGES

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

8. 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.

9. 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.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Angon PB, Mondal S, Jahan I, Datto M, Antu UB, Ayshi FJ, Islam MS. 2023. Integrated pest management (IPM) in agriculture and its role in maintaining ecological balance and biodiversity. Advances in Agriculture. 2023;(1): 5546373.
2. Nicholson GM. Fighting the global pest problem: Preface to the special toxicon issue on insecticidal toxins and their potential for insect pest control. Toxicon. 2007;49:413-422.

3. Tudi M, Daniel Ruan H, Wang L, Lyu J, Sadler R, Connell D, Phung DT. Agriculture development, pesticide application and its impact on the environment. International Journal of Environmental Research and Public Health. 2021;18(3):1112.
4. Al-Zaidi AA, Elhag EA, Al-Otaibi SH, Baig MB. Negative effects of pesticides on the environment and the farmers awareness in Saudi Arabia: a case study. Journal of Animal Plant Science. 2011;21:605-611.
5. Omer AM. Energy, environment and sustainable development. Renewable and Sustainable Energy Reviews. 2008;12(9): 2265-2300.
6. Daraban GM, Hlihor RM, Suteu D. Pesticides vs. biopesticides: From pest management to toxicity and impacts on the environment and human health. Toxics. 2023;11(12):983.
7. Kumar KK, Sridhar J, Murali-Baskaran RK, Senthil-Nathan S, Kaushal P, Dara SK, Arthurs S. Microbial biopesticides for insect pest management in India: Current status and future prospects. Journal of Invertebrate Pathology. 2019;165:74-81.
8. Rojas-Sánchez B, Guzmán-Guzmán P, Morales-Cedeño LR, Orozco-Mosqueda MDC, Saucedo-Martínez BC, Sánchez-Yáñez JM, Santoyo G. Bioencapsulation of microbial inoculants: Mechanisms, formulation types and application techniques. Applied Biosciences. 2022; 1(2):198-220.
9. Shah ST, Basit A, Sajid M, Mohamed HI. Microorganism: A potent biological tool to combat insects and herbivores. Plant Growth-promoting Microbes for Sustainable Biotic and abiotic stress management. 2021;505-555.
10. Burges HD. Formulation of mycoinsecticides. In Formulation of microbial biopesticides: Beneficial microorganisms, nematodes and seed treatments. Dordrecht: Springer Netherlands. 1998;131-185.
11. Vashisth S, Chandel YS, Sharma PK. Entomopathogenic nematodes-A review. Agricultural Reviews. 2013.34(3):163-175.
12. Leggett M, Leland J, Kellar K, Epp B. Formulation of microbial biocontrol agents–an industrial perspective. Canadian Journal of Plant Pathology. 2011;33(2): 101-107.
13. Angus TA, Luthy P. Formulation of microbial insecticides, in Microbial Control of Insects and Mites (eds H. D. Burges and N. W. Hussey), Academic Press, London. 1971;623-38.
14. Date RA. Microbiological problems in the inoculation and nodulation of legumes. Plant and Soil. 1970;32:703-25.
15. Couch TL, Ignoffo CM. Formulation of insect pathogens, in microbial control of pests and plant Diseases 1970-1980 (ed. H. D. Burges), Academic Press, London. 1981;621-34.
16. Kumar J, Ramlal A, Mallick D, Mishra V. An overview of some biopesticides and their importance in plant protection for commercial acceptance. Plants. 2021; 10(6):1185.
17. Archana, H. R, Darshan, K, Lakshmi, M. A, Ghoshal, T, Bashayal, B. M, Aggarwal, R. Biopesticides: A key player in agro-environmental sustainability. In Trends of Applied Microbiology for Sustainable Economy. Academic Press. 2022;613-653.
18. Damalas CA, Eleftherohorinos IG. Pesticide exposure, safety issues, and risk assessment indicators. International Journal of Environmental Research and Public Health. 2011;8(5):1402-1419.
19. Mathur SC. Future of Indian pesticide industry in next millennium. Pestcide Information. 1999;24(4):9-23.
20. Smith K, Evans DA, El-Hiti, GA. Role of modern chemistry in sustainable arable crop protection. Philosophical Transactions of the Royal Society B. 2008;363:623-637.
21. Hazra DK, Purkait A. Role of pesticide formulations for sustainable crop protection and environment management: A review. Journal of Pharmacognosy and Phytochemistry. 2019;8(2):686-693.
22. Auffan M, Rose J, Bottero JY, Lowry GV, Jolivet JP, Wiesner, MR. Towards a definition of inorganic nanoparticles from an environmental, health and safety perspective. Nature Nanotechnology. 2009;4(10):634-641.
23. Yousef HA, Fahmy HM, Arafa FN, Abd Allah MY, Tawfik YM, El Halwany KK, Bassily ME. Nanotechnology in pest management: Advantages, applications, and challenges. International Journal of Tropical Insect Science. 2023;43(5):1387-1399.
24. Frey PM. Biocontrol agents in the age of molecular biology. Trends in Biotechnology. 2001;19(11):432-433.
25. Ndolo D, Njuguna E, Adetunji CO, Harbor C, Rowe A, Den Breeyen A, Hospet R.

Research and development of biopesticides: Challenges and prospects. Outlooks on Pest Management. 2019; 30(6):267-276.
26. Balachandran A, Sreenilayam SP, Madanan K, Thomas S, Brabazon D. Nanoparticle production via laser ablation synthesis in solution method and printed electronic application-A brief review. Results in Engineering. 2022;16:100646.
27. Bihal R, Al-Khayri JM, Banu AN, Kudesia N, Ahmed FK, Sarkar R, Abd-Elsalam K A. Entomopathogenic fungi: An eco-friendly synthesis of sustainable nanoparticles and their nanopesticide properties. Microorganisms. 2023;11(6):1617.
28. Chaud M, Souto EB, Zielinska A, Severino P, Batain F, Oliveira-Junior J, Alves T. Nanopesticides in agriculture: Benefits and challenge in agricultural productivity, toxicological risks to human health and environment. Toxics. 2021;9(6):131.
29. Tang Y, Zhao W, Zhu G, Tan Z, Huang L, Zhang P, Rui Y. Nano-pesticides and fertilizers: solutions for global food security. Nanomaterials. 2023;14(1):90.
30. Sasson Y, Levy-Ruso G, Toledano O, Ishaaya I. Nanosuspensions: Emerging novel agrochemical formulations. In Insecticides design using advanced technologies. Springer, Berlin, Heidelberg. 2007;1-39.
31. Auffan M, Rose J, Bottero JY, Lowry GV, Jolivet JP, Wiesner, MR. Towards a definition of inorganic nanoparticles from an environmental, health and safety perspective. Nature Nanotechnology. 2009;4(10):634-641.
32. Mekuye B, Abera B. Nanomaterials: An overview of synthesis, classification, characterization, and applications. Nano Select. 2023;4(8):486-501.
33. Kydonieus AF. (Ed.). Controlled release technologies: Methods, theory, and applications. Boca Raton, FL: CRC Press. 1980;1:13.
34. Wilkins RM. Biodegradable polymer methods. In controlled delivery of crop protection agents; ed R M Wilkins, Taylor and Francis: Bristol, PA. 1990;149-165.
35. Sugavanam B. UNIDO's activities on pesticides. In Recent Developments in the Field of Pesticides and their Application to Pest Control (eds K. Holly, L.G. Copping and G.T. Brooks), UNIDO, Vienna. 1990;262-71.
36. Rajamani M, Negi A. Biopesticides for pest management. Sustainable bioeconomy: Pathways to Sustainable Development Goals. 2021;239-266.
37. Biondo F, Baldassarre F, Vergaro V, Ciccarella G. Controlled biocide release from smart delivery systems: Materials engineering to tune release rate, biointeractions, and responsiveness. In Nanotechnology-Based Sustainable Alternatives for the Management of Plant Diseases. Elsevier. 2022;31-147.
38. Singh MN, Hemant KSY, Ram M, Shivakumar HG. Microencapsulation: A promising technique for controlled drug delivery. Research in Pharmaceutical Sciences. 2010;5(2):65.
39. Margalit J, Markus A, Pelah Z. Effect of encapsulation on the persistence of *Bacillus thuringiensis* israelensis, serotype H14, a potential mosquito larvicide. Appl. Microbiol. Biotechnolo. 1984;19:382-3.
40. Burges HD. Formulation of microbial biopesticides: Beneficial microorganisms, nematodes and seed treatments. Springer Science & Business Media; 2012.
41. Vemmer M, Patel AV. Review of encapsulation methods suitable for microbial biological control agents. Biological Control. 2013;67(3):380-389.
42. Connick WJ, Jr Formulation of living biological control agents with alginate, in Pesticide Formulations: Innovations and Developments, ACS Symposium Series 371 (eds B. Cross and H. B. Scher), American Chemical Society, Washington, DC. 1988;241-50.
43. McLaughlin RE. Vidrine MF. Point source introduction system for control of *Psorophora columbiae* (Diptera: Culicidae) by Bacillus thuringiensis serotype H-14: results of a large scale operational test. Environmental Entomology. 1984;13:366-70.
44. Szopa D, Mielczarek M, Skrzypczak D, Izydorczyk G, Mikula K, Chojnacka K, Witek-Krowiak A. Encapsulation efficiency and survival of plant growth-promoting microorganisms in an alginate-based matrix–A systematic review and protocol for a practical approach. Industrial Crops and Products. 2022;181:114846.
45. Drummond JN. Water Dispensible Granules-Past, present, and future. In Pesticide Formulation and Adjuvant Technology. CRC Press. 2018;69-92.

46. Georgis R, Dunlop DB. Water dispersible granule: a novel formulation for nematodebased bioinsecticides, in Proceedings of the Brighton Crop Protection Conference - Pests and Diseases, British Crop Protection Council, Farnham. 1994;1:31-6.
47. Bell GA. The structure/physical property relationships of a model water dispersible granule. Pesticide Sci, 1990;29:467-73.
48. Shera PS, Arora R. Recent developments in pesticide formulation technology. Theory and Practice of Integrated Pest Management. 2017;141.
49. Preininger C, Sauer U, Bejarano A, Berninger T. Concepts and applications of foliar spray for microbial inoculants. Applied microbiology and biotechnology. 2018;102:7265-7282.
50. Vemmer M, Patel AV. Review of encapsulation methods suitable for microbial biological control agents. Biological Control. 2013;67(3):380-389.
51. Mulqueen P. Recent advances in agrochemical formulation. Advances in Colloid and Interface Science. 2003;106(1-3):83-107.
52. Thang NH, Chien TB, Cuong DX. Polymer-based hydrogels applied in drug delivery: An overview. Gels. 2023;9(7):523.
53. Roy A, Singh SK, Bajpai J, Bajpai AK. Controlled pesticide release from biodegradable polymers. Central European Journal of Chemistry. 2014;12:453-469.
54. Mulqueen P. Recent advances in agrochemical formulation. Advances in Colloid and Interface Science. 2003;106(1-3):83-107.
55. Irsad Shahid M, Haq E, Mohamed A, Rizvi PQ, Kolanthasamy E. Entomopathogen-based biopesticides: Insights into unraveling their potential in insect pest management. Frontiers in Microbiology. 2023;14:1208237.
56. Parajuli S, Shrestha J, Subedi S, Pandey M. Biopesticides: A sustainable approach for insect pest management: Biopesticides in Sustainable Pest Management; 2022.
57. Most BH, Quinlan RJ. Formulation of biological pesticides, in fundamental and applied aspects of Invertebrate Pathology, Proceedings of the IV International Colloquium on Invertebrate Pathology, Wageningen (eds R. A. Samson, J. M. Vlak and D. Peters), Society for Invertebrate Pathology. 1986;624-7.
58. Skovmand o, Eriksen AG. Field trials of a fizzy tablet with *Bacillus thuringiensis* var. israelensis in forest spring ponds in Denmark. Bull. Soc. Vector Eco. 1993;18: 160-3.
59. Seenivasagan T, Sharma KR, Prakash S. Electroantennogram, flight orientation and oviposition responses of *Anopheles stephensi* and *Aedes aegypti* to a fatty acid ester-propyl octadecanoate. Acta Tropica. 2012;124(1):54-61.
60. Hiromoto, B. U.S. Patent No. 7,297,351. Washington, DC: U.S. Patent and Trademark Office; 2007.
61. Kanehara M, Suzuki M. Readily dispersible insecticide granules, Japanese Patent JP 60 258101, American Cyanamid Company; 1960.
62. Littler C. Herbicidal Pellets, US Patent 2992090, E.!. DuPont et de Nemours and Company; 1958.
63. Johnson JL, Kimmler J. Herbicidal extruded granular compositions, European Patent EP 0623281 AI, American Cyanamid Company; 1993.
64. Bell G. The structure/physical property relationships of a model water dispersible granule. Journal of Pesticide Science. 1990;29:467-73.
65. DeChant P, Devisetty BN. Formulation and delivery of *Bacillus thuringiensis* subspecies israelensis and *Bacillus sphaericus* in combination for broad spectrum activity and management of resistance to biological mosquito larvicides (US Patent No. 7989180 B2). U.S. Patent and Trademark Office; 2011.
66. Su T, Mulla MS. Field evaluation of new water-dispersible granular formulations of *Bacillus thuringiensis* ssp. israelensis and *Bacillus sphaericus* against Culex mosquitoes in microcosms. Journal of the American Mosquito Control Association, 1999.15(3):356–365
67. Vimala Devi PS, Duraimurugan P, Chandrika KSVP, Vineela V. Development of a water dispersible granule (WDG) formulation of *Bacillus thuringiensis* for the management of Spodoptera litura (Fab.):Biocontrol Science and Technology; 2021.
DOI: 10.1080/09583157.2021.1895073
68. Malaikozhundan B, Vaseeharan B, Vijayakumar S, Thangaraj MP. Bacillus thuringiensis coated zinc oxide nanoparticle and its biopesticidal effects on the pulse beetle, *Callosobruchus*

maculatus. Journal of Photochemistry and Photobiology B: Biology. 2017;174:306-314.

69. Patil S, Rajkuberan C, Joseph J. Biogenic nanoparticles as a strong larvicidal agent in integrated pest management. In Biogenic Nanomaterial for Health and Environment. CRC Press. 2024;97-110.
70. Wu J, Du C, Zhang J, Yang B, Cuthbertson AG, Ali S. Synthesis of Metarhizium anisopliae–chitosan nanoparticles and their pathogenicity against *Plutella xylostella* (Linnaeus). Microorganisms. 2021;10(1):1.
71. Chinnaperumal K, Govindasamy B, Paramasivam D, Dilipkumar A, Dhayalan A, Vadivel A, Sengodan K, Pachiappan P. Bio-pesticidal effects of *Trichoderma viride* formulated titanium dioxide nanoparticle and their physiological and biochemical changes on *Helicoverpa armigera* (Hub.). Pestic. Biochem. Physiol. 2018;149:26–36.
72. Kamalakannan S, Gobinath C, Ananth S. Synthesis and characterization of fungus mediated silver nanoparticle for toxicity on filarial vector, Culex quinquefasciatus. Int. J. Pharm. Sci. Rev. Res. 2014;24:124–132.
73. Berdy J. Bioactive microbial metabolites. The Journal of Antibiotics. 2005.58(1):1-26.
74. Khooshe-Bast Z, Sahebzadeh N, Ghaffari-Moghaddam M, Mirshekar A. Insecticidal effects of zinc oxide nanoparticles and *Beauveria bassiana* TS11 on *Trialeurodes vaporariorum* (Westwood, 1856) (Hemiptera: Aleyrodidae). Acta Agric. Slov. 2016;107:299–309.
75. Bashir O, Claverie JP, Lemoyne P, Vincent C. Controlled-release of *Bacillus thurigiensis* formulations encapsulated in light-resistant colloidosomal microcapsules for the management of lepidopteran pests of Brassica crops. Peer J. 2016;4:e2524.
76. Melo-Santos MAVD, Sanches EG, Jesus FJD, Regis L. Evaluation of a new tablet formulation based on Bacillus thuringiensis sorovar. Israelensis for larvicidal control of Aedes aegypti. Memórias do Instituto Oswaldo Cruz. 2001;96:859-860.
77. Cokmus C, Elçin YM. Stability and controlled release properties of carboxymethylcellulose-encapsulated *Bacillus thuringiensis* var. Israelensis. Pesticide Science. 1995;45(4):351-355.
78. Liu CP, Liu SD. Formulation and characterization of the microencapsulated entomopathogenic fungus Metarhizium anisopliae MA126. Journal of Microencapsulation. 2009;26(5):377-384.
79. Prabakaran G, Padmanabhan V, Balaraman K. Development of a self floating slow release formulation of *Bacillus thuringiensis* var. Israelensis and its Larvicidal Activity. 2001.
80. Lee SJ, Kim S, Skinner M, Parker BL, Kim JS. Screen bag formulation of Beauveria and Metarhizium granules to manage *Riptortus pedestris* (Hemiptera: Alydidae). Journal of Asia-Pacific Entomology. 2016;19(3):887-892.
81. Qiu HL, Fox EG, Qin CS, Zhao DY, Yang H, Xu JZ. Microcapsuled entomopathogenic fungus against fire ants, *Solenopsis invicta*. Biological Control. 2019;134:141-149.
82. Baldiviezo LV, Nieva LB, Pedrini N, Cardozo RM. Microencapsulation of a native strain of the entomopathogenic fungus *Beauveria bassiana* and bioinsecticide activity against pyrethroid-resistant *Triatoma infestans* to vector control of Chagas disease in the argentine Gran Chaco region. Tropical Medicine and Infectious Disease. 2023;8(5):245.
83. Eski A, Demirbağ Z, Demir I. Microencapsulation of an indigenous isolate of Bacillus thuringiensis by spray drying. Journal of microencapsulation. 2019.36(1):1-9.
84. Marcombe S, Darriet F, Agnew P, Etienne M, Yp-Tcha MM, Yébakima A, Corbel V. Field efficacy of new larvicide products for control of multi-resistant *Aedes aegypti* populations in Martinique (French West Indies). The American Journal of Tropical Medicine and Hygiene. 2011;84(1):118.
85. Batta YA. Invert emulsion: Method of preparation and application as proper formulation of entomopathogenic fungi. Methods X. 2016;3:119-127.
86. Lei CJ, Ahmad RHIR, Halim NA, Asib N, Zakaria A, Azmi WA. Bioefficacy of an oil-emulsion formulation of entomopathogenic fungus, *Metarhizium anisopliae* against adult Red Palm Weevil, *Rhynchophorus ferrugineus*. Insects. 2023;14(5):482.
87. De Oliveira DGP, Lopes RB, Rezende JM, Delalibera Jr, I. Increased tolerance of *Beauveria bassiana* and *Metarhizium anisopliae* conidia to high temperature provided by oil-based formulations. Journal of Invertebrate Pathology. 2018;151:151-157.

88. Lee JY, Woo RM, Woo SD. Formulation of the entomopathogenic fungus *Beauveria bassiana* JN5R1W1 for the control of mosquito adults and evaluation of its novel applicability. Journal of Asia-Pacific Entomology. 2023;26(2):102056.
89. Valent BioSciences. DiPel®. Available:https://www.valentbiosciences.com/cropprotection/products/dipel/ (Accessed on 12 February 2021).
90. Lopes RB, Faria M. Influence of two formulation types and moisture levels on the storage stability and insecticidal activity of *Beauveria bassiana*. Biocontrol Science and Technology. 2019;29(5):437-450.
91. Remya S, RANI OR. Development of capsule formulation of *Beauveria bassiana* (Balsamo) Vuillemin. Journal of Biological Control. 2020;34(3).
92. Namasivayam SKR, Vidyasankar A. Biocompatible formulation of potential fungal biopesticide *Nomuraea rileyi* (f.) Samson for the improved post treatment persistence and biocontrol potential. Nature Environment and Pollution Technology. 2014;13(4):835.
93. Meirelles LN, Mesquita E, Corrêa TA, Bitencourt RDOB, Oliveira JL, Fraceto LF, Bittencourt VREP. Encapsulation of entomopathogenic fungal conidia: Evaluation of stability and control potential of Rhipicephalus microplus. Ticks and Tick-Borne Diseases. 2023;14(4):102184.
94. Felizatti AP, Manzano RM, Rodrigues IMW, da Silva MFDGF, Fernandes JB, Forim MR. Encapsulation of *B. bassiana* in biopolymers: Improving microbiology of insect pest control. Frontiers in Microbiology. 2021;12:704812.
95. Ropek D, Kulikowski E. Potential of hydrogel application for plant protection. Ecological Chemistry and Engineering. A. 2009;16(9):1191-1198.
96. Lei CJ, Halim NA, Asib N, Zakaria A, Azmi WA. Conidial emulsion formulation and thermal storability of Metarhizium anisopliae against red palm weevil, *Rhynchophorus ferrugineus* Olivier (Coleoptera: Dryophthoridae). Microorganisms. 2022;10(7):1460.
97. Abdulqader AZ, Omar DB, Awang RM, Ahmed AM, Ali Q, Islam Y, Saleem MH. A novel approach of nanoemulsion formulations of *Metarhizium anisopliae* to control *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Dryophthoridae) in Malaysia. In *VII* International Date Palm Conference. 2022;1371:121-138.
98. Wilson K, Grzywacz D, Curcic I, Scoates F, Harper K, Rice A, Dillon A. A novel formulation technology for baculoviruses protects biopesticide from degradation by ultraviolet radiation. Scientific Reports. 2020;10(1):13301.
99. Armengol G, Hernandez J, Velez JG, Orduz S. Long-lasting effects of a *Bacillus thuringiensis* serovar israelensis experimental tablet formulation for *Aedes aegypti* (Diptera: Culicidae) control. Journal of Economic Entomology. 2006; 99(5):1590-1595.
100. Lei CJ, Ahmad RHIR, Halim NA, Asib N, Zakaria A, Azmi WA. Bioefficacy of an oil-emulsion formulation of entomopathogenic fungus, Metarhizium anisopliae against adult Red Palm Weevil, *Rhynchophorus ferrugineus*. Insects. 2023; 14(5):482.

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