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Article

Biopesticides as Eco-friendly Substitutes to Synthetic Pesticides: An Insight of Present Status and Future Prospects with Improved Bio-effectiveness, Self-lives, and Climate Resilience

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Abstract: Synthetic pesticides are well-known not just for their efficiency in pest control, but also for their adverse effects on humans, ecology, and living biome's ecological relationships. Biopesticides are biodegradable, environment-friendly, and non-destructive insecticides that are safe for creatures. They leave no harmful residues in food or feed. Botanical, microbiological, and biochemical biopesticides are the three types of biopesticides. 3,000 tons of biopesticides are produced every year, accounting for around 2.5% of the overall pesticide market. Biopesticides are currently accessible in a variety of forms, including dust, granules, powders, emulsions, suspension concentrates, and so on. The Central Insecticide Board and Registration Committee (CIBRC) in India requires data on chemistry, bioefficacy, toxicity, packaging, and labeling to register biopesticides. Although India has registered 970 biopesticide products, lesser effectiveness, shorter shelf-life, lack of knowledge, and lengthy registration process remain hurdles. New and improved formulation methods might improve biopesticide efficacies, self-lives, and climate resiliency while lowering prices and making them economically competitive with synthetic chemicals. The main types of biopesticides, their benefits and downsides, worldwide and Indian market scenarios, formulations, registration procedures, and current advancements for users and environment-friendly applications and sustainable agriculture are all covered in this review article.

Keywords: Biopesticides, Eco-safe, Registration, Advanced formulations, Climate resilience, Shelf-life

1. Introduction

By 2050, the world population is predicted to exceed nine billion. To fulfill this tremendous food demand, we must produce more food while utilizing less arable land and water per capita [1]. However, the insect results in a nearly 45% reduction in yearly food output. As a result, synthetic pesticides are employed to both lower insect populations and increase agricultural yields including insecticides, fungicides, herbicides, nematicides, rodenticides, and other pesticides [2]. Pesticides are utilized in around 2 million tons over the world, with 47.5% being herbicides, 29.5% being insecticides, 17.5% being fungicides, and 5.5% being other pesticides [3]. Although synthetic pesticides increased productivity, their overuse and indiscriminate use had negative consequences for soil health, water quality, product quality, and developed issues such as toxic residues in food and feed, insect and pest resurgence, secondary pest outbreaks, and genetic variation in crop plants [4]. Alternative pest control approaches have sparked debate in order to address the concerns connected with synthetic pesticide use.

In the era of sustainable food production, biopesticides have arisen as a contemporary tool. Biopesticides are viable alternatives to conventional pesticides, with the potential to reduce insect resistance, soil and water pollution, biodiversity damage, and major public health concerns. Whatever the advantages, the biopesticide businesses' overall issue is to live up to the promises and expectations of end-users, markets, and the general public. The use of biopesticides is subject to many constraints. However, technological hurdles and long-term sustainability are the most pressing concerns that must be addressed right away. Keeping these perspectives in mind, the major emphasis of this study is put on a discussion of several biopesticide categories, commercial formulations, registration procedures, worldwide status, restrictions, and future research possibilities.

2. What are biopesticides?

Biopesticides are pesticides derived from living creatures found in nature, such as plants, animals, and microorganisms (bacteria, viruses, and fungus), and are used in agriculture to keep pests below the threshold level. It protects crops from dangerous infections using non-toxic and environmentally favorable techniques. Biopesticides are also effective in little amounts. They have no residual effects, which is a key worry for consumers these days. Because biopesticides are effective, biodegradable, non-toxic, have several modes of action, and are made from readily available raw materials, their relevance has grown [5]. Botanical, biochemical, and microbiological pesticides are among the subclasses of biopesticides. Plant diseases such as fungus, viruses, bacteria, and nematodes are affected by pesticide-like chemicals found in pesticide-producing plants [6].

3. Advantages of biopesticides

Biopesticides are made in the same way as chemical pesticides are made from biological agents. Biopesticides are now favored over synthetic pesticides since they are less harmful to the environment [7]. The most critical criteria for successful control are a suitable formulation as well as timely spraying. Biopesticides for pest control have previously been created for many crops, and they offer the following benefits.

(1) It is less toxic than synthetic pesticides

(2) Only the target pest and closely related organisms are affected

(3) Sometimes effective in small quantities

(4) Decompose rapidly

(5) Low residues in food and reducing the risk to consumers

(6) Avoiding pollution problems [8].

4. Categories of biopesticides

Biopesticides are compounds that are found in nature or are produced by living organisms. Botanical biopesticides, microbiological biopesticides, and biochemical biopesticides are classed according to the presence of active ingredients [9].

4.1 Botanical biopesticides

Botanical pesticides are made from leaves, barks, flowers, fruits, roots, cloves, seeds, stems, and rhizomes, among other components of plants (Table 1). The chosen plant component is determined by the bioactive chemicals that are studied for their quantity within the relevant plant part [10]. Myrtaceae, Lauraceae, Rutaceae, Lamiaceae, Asteraceae, Apiaceae, Cupressaceae, Poaceae, Zingiberaceae, Piperaceae, Liliaceae, Apocynaceae, Solanaceae, Caesalpinaceae, and Sapotaceae have been employed as sources of bioactive chemicals with anti-pest action [11,12]. Toxicity, repellency, structural change, and growth restriction are mechanisms of action for these insecticides on their target pests [14]. Secondary metabolites with antibacterial, antioxidant, antifungal, and insecticidal characteristics, including alkaloids, tannins, steroids, phenols, flavonoids, terpenes, and resins, are the active constituents of botanical pesticides [11]. Plant extracts have a variety of effects on insects, including repellency, toxicity, oviposition and feeding inhibition, fatal activity, and interference with physiological functions [15]. In the red flour beetle (*Tribolium castaneum*), extracts of garlic (*Allium sativum*) and turmeric (*Curcuma longa*) produce repellence, toxicity, death, and suppression of progeny emergence [16]. Fungal cell walls, cell membranes, and cell organelles are all hazardous to secondary metabolites of botanical pesticides [17]. These compounds also prevent spore germination, mycelia growth, germ tube elongation, and the formation of essential enzymes, DNA, and protein synthesis [18].

Table 1. List of some botanical plants, major active ingredients, and their target pathogens

Name of Plants	Target Pathogen	Major active ingredients	Source
Cinnamon spp	*Staphylococcus aereus, Escherichia coli*	Eugenol, eugenyl acetate	[19]

Allium cepa	*Escherichia coli*	2,2-diphenyl-1picrylhydrazyl	[20]
Centella aciatica	*Listeria monocytogenes*	germacrene A, germecrene B, germacrene D	[21]
Salvia officinalis	*L. monocytogenes, P. aeruginosa and P. mirabilis.*	Camphor, α-thujone	[22]
Lavandula angustifolia	*Micrococcus flavus*	Linalool, linalyl acetate	[22]
Euphorbia Tirucalli	*Staphylococcus spp*	hydroxycinnamic acid.	[23]
Azadirachta indica	*Aspergillus niger, Microsporum. gypseum, Aspergillus flavus*	Azadirachtin, nimonol, epoxyazadiradione	[24]

4.2 Microbial biopesticides

Microorganisms (bacteria, viruses, fungi, protozoans, and algae) are used as active ingredients in microbial pesticides. In the field, this class of biopesticides can effectively reduce populations of harmful insect pests, plant pathogens, and weeds (Table 2). Microbial pesticides have active components that are particular to their target pests. They are broad-spectrum and control a variety of pests. Microbial insecticides work by producing toxins that are unique to the bugs that are causing the illness to be controlled [25]. Entomopathogenic microorganisms enter the insect body through the cuticle, multiply quickly in the host intestine, and kill the host.

Table 2. List of several significant microbial pesticides and their target insect pests

Name	Target Insect	Source
	Entomopathogenic bacteria	
Lecanicillium longisporum	Hemitera	[26]
Paenibacillus popilliae	Japanese beetle (*Popillia japonica*)	[27]
	Entomopathogenic virus	
Corn earworm NPV (Heze SNPV)	Corn earworm (*Helicoverpa zea*), tobacco budworm (*Helioth virescens*)	[28]
Alfalfa looper NPV(AucaMNPV) Noctuidae	Noctuidae	[29]
	Entomopathogenic fungi	

Nomuraea rileyi	Lepidoptera	[30]
Lecanicillium longisporum	Hemiptera	[31]
	Entomopathogenic Nematodes	
Heterorhabdits species	Lucerne weevil (*Hypera postica*)	[32]
Steinernema carpocapse	Cutworm (*Agrotis ipsilon*)	[33]

Pathogenesis is caused by insecticidal poisons generated by microbial pathogens. Peptides were discovered to be microbial poisons [34]. The chemical structure, toxicity, and specificity of these peptides vary widely. The most common insect pathogenic bacteria used as a microbial biopesticide is *Bacillus thuringiensis* (Bt). During the development of bacterial spores in the insect midgut, it produces -endotoxin. This chemical can cause gut cell lysis when consumed by sensitive insects [35]. Bioproducts based on entomopathogenic baculoviruses and fungi are examples of microbial pesticides. Baculoviruses infect insects and arthropods and are host-specific and selective. Nucleopolyhedron viruses (NPV) and Granuloviruses are the two types of viruses (GV). There are around 13 NPV that are registered virus-containing biopesticides worldwide [36]. In the horticulture business, there are over 170 entomopathogenic fungi-based biopesticide treatments that have been developed for use against at least five insect and acarine orders, including greenhouse crops, fruits, and field vegetables, as well as broad-acre crops. Nearly half of these bioproducts were created and provided by Central and South American enterprises [37].

4.3 Biochemical pesticides

These are naturally occurring substances that use harmless techniques to keep pests at bay. Plants, animals, and insects provide the basis for biochemical insecticides. Insect sex pheromones that function as matting disruptors, as well as plant extracts that lure insect pests to traps, are among these substances. Pheromones are volatile molecules released by living creatures to communicate with members of the same species of the opposite sex. Plant growth regulators or chemicals that repel or attract pests and obstruct growth or mating are examples. Tobacco caterpillars, rice green leafhoppers, rice cutworms, and numerous species of mites are all very susceptible to these chemicals [38].

Plant secondary metabolites are utilized as biopesticides because they prevent herbivores from eating them. Pyrethrin is an insecticidal chemical generated by *Chrysanthemum cinerariaefolium* as a secondary metabolite [39]. Neem (*Azadirachta indica)* oil, produced from the seeds of the neem tree, is the most frequently used insecticidal botanical ingredient [40]. The insecticides azadirachtin and salannin are derived from neem trees. Azadirachtin is also a growth regulator and a feeding deterrent for insects. Azadirachtin-treated insects die within a few days due to moulting and operate as a repellant, especially when applied to a plant. In this category, commercial Azadirachtin products include Spined Soldier Bug Attractors^{TM}, which are used to combat *Leptinotarsa decemlineata*, a Podius maculiventris aggregation hormone [41]. Methoprene and hydroplane against *Sitophilus oryzae* and *Sitophilus granarius*, respectively, have been found as insect growth regulators that may be used alone or in conjunction with pesticides against stored grain pests [42].

5. Commercial formulations of biopesticides

Biopesticide active components are created in the same way as synthetic pesticides are. The active ingredients are mixed with surfactants, stabilizers, spreads, synergists, stickers, coloring agents, anti-freezing compounds, and dispersants to create a final product with better environmental protection, greater biological agent survival, controlled rates, and improved bioactivity and storage stability. Users prefer this since it allows them to utilize the same equipment for several treatments [43,44]. Biopesticides are typically formulated as dust (DP), granules (GR), dry formulations for dilution in water, water-dispersible granules (WG) and wettable powders (WP), and liquid formulations for dilution in water – emulsions, suspension concentrates (SC), oil dispersions (OD), suspo-emulsions (SE), capsule suspensions (CS), and ultra-low volume (UL) formulation [45,46].

5.1 Dusts (DP)

Formulated by sorption of an active ingredient on finely ground, solid mineral powders (talc, clay, and so on) with particle sizes ranging from 50−100 µm. Either mechanically or manually dust can be applied directly to the targets. Anti-caking agents, ultraviolet protectants, and adhesive materials are used as inert ingredients to enhance adsorption. The concentration of active ingredients is nearly 10%. It poses adverse health hazards to users [47].

5.2 Granules (GR)

Granule formulations are made from kaolin, silica, attapulgite, polymers, starch, and powdered plant leftovers [48]. The active components are present in a concentration of 5–20%. Granule products are made in a relatively straightforward manner. A powder mixture is mixed with a little amount of liquid to make a paste, which is then extruded and dried to produce the active component. Granular biopesticides are commonly used in soil to control soil-dwelling insects, weeds, and nematodes, as well as for plant root absorption. Granules gently release the active substance once they've been applied. Some granules require soil moisture to release their active components [45,49]. Its example is *Metarhizium anisopliae* 10% GR.

5.3 Wettable powders (WP)

These are made by combining an active substance with a surfactant, wetting and dispersion agents, and inert fillers, then grinding the mixture to the desired particle size (about 5 microns). Because of their dustiness, these items cause skin and eye discomfort for makers. For these reasons, suspension concentrates or water-dispersible granules, which have been the most extensively used pesticide formulations, gradually suppress wettable powders [45]. WPs have received a lot of attention in comparison to other solid formulations because of their extended storage stability, good water miscibility, and ease of application using spraying equipment [50]. Examples of WPs are *Trichoderma viride* 1% WP and *Pseudomonas fluorescens* 1% WP.

5.4 Emulsions

The emulsion is made up of liquid droplets that are scattered in an immiscible liquid (the dispersed phase droplet size ranges from 0.1 to 10 m). Either an oil in water (EW) or a water in oil (WIO) emulsion can be used (EO). Before using, both products must be combined with water. The proper selection of emulsifiers is critical for emulsion stability. Because oil is the exterior phase of the formulation, losses due to evaporation and spray drift are negligible in the case of water in oil. Emulsion performance may be harmed by lower shelf stability and occasional phytotoxicity [50]. Examples of WPs are Triacontanol 0.05% EC and Azadirachtin 10% EC.

5.5 Suspension concentrates (SC)

SC is a dispersion of a finely powdered, solid active component in a liquid phase, most commonly water. Because the solid particles do not dissolve in the liquid phase, the mixture must be stirred before use to ensure that the particles are dispersed equally. To provide the requisite stability, it incorporates wetting and dispersion agents, thickening agents, antifoaming agents, and other ingredients. Wet grinding can be used to make it. This formulation has a particle size range of 1−10 µm. During the grinding process, inert substances adsorbed onto particle surfaces prevent tiny particles from re-aggregating. Because a larger surface area allows for quicker access of the active component to plant tissues, small particles have better bio-efficacy in applications. Pouring and measurement; operator and environmental safety, and cost are all benefits of SC over dry formulation [45,51]. Examples of WPs are *Metarhizium anisopliae* 2.0% SC and *Beauveria Bassiana* 10% SC.

5.6 Ultra-low volume liquids (UL)

These formulations have a high concentration of active chemicals that are highly soluble in a crop-friendly liquid (ultra-low volume liquid). Drift control additives and surface-active compounds are frequently found in UL. Before usage, these products are not diluted with water. Liquids with ultra-low volumes are simple to carry and utilize [51].

6. Global biopesticide market

Approximately 1400 biopesticide products were sold worldwide [52]. Biopesticides are produced in over 3,000 tons per year around the world. Although biopesticides are only used for 2% of plant protection compared to other control methods, global demand is growing at a rate of 10% per year [53]. Wettable powders, liquid concentrates, and ready-to-use dust and granules are all commercially available. Bacterial products derived from Bt are the most commonly used among these [54]. Around 200 Bt-based products account for roughly 53% of the global biopesticide market [55]. Only 5% of biopesticides are sold in Asia [56], whereas 45% are produced in the United States, Mexico, and Canada.

7. Biopesticides in India

When neem was utilized as an alternative to chemical pesticides in India, the notion of biocontrol was in use. Farmers have been utilizing neem for a variety of medically significant purposes in addition to vegetable protection [57]. Microbial-based insecticides emerged as an emergent requirement when synthetic chemicals failed to control *Helicoverpa armigera, S. litura*, and other cotton pests [58,59]. Biocontrol was known at the time as the sole technique to control the widespread resistance of chemical pesticides against diverse pest insects in a safe, cost-effective, and environmentally responsible manner. Biopesticides eventually became the most essential component of IPM, which had previously relied on chemical pesticides.

Under a contract with the Plant Protection Research Institute (PPRI), Bio-Control Research Laboratories (BCRL), a part of Pest Control (India) Limited, began commercial manufacturing of biocontrol agents for the first time [60]. Biopesticide manufacturing and application are supported by the Ministry of Agriculture and the Department of Biotechnology, and research institutes provide biopesticides to farmers at no cost through extension services [61]. Many researchers have found bacteria with significant biocontrol potential in recent years, and these microbes are now being economically utilized on a big basis [62−65]. The majority of the compounds come from bacteria and fungi that are hostile to each other (most notably *Bacillus thuringenesis* and *Pseudomonus fluorescens*) (mainly *Trichoderma* spp.). However, nuclear polyhedral viruses (NPV) and granuloviruses (GV) are the most common viral biopesticides [66]. Only 12 biopesticides (from Bt, Trichoderma, Pseudomonas, and Beauveria species) had been registered by 2006, but 194 chemical pesticides had been listed [67]. In India, biopesticide consumption increased from 219 metric tons (MT) in 1996–1997 to 683 MT in 2000–2001, while chemical pesticide consumption decreased from 56,114 MT to 43,584 MT during the same period [68]. According to data from the Directorate of Plant Protection, Quarantine and Storage, the Central Insecticides Board, and Registration Committee (CIBRC) of India currently have 970 types of biopesticide products registered. Figure 1 shows that biopesticide consumption in India has increased significantly over the last 5 years. The businesses produce 66% of fungal biopesticides, 29% of bacterial biopesticides, 4% of viral biopesticides, and 1% of other (plant-based, pheromones) biopesticides, respectively.

8. Registration/regulation of biopesticides in India

The Insecticide Act (1968) (as revised in 2000) is a single law governing the import, manufacturing, sale, transportation, distribution, and use of all forms of insecticides, including biopesticides, in India. Insecticides Rules, 1971, were enacted by the Central Insecticide Board (CIB), and they control the manufacturing, award of a license, license expiration, product labeling, packaging, and sale, as well as the usage of pesticides. The data on the effectiveness and safety of goods for humans and animals is supplied by the Registration Committee (RC). The law also stipulates that pesticide samples be verified for quality regularly. Shelf-life, cross-contamination, moisture content, and packaging are factors to consider when using biopesticides. Not only has CIB simplified the registration standards and data requirements, but it has also specified the minimal infrastructure needs for biopesticide manufacturing. Data for eucalyptus extract, rotenone, cymbopogom plant extract, pyrethrum extract, and neem-based products is required separately. The Indian Council of Agricultural Research (ICAR) and a few State Agricultural Universities (SAUs), the Council of Scientific and Industrial Research (CSIR), or Indian Council of Medical Research (ICMR) institutes must generate bio-efficacy data for bacterial and fungal biopesticides. The registrants must supply data from two separate agro-climatic regions at ambient temperature, as well as meteorological data, in order to claim shelf-life.

9. Constraints

The active ingredients in biopesticides are derived from living organisms. By preserving product quality, attention is required at all stages, from the start of manufacture to on-field application. The lack of suitable information, bad handling, insufficient machinery, wrong distribution, and a variety of other factors can degrade product quality and cause market value loss. The following sections go through the major roadblocks to biopesticide development and expansion.

9.1 Poor qualities and shelf-lives

Poor quality is a serious problem that hindered biopesticides' takeover of the market. Several products of biopesticides that are being sold in the market have a low count of microorganisms and are contaminated [69−71]. Poor field performance is due to the reduced shelf life of products and declines in the demand of farmers. Proper storage structure which is absent among the producers, shopkeepers, and farmers can improve the shelf life of products. Shelf lives also depend on the production system, carriers, packaging materials, and mode of transport. Survival of bacteria in the formulation is affected by the culture medium of bacterial cultivation, physiological state of the bacteria when harvested from the medium, drying technology, use of protective materials, rate of dehydration, and absence or presence of contaminants [72]. For long-term survival during the storage of biopesticides, moisture content must be low. In this way, the bacteria in the formulation remain inactive, resistant to environmental stresses, and insensitive to contamination [73]. To increase shelf life as well as to maintain the quality of the products, appropriate formulations which can be reflected by long-term storage are required.

9.2 Lack of trust and inconsistent field performance

Lack of trust and inconsistent field performance of biopesticides is a major reason for their lagging behind [70,71]. Key factors responsible for the unexpected results of biopesticides are abiotic soil factors such as pH, textural type, moisture, and temperature in the fields [74]. The main barrier to the successful use of biopesticides is the maintenance of sufficient activity over a prolonged period [71]. Building up farmers' trust in proper stress-tolerating formulations may improve the stability of products, viability, and constancy to alleviate the problem of inconsistency in natural field conditions. Extensive research must be carried out to develop proper formulations working efficiently in diverse agroclimatic conditions [75,76]. Successes of biopesticides depend on the compatibility of technicals with chemicals and application methods.

9.3 Regulatory framework

Registration is the biggest hurdle in the development of biopesticides. Most of the time, production is less expensive than registration and time-consuming [77]. Another issue is export and import of chemical pesticides are much easier as compared to biopesticides. Government can take up the quick decision to approve new biomolecules. To register a new bioproduct limited data have to be submitted to the Environmental protection agency (EPA) [78]. The governments can construct regulations at the global level through the organization of conferences, meetings, and workshops to promote the status of bioproducts. At present rules, and regulations regarding the registration, use, import, and export vary from country to country. The regulation can introduce uniform acts or laws which should be accepted globally and so there will be a common policy regarding the use of biopesticides.

9.4 Competition with chemical pesticides

Practically, biopesticides are not as effective as synthetic chemicals. Farmers opt for chemical pesticides over biopesticides as the number of chemical pesticides required to control a vast quantity of pest population is low. It was reported that with the absence of chemical pesticides, global losses would have risen from 42 % to approximately 70 % [79]. Nonavailability in the local market, absence of a quick knockdown effect, and high cost also limit the interest of the farmers in bioproducts. Confidence towards biopesticides can be developed through peeling off the previously mentioned hurdles.

10. Bio-effectiveness and shelf-life improvement through advanced formulations

Battelle is going on to develop biopesticide products that are more sustainable, targeted, stable, usable, or effective. New formulations are urgently needed to meet the needs of farmers while protecting human health and the environment.

10.1 Multi-active ingredient formulations

Multi-active formulations reduce the number of individual applications required, making crop protection more cost-effective for farmers. However, combining multiple active ingredients in one formulation vastly increases the complexity of the formulation. Several active ingredients interact adversely with each other to cause chemical degradation. Suspo-emulsions, encapsulation, oil dispersion (OD), and water-dispersible granulation can solve these problems.

Suspo-emulsions (SE) are a mixture of suspension concentrate and emulsion. The product demands formulating because it is necessary to develop a homogeneous emulsion component simultaneously with a particle suspension component that remains stable in the final formulation of the product. To overcome the problem of hetero flocculation between oil droplets and solid particles proper selection of dispersing and emulsifying agents is necessary. An extensive storage stability test is necessary for this formulation development [80].

Water dispersible granules are designed to be suspended in water, i.e., granules break up to form uniform suspension similar to that formed by a wettable powder. WGs are relatively dust-free and have good storage stability as compared to wettable powders. These are formulated by extrusion granulation, fluid bed granulation, spray drying, etc. The products contain dispersing agents and wetting agents but the concentration of dispersing agents is usually higher as compared to wettable powders. Water dispersible granules are usually more expensive than older types of formulations (dust, wettable powders). Regarding safety and greater convenience in application make WGs more desirable for many users [80]. An example is pyroclostrobin 20% WG.

10.2 Moving to oil-dispersions

Many biopesticides are moisture sensitive. Moving to Oil Dispersion (OD) formulations helps to make them stable with improved biological efficacy. Existing water-based formulations can be transformed into OD formulations to improve stability and enable co-formulation with other actives. Dispersions of solid active ingredients in non-aqueous liquid for dilution before use. The non-aqueous liquid is most often oil, but the best choice is plant oil. In that way retention, spreading and penetration are improved. Oil dispersion provides several important characteristics, such as the ability to deliver water-sensitive active ingredients and use an adjuvant fluid instead of water to increase and broaden pest control. This formulation is produced in the same way as a suspension concentrate. Inert ingredients for this type of formulation must be carefully selected to prevent instability problems [81].

10.3 Capsule suspension (CS) & flowable seed treatment (FS) formulations

Encapsulation enables new possibilities for biopesticides to improve shelf stability or create products that are activated by specific environmental triggers. The sustainability of encapsulated and seed treatment products can also be improved by moving to bio-based polymers that safely degrade in the environment. Capsule suspension (CS) is a stable suspension of the micro-encapsulated active ingredients in an aqueous continuous phase, intended for dilution with water before use. Bio-agent as its active ingredient is encapsulated in capsules (coating) made of starch, cellulose, and other polymers. In that way, the bio-agent is protected from extreme environmental conditions (UV radiation, rain, and temperature), and its residual stability is enhanced due to slow (controlled) release. Encapsulation in microcapsules has been extensively used to give smaller size and high efficiency to fungal biopesticide formulations [50,82]. Microcapsule suspensions need to be stabilized with surfactants and thickeners in the same way as suspension concentrate and similar additives are used. Despite the clear benefits of this controlled release formulation, its commercial development is rather slow [83,84].

10.4 Improving the stability of microbial formulations

Microbial formulations using live microbes have shown promise for controlling insects and fungi with biostimulant properties. However, many microbial formulations have limited shelf life even in highly controlled conditions. Microbiologists and formulation chemists are working side-by-side to create long-lasting, climate-resilient microbial formulations for both spray applications and seed treatments.

10.5 Localizing biopesticide formulations

Many biopesticide formulations created in one part of the world may not be effective in other parts of the world. Changes to a formulation may also be needed to be effective for the specific crop pests, weeds, and pathogens found in the region.

10.6 Formulating for drone application and precision agriculture

One emerging method uses drones for the precision application of crop protection or growth agents. To accommodate the smaller payload capacity of agricultural drones, super-concentrated formulations are needed. Advancements are going on to create high-load, low-viscosity formulations that are stable and suitable for drone dispersion.

11. Conclusion

Because of their long-lasting residual effects, the use of synthetic pesticides in pest management presents substantial risks to the environment, non-target creatures, and human health. Due to residue-free agricultural products, biodegradability, and human and environmental safety, biopesticide is a green tool for managing crop pests. Organic farming has boosted the use of biopesticides by farmers due to the high demand for residue-free food and feed. The government's registration procedures and export-import policies must be flexible. More research is needed to produce better formulations and extend shelf life. Farmers' meetings, seminars, and leaflet distribution should be held by extension agents and non-governmental organizations (NGOs) to raise knowledge about the handling, usage, advantages, and efficacy of biopesticides among farmers. For a greater adoption of this technology, producers must be trained in both production and quality control. As a result, the application of biopesticide is an environmentally benign crop protection technique for long-term environmental development.

Biopesticides are gaining popularity across the world as a green way to keep insect populations under control. Proper formulations, transporters, adjuvants, wetting, and dispersion agents help to extend shelf life. The commercialization of biopesticides need to be aided by research into manufacturing technologies, formulation development, and delivery systems. The present method for registration and regulation should be revised. Additional biopesticide markets should be investigated.

Availability of data and materials: Not applicable

List of Abbreviations: DP: Dusts; GR: Granules; WG: Water dispersible granules; WP: Wettable powders; SC: Suspension concentrates; OD: Oil dispersions; SE: Suspo-emulsions; CS: Capsule suspensions; UL: Ultra low volume;

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