Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 04, Issue: 03 (MAY-JUNE, 2024)
Available online at http://www.agriarticles.com
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Revolutionizing Pest Management: The Rise of Microbial, Phyto and Nano Biopesticides

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The entire world population is around 7.7 billion, which is growing steadily. One of the main predicaments is the lack of quality food for human beings due to environmental biotic and abiotic problems such as weeds, pests, and diseases. Over 65,000 kinds of pests are recorded, including weeds, arthropods, and fungi or are also regarded primarily as plant pathogens. The recent evidence recommended that pests prompted an 8-10% loss in wheat crops, 20% in sugar, 25% in rice, 30% in pulses, 35% in oilseeds, and 50% in cotton. The estimated annual crop loss caused by pests and diseases is USD 2000 billion. Therefore, different pesticidal technologies should be extended in these circumstances, particularly in developing countries, to subdue these food predicaments. For the last several years, pest management in industrialized counties has depended on the application of pesticides. Hence, the application of pesticides was raised above 1900% within the 1940s-1980s. According to a calculation, today, 2.3 billion kg of pesticides have been applied annually, making up to $ 58.5 billion of the global exchange.

Every year, almost 25% of the world's crop production is destroyed by pests. Many types of pests including *Acalitus vaccinia* (Blueberry bud mite), *Acrobasis vaccinia* (Cranberry fruit worm), *Acrosternum hilare* (Green stink bug), *Agrotis ipsilon* (Black cutworm), *Altica Sylvia* (Blueberry flea beetle), *Aphis gossypii* (Cotton aphid), and *Bemisia tabaci* (Sweet potato whitefly) are detrimental to crop production due to their huge nutritional needs. Thus, the challenge is to enhance the resistance of crops against pests without disturbing the crop yields. According to recent advances, the use of synthetic pesticides has increased to kill pests for better crop production. Pesticides are substances or a mixture of substances that are used to kill, resist, and repel pests.

The pesticides are divided into chemical, biological, synthetic, microbial, biopesticides, biochemical, and plant-incorporated pesticides. Chemical pesticides are delivered to plants either directly for seed treatment and weed control or indirectly through spraying the chemical on plants. Some chemical pesticides show good pesticidal activity, but they exert negative impacts both on human health and the environment; for example, methyl bromide has been reported as a good pesticide over the last 40 years against soil-borne pathogens, pests, and nematodes in many crops like tomato, melon, pepper, and strawberry. But later on, due to its ozone depletion negativity, it was banned in 2015 following the

Montreal Protocol. Moreover, some other chemicals like chloropicrin and dazomet are restricted in some areas due to their concern about food safety and human health.

Biopesticides, often known as biological pesticides, are insecticides derived from microorganisms or natural substances. Biopesticides are divided into three categories: microbial biopesticides, botanical biopesticides, and plant-incorporated protectants. As an alternative to conventional insecticidal methods, biopesticides have recently gained much attention due to their potential target specificity, fewer harmful side effects, capacity to disintegrate fast, and high efficacy. Several substances have been investigated as biopesticides in recent years, including *Clitoria ternatea* extract, oxymatrine (an alkaloid component), stilbenes in grape cane, Talaromyces flavus strains (SAY-Y-94-01), and olive mill oil. The usage of biopesticides, which represent less of a hazard to the environment and human health than synthetic pesticides, should be done with caution.

The nano-biopesticides have superiority over the biopesticides and conventional techniques for many reasons, including environmentally friendly behaviour, desired results within a few hours after applications, biodegradability, easy delivery to plants, and release slowly from the vector. Furthermore, their small size makes them an effective carrier when combined with pesticides that can easily enter the plants. Another advantage of nano-biopesticides is that they did not have an adverse effect on soil microorganisms and phototoxicity of Ag-based nano-particles was suppressed by nano-coating them with biocompatible polyvinyl pyrrole compounds. The nano-biopesticides can be synthesized by following two ways: either by extracting the biological active pesticidal compound (APC) from plants and blended it with nano-particles and inserted it into a suitable polymer that acts as a supporting material, or APC secrete the metallic salt with bind with nano-particles (NPs) that haemolyse and merge into an appropriate polymer.

The accumulative data revealed that nano-biopesticides contain secondary plant metabolites and their mediated metal oxide nanomaterials. It was found that biopesticides have gained importance over chemical pesticides during the past few decades due to their eco-friendly behaviour, high efficiency, and fewer side effects. The evidence reported that recently much research had been carried out on nano-biopesticides; either pests are attaining chemical pesticide resistance, or a small number of insecticides have expired due to severe environmental and human concerns.

Microbial pesticides

Microbial pesticides consist of substances derived from microorganisms like bacteria, fungi, viruses, protozoa, and algae, which are used in the control of pests (Adeleke et al., 2022c). Microbes use the toxic metabolites produced to destroy and prevent the growth of pests. Microbial pesticides are applied to the environment through different techniques, such as emulsion, electrospraying system, fluidized bed, spray drying, extrusion, lyophilization, spray cooling, and coacervation (De Oliveira et al., 2021).

The major categories of microbes used as biopesticides include bacteria genera, Chromobacterium, Pseudomonas, and Yersinia, fungal genera Beauveria, Paecilomyces, Verticillium, Hirsutella, Metarhizium, and Lecanicillium and nematodes belonging to the genera Steinernema and Heterorhabditis (Chang et al., 2003; Kumar et al., 2021; Adeleke et al., 2022b). A fungi species, Trichoderma sp. has been reported to prevent the activity of numerous fungi inhabiting the soil that cause root rot, black gram, and green gram in chickpeas, and groundnut (Samada and Tambunan, 2020). Likewise, *Beauveria bassiana* and *M. brunneum* have been reported in the control of thrips, beetles, weevil, aphids, whiteflies, and mites' infestation in ornamental crops, fruits, and vegetables. Of all the bacterial pesticides, *Bacillus thuringiensis* (Bt) is well known and have been made into products available for commercial purpose. Bacillus thuringiensis is a Grampositive bacteria that acts as an insecticide by producing exudates, such as poisonous parasporal crystals and endospores which when consumed by insects get dissolved in their midgut by the alkaline environment and release delta-endotoxin, a protein that has a lethal effect on insects. Adhesion is primarily achieved through hydrophobic interactions between the cuticle and the spore. The number of spores attached to the host's body determines their efficacy. The spore germinates in response to chemical cues on the cuticle and then develops an aspersorium, which is the penetration structure. The fungus penetrates the layers of the cuticle through a combination of mechanical pressure and enzyme degradation. Generally, microbial pesticides exert no adverse effects on the environment, producers, and consumers of agricultural products because their ingredients are generally considered safe and are target specific.

Phytopesticides

Essential oil and extract from different parts of plants have been successfully used to control plant diseases. They attract, repel, prevent respiration, detect host plants from specific pests, destroy the eggs and larvae of pests, and destroy pests from feeding on plants. Essential oil from *Coleus aromaticus* Benth., *Hyptis suaveolens* (L.), *Azadirachta indica*, *Ageratum conyzoides* L., and Achillea sp., have been reported to control the infestation of *Tribolium castaneum* (Herbst), a red flour beetle that destroys many crop species. Other plant parts, such as bark, flowers, roots, leaves, peels, seeds, and buds can be used to control different plant pathogens. Plant families that have been reported to contain bioactive compounds with activity against important crop pests include Myrtaceae, Lauraceae, Rutaceae, Lamiaceae, Asteraceae, Apiaceae, Cupressaceae, Poaceae, Zingiberaceae, Piperaceae, Liliaceae, Apocynaceae, Solanaceae, Caesalpinaceae, and Sapotaceae (Gakuubi et al., 2016).

Pesticides derived from pyrethrum target insect nerve cells, thus causing paralysis and death. Also, neembased pesticides with antifeedant and repellent properties, induce moulting abnormalities, hinder oviposition, and disrupt the endocrine system. Pesticides from plants have been well-reported to interfere with the normal metabolism of insect pests, which include the octopamine and acetylcholinesterase pathways. Acetylcholinesterase is an enzyme used by insects in their neuronal communication and neuromuscular functions and can be toxic to insects by destroying the membrane of the postsynaptic junction and the current of the nerve. Octapamine on the other hand is a hormone involved in neuromodulation and neurotransmission in insects and can impair the muscle juncture and homeostasis of the body fluids of insects (Dassanayake et al., 2021).

Nanobiopesticides

Nanobiopesticides can be defined as biological protection products that are developed using nanotechnology to enhance efficacy and reduce an environmental load of pesticides. Nanobiopesticides are formulated from nanomaterials and applied specially fixed on a hybrid substrate, encapsulated in a matrix or functionalized nanocarriers for external stimuli or enzyme-mediated triggers. They are nanostructures with two or three dimensions used for carrying agrochemical ingredients and can help increase water solubility and bioavailability, and protect agrochemicals against environmental degradation. It also helps revolutionize the control of pathogens, weeds, and insects in crops (Yadav et al., 2020). They are available in different forms, such as nano-gel, nano-encapsulation, nano-fibres, nano-sphere, etc. Nanoparticles in recent years are being reported to be very helpful in agriculture They have been used as active ingredients and carriers to stabilize many agrochemicals and their products from them include nanofertilizers, nanopesticides, etc. For instance, pesticides from nanomaterials, such as magnesium oxide, magnesium hydroxide, copper oxide, and zinc oxide derived from aqueous extracts of Chamaemelum nobile flowers, Punica granatum peels, green peach aphid (GPA) and Olea europaea leaves have been reported in the control of insects. Also, silver nanoparticles derived from the leaf extract of Euphorbia hirta have been explored in the control of the causative agent of cotton bollworm, *Helicoverpa armigera*. The ability of copper oxide nanoparticles and zinc oxide nanoparticles to control Alternaria citri, a causative agent of citrus black rot disease in the plant has as well been reported. In addition, used combined and individual zinc oxide and copper oxide to control citrus black rot disease in a potato dextrose medium. The fungal and insecticidal effects of copper nanoparticles have been demonstrated against *Tribolium castaneum*, a pest that affects grain.

The major interactions which occur between plants and nanoparticles have been studied using different techniques, which include fluorescence spectroscopy, microscopy, and magnetic resonance imaging. The effectiveness of nanobiopesticides can be determined by the composition, surface charge, concentration, size, and chemical and physical changes. The critical role of nanoformulations in reducing active ingredient degradation, improving water solubility equilibrium, and increasing the biological availability of active ingredients is well understood, and this has helped in avoiding endemic pest infestation, plant injury, and economic loss by lowering the quality and quantity of agricultural products and food. Because of their small size and larger surface area, nanopesticides' chemical properties differ significantly from conventional pesticides, and these properties can be used to develop an efficient assemble of a structure with several advantages, such as the possibility of better interaction and mode of action at a target site of the desired pest. Nanosized products exhibit greater selectivity without impairing compound bioactivity against the target pathogen. Their increased toxicity can also increase pest penetration (Priya et al., 2018).

Nanoparticle application reduces drifting and leaching issues and allows for the use of a smaller amount of active compound per area, as long as the formulation can provide optimal concentration delivery for the target insecticide for longer periods. There are several methods for creating pesticide nanoproducts, such as nanoemulsions, nanocapsules, and inorganic engineered nanoparticles (such as metal oxides, metals, and clays), and can be further developed to improve the efficacy of existing pesticides, reduce their environmental toxicity, or both. On a general note, biopesticides have been reported to be capable of controlling pests but their sole use for sustainable agriculture may not be realistic, majorly because they are not readily available in many locations and their mode of action can be very slow. Hence, they should be incorporated with the existing synthetic pesticides and be applied majorly close to the harvest period of crops since residual chemicals observed in plants are those majorly applied close to harvest periods. Furthermore, this will help to maintain suitable agriculture, pending the improvements of biopesticides.

Molecular mechanisms of the application of biopesticides It is very important to understand the molecular mechanisms underlying the action of biopesticides at each stage of action to ensure better control strategies over pests. Understanding the biopesticides mechanisms of action against insect pests at the molecular level will allow for synergistic approaches among biopesticides, which have different mechanisms of action without an overlapping mechanism. This will also give allowance for the exploration of different toxic molecules present in biopesticides that can enlarge the pesticidal arsenal of these biopesticides. The widely used biopesticides and their mechanisms of action at the biochemical level have been described.

However, the entomopathogenic fungus, *Beauveria bassiana* has gained wide acceptance and can be used as a model to describe the molecular mechanism of biopesticides' application. *Beauveria bassiana* is an example of an entomopathogenic fungus that has been widely used as biopesticide because it is highly efficacious against a lot of arthropod hosts. However, to understand their effectiveness and sustainability against pests, there is a need to fully evaluate their molecular mechanism of pathogenicity beyond the conventional approach. The mechanism of pathogenicity of begins with adhesion to the host pest, penetration of cuticle, and colonization of the pest heaemocoel. The hydrophobins-coated aerial conidia of *B. bassiana* allow its hydrophobic interaction with the cuticles of insects.This hydrophobicity of the B. bassiana aerial conidia can be influenced by the role that several genes expressed by *B. bassiana* play in lipid homeostasis. It has been revealed by transcriptomics analyses that there is an upregulation of gene expressions for hydrophobins and Metarhizium adhesion-like protein 1, 2 (MAD 1, MAD2) by *B. bassiana* which are crucial for its hydrophobic attachment to the cuticle of insect. The transportation and storage of lipids in the conidia, and maintenance of the lipid homeostasis of *B. bassiana* is possible when mammalian-like perilipin 1 (MPL1) genes are over express. The role that the MPL1 gene plays is crucial because its deletion causes a reduction in the turgor pressure of the appressoria impairing the adhesiveness of *B. bassiana*. Also, the surface sensing and signaling for the germination of conidia and formation of appressoria is made possible by CFEM-domain containing genes in *B. bassiana*. Proteomics has also revealed that B. bassiana secretes sphingomyelin phosphodiesterase, which allows it to disrupt the membrane of the host insect upon contact with the cuticles of the insect (Santi et al., 2019). Once *B. bassiana* completed adhesion to the host insect, its conidia germinate and develop appressoria to allow penetration into the cuticle of the host. The penetration efficiency of B. bassiana usually increased when the structural outlook of the appressorium allows the synergistic functioning of enzymatic digestion and mechanical pressure. The hyphae of *B. bassiana* germinate in the exoskeleton of the insect as the penetration proceeds and *B. bassiana* produces secondary hyphae inside the cuticle. The hyphae switch to blastospores (motile, more hydrophilic, and better evade the insect's host immunity) when exposed to hyperosmotic environment in the haemocoel.

Through transcriptomics, it has been reported that chitin synthase is responsible for chitin production, and β-1,3-glucanases soften the cell wall to allow germination, while several cell wall proteins conferring genes give the cell wall of *B. bassiana* its building blocks. Genes necessary for the cell body differentiation in *B. bassiana* include osmosensor Mos1, signaling-related genes, and mitogen-activated-protein kinases (MAPKs) like protein kinase. For penetration into the cuticle of the host insect, notable proteases, lipases, chitinases, and carboxypeptidases have been reported and these include subtilisin-like protease (Pr) isoform 1A (Pr1A) and 1B (Pr1B), cytochrome P450s (CYPs) and GH18 family chitinases. In response to the penetration into the cuticle of the insect, the insect activates melanization and produces antimicrobial peptides (AMPs), reactive oxygen species (ROS), and protease inhibitors. Stress management and immune-evasion related genes are upregulated to overcome the host insect defence mechanisms. Glutathione S-transferases (GSTs), catalases, peroxidases, superoxide dismutase (SODs), thioredoxins, and oxidoreductases are anti-oxidative enzyme-producing genes over-expressed in B. bassiana (Lai et al., 2017). Heat shock proteins (HSPs) are expressed to maintain internal cellular integrity against diverse types of stress. Another mechanism used by *B. bassiana* is the production of secondary metabolites that are toxic to the insect cell. These metabolites include oosporeins, beauvericin, isarolides, beauverolides, tenellins, and bassianolide (Chandler, 2017).

Table 1. Different Biopesticides, phtopesticides, nanobiocides and their pest control.

Organism	Target Pest(s)
1. Entomopathogenic Viruses (Nucleopolyhedroviruses)	
- PiraGV (Autographa californica multiple nucleopolyhedrovirus)	Imported cabbageworm
- Potato tuber moth granulovirus (PhopGV)	Potato tuber moth
Entomopathogenic Fungi	

- *Paecilomyces lilacinus*	Soil nematodes
- *Beauveria bassiana*	Whitefly
- *Hirsutella thompsonii*	Spider mites and whitefly
- *Isaria fumosorosea*	Termites, grasshoppers, caterpillars, and beetles
- *Metarhizium brunneum*	Insects and mealybugs
- *Paecilomyces fumosoroseus*	Nematodes
- *Verticillium lecanii*	Nematodes, mites & thrips, scale insects, mealy bugs
- *Myrothecium verrucaria*	Nematodes
- *Lagenidium giganteum*	Pest mosquito species
2. Entomopathogenic Bacteria	
- *Bacillus thuringiensis*	Elm Leaf Beetle, Alfalfa weevil
- *Bacillus thuringiensis* var. *israelensis*	Fungus gnats, black flies, larvae of mosquitoes
- *Bacillus sphaericus, Bacillus lentimorbus,* and *Bacillus popilliae*	Larvae of Aedes spp., *Culiseta, Psorophora,* and Culex mosquitoes
3. Entomopathogenic Nematodes	
- *Heterorhabditis taysearae*	*Bactrocera dorsalis*
- *Steinernema carpocapsae, Heterorhabditis bacteriophora*	Larvae of cabbage white butterfly
- *Steinernema feltiae, Steinernema carpocapsae, Steinernema riobrave*	Armyworm
- *Steinernema feltiae, Steinernema carpocapsae, S. bicornutum*	Leafminers
- *Heterorhabditis indica* and *H. bacteriophora, Steinernema carpocapsae*	Potato tuber moth
4. Nanobiopesticides	
- Nano-sized particles derived from *Mesocyclops longisetus*	*Culex quinquefasciatus* (mosquito)
- Nano-sized particles derived from *Mesocyclops scalpelliformis*	*Culex quinquefasciatus* (mosquito)
- Silver nanoparticles	Alternaria solani and Alternaria alternate fungi
- Silver nanoparticles	*Xanthomonas axonopodis* pv. citri, *X. oryzae pv. oryzae* bacteria and Ustilaginoidea virens fungus
- Gold nanoparticles	*Culex quinquefasciatus, Anopheles stephensi* and *Aedes aegypti* mosquitoes
Phytopesticides	
- Lantana camara plant	Eggs of root-knot nematode (*Meloidogyne incognita*)
Azadirachta indica	*Colletotrichum coccodes*

Integrated pest management system

Integrated Pest Management (IPM) system refers to the mechanism of controlling pests using different techniques, such as habitat manipulation, biological and chemical control measures, use of pestresistant varieties, and the modification of cultural practices. These techniques can be merged to ensure the long-term protection of plants (Deguine et al., 2021).

For instance, IPM has been used in the control of Tuta absoluta, a deadly pest that affects tomatoes globally, and has developed resistance to insecticides (Desneux et al., 2021). Here, the synthetic pesticides and biological pesticides include the release and conservation of sex pheromones and arthropod natural enemies (Desneux et al., 2021). The use of IPM has been reported to be costeffective and reduces the loss of crop yield (Hagstrum and Flinn, 2018). Currently, the adoption of IPM is limited owing to several factors, which include awareness, user preference, production industry, technology, policy, and culture (Deguine et al., 2021). It is, therefore, necessary to increase awareness of the inclusion of biological pesticides from microorganisms, plants, and nanobiopesticides in IPM.

The awareness of many people about IPM will be an advantage to encourage producers to produce more of it, enhance its.

Biopesticide Type	Advantages	Disadvantages
Microbial pesticides	Specific mode of action, Short residual effect, Environment friendly, Sustainable production, Cost-effective, Easy mass production, No greenhouse gas emission	Short shelf life, Stability challenges, Uncertain exposure rates/levels and duration, easily degraded, Short-lasting effects, Stringent regulations (reduced availability)
Plant pesticides	Cost-effective and sustainable, Derived from various plant species, Specific mode of action	Limited pest control (may require multiple applications), Quality dependence on raw materials, Inconsistent product quality, Tedious registration process
Nanobiopesticides	Cheaper, more stable, and sustainable, No residual effects, No greenhouse gas emission	Difficult dosage control (small size), Limited field application research, Tedious and time-consuming regulations, Slow mode of action

Future prospects and conclusion

A lot of crops are lost yearly to pest, but the emergence of synthetic pesticides has helped to reduce the loss. Nevertheless, the adverse effects of synthetic pesticides limit their use; thus, promoting the use of biological pesticides. Since biopesticides have proven as good alternative to chemical pesticides, it will be very important to explore them for maximum use in agriculture. The demand and availability of biopesticides are very poor, hence discouraging the producers and the users, respectively. Therefore, making grants or capital available for researchers, entrepreneurs, producers, and marketers will help to enhance the production and availability of bio pesticides. The shelf-life of biopesticides is short, as they require special temperatures and conditions for survival during transportation and storage. Hence, more research to unravel the mechanisms to make biopesticides more stable and improve their shelf-life will go a long way in increasing their efficiency.

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