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Nano-Biopesticides as an Emerging Technology for Pest Management

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Abstract

With an increasing world population, the demand for quality food is rising. To meet safe food demand, it is necessary to double or maybe triple agriculture production. Annually, almost 25% of the world crop is destroyed due to pests. During the past few decades, different pesticides, including chemical, synthetic, biological, and botanical have been adopted to achieve adequate results against pests for agriculture interests and plant safety. Globally, more than 200,000 people died every year due to direct chemical and synthetic pesticides poisoning. But these pesticides did not achieve the desired results due to delivery problems, less stability, low biodegradability, less specificity, and high cost. To overcome these problems, the rapidly emerging field of nanotechnology is considered an important achievement in the agriculture sectors in order to improve pest mortality rates and crop production. The nano-biopesticides attained special attention against the insect pests due to their small size (1-100 nm), large surface area, high stability, cost-effectiveness, fewer toxicity, and easy field application. The current chapter highlights the relevance of nano-biopesticides for pest insect management on several crops of agricultural concern. The mechanisms of action, delivery, and environmental sustainability of nano-biopesticides are also discussed in the present chapter.

Keywords: Pest management, nanotechnology, Nano-biopesticides, environmental sustainability, crop yield, agriculture

1. Introduction

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 [1]. Over 65,000 kinds of pests are recorded, including weeds, arthropods, and fungi or are also regarded primarily as plant pathogens [2]. 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 [1]. For the last several years, pest management in industrialized countries 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 [2, 3].

Every year, almost 25% of the world's crop production is destroyed by pests [4]. Many types of pests including *Acalitus vacciniae* (Blueberry bud mite), *Acrobasis vacciniae* (Cranberry fruit worm), *Acrosternum hilare* (Green stink bug), *Agrotis ipsilon* (Black cutworm), *Altica sylviae* (Blueberry flea beetle), *Aphis gossypii* (Cotton aphid), and *Bemisia tabaci* (Sweet potato whitefly) are detrimental to crop production due to their huge nutritional needs [5]. 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 [5, 6]. Pesticides are substances or a mixture of substances that are used to kill, resist, and repel pests. The total consumption of pesticides in developed countries is about 3000 g/ha [7]. Synthetic pesticides have received much attention due to their broad spectrum of insect control and ability to kill pests in the agroecosystem. Plants and their secondary metabolites, including alkaloids, organic acids, and glycoalkaloids are considered promising sources of plant effecting pests (known as biopesticides) [8].

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 [9].

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 [10]. 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 [11, 12]. The usage of biopesticides, which represent less of a hazard to the environment and human health than synthetic pesticides, should be done with caution. Certain products have been licensed for usage as biopesticides, although they still pose health concerns [13, 14]. However, in this regard, nanotechnology has gained special attention and has become a novel field during the last couple of years due to its multidisciplinary applications in pharmacology, agriculture, pest management, and parasitology fields [15]. Nano-particles are the most rapidly expanding area of nanotechnology, which provides the solution to many environmental problems due to their eco-friendly behavior and cost-effectiveness, small size (1-100 nm), and large surface area. According to emerging evidence, nanotechnology has been proven to be an effective tool for the formulation of new nanocomposites against pests and improving crop varieties [16].

The nano-biopesticides have superiority over the biopesticides and conventional techniques for many reasons, including environmentally friendly behavior, desired results within a few hours after applications, biodegradability, easy delivery to plants, and release slowly from the vector [15]. 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 [17]. 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 hemolyze and merge into an appropriate polymer. The APC integrated with NPs and merged into a compatible vector including micelles, liposomes, nanosphere, polymer, and nanofiber. These ingredients were used as a spray to kill the insect pests for food protection [18].

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 behavior, 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. However, this situation demands novel plant-based pesticides on the nanoscale to formulate the nano-biopesticides for pest management. Recently, different biopesticides have been reported against different pests such as *Bacillus firmus* and *Bacillus sphaericus*, which are used against diamondback moths, while *Trichoderma harzianum* and *Trichoderma viride* are used against root rots and wilts, *Beauveria bassiana* against mango hoppers, neem-based nano-biopesticides against whitefly, and *Bacillus thuringiensis* against *israelensis* but they have not shown an effective impression on pests. However, future studies are needed to overcome and improve nano-particle release rates and delivery [19–21]. Therefore, the present chapter demonstrated the importance of nano-biopesticides for pest insect management on different crops for agricultural interest to overtake these situations. Moreover, the present chapter explains the mechanism of action, delivery, and environmental sustainability of nano-biopesticides.

2. Pesticides

Agricultural output has been increased dramatically in the early 20th century, especially in the United States, to keep up with the rapidly growing human population. During the last century, the world's population has tripled from 1.5 billion in 1900 to 6.1 billion in 2000. The world's population has grown by one billion people in the past decade, and the UN predicts it could reach 9.4 to 10 billion by 2050 if current growth rates continue [22]. A lateral increase in food production was needed during the 20th century to keep up with the increase in the world population. This was accomplished via the use of fertilizers and other agricultural inputs throughout the twentieth century. Bio-fertilizers (such as guano) were first used in the late 1800s; inorganic phosphate fertilizers (such as urea) were first used in the early 1900s and have steadily gained in favor ever since [23]. Phosphates helps to increase the crop diversity and yields and aided in the unprecedented “green revolution” for agricultural productivity. This caused a tenfold increase in grain

production per unit surface area of agricultural land, leading to a global food surplus [24]. An increasing global population and increased phosphate production were shown to be positively linked throughout the 20th century, with an R^2 of 0.97 for the period 1900–1988 [25].

Synthetic crop preservation agents were introduced to the market in the 1940s, which increased food output. It grew from 0.2 million tons in 1950 to over 5 million tons in 2000, up from 0.2 million tons the year before. Between 1950 and 2000, pesticide production grew by about 11%, from 0.2 million tons to over 5 million tons. Crop preservation chemicals, sometimes known as pesticides, are composed of various composites, including growth regulators, neonicotinoids, organochlorines, pyrethroids, organophosphates, carbamates, and more recently, biopesticides. This wide spectrum of chemicals and insecticides has been developed throughout history to protect crops from pests and diseases. All sorts of pesticide sales grew; however, herbicides were the group that extended the most, accompanied by fungicides and insecticides. Pesticide application has suffered owing to lack of global uniformity, high cost of chemicals, human resources, and the vast diversity of pests present in each climatic or geographical area. Using FAO data, it was found that the mean pesticide application rates per hectare of arable land ranged from 6.5 to 60 kg/ha, with the greatest mean values occurring in Asia and a few South American nations. Unlike Western Europe and North America, Asia has not witnessed a rise in the usage of herbicides in both urban and agricultural areas. Compared to the widespread use of insecticides, herbicide usage in Asia has remained relatively low in recent years, according to World Bank and International Food Policy Research Institute data [26].

Throughout the twentieth century, ancient synthetic pesticides intended for agricultural pest control, such as DDT, were often used to treat human parasites and animal ticks. So, for example, DDT was designed to be used in agricultural pest control. Despite of being prohibited, it is nevertheless extensively used as a food prophylactic for various fish in South Asia, and to control home pests and malaria vectors globally, albeit seldom illegally [27]. Pesticides have been administered in agricultural settings for decades, employing techniques ranging from truck and aircraft spraying to old-fashioned field worker spraying. Studies on the effects and toxicity of manufactured chemicals on human health and well-being have shown that individuals report euphoria after pesticide application. This research included peasants, farmworkers, and their families following pesticide treatments. They previously discovered that unintentional poisoning affects about 355,000 individuals annually and is linked to high susceptibility and poor chemical management. They also discovered that increased sensitivity and poor management of hazardous substances are closely linked to such toxicities [28]. The research was conducted to assess the number of pesticides in the environment that killed various animals. Among the animals that resided there were fish, birds, bees, amphibians, and tiny mammals. It was also noted how much they were killed and how they were slaughtered [29].

Following the introduction of synthetic chemicals into the environment, it was only a short amount of time before it was thought that crop protection pesticides were causing disease both locally and internationally [26]. Many believe that sprayed on-crop DDT is deported into water bodies, quickly converted into DDE, and bio-accumulated in aquatic food systems before being reintroduced into the environment and ultimately reaching people. To manufacture endosulfan at this time, a rigorous and scientific decision-making procedure is undertaken. Additionally, this strategy includes scientific research to enhance food production, food safety, and environmental security in addition to the other objectives listed above [26].

Common use of synthetic pesticides inhibits the development of plant pathogen strains resistant to these chemicals, causing the reemergence of illnesses in the

environment. Pesticides are being used more often by farmers, which is good [30]. Synthetic pesticides include active ingredients that are absorbed and retained by plants after application. People suffer chronic health issues due to the high concentration of harmful chemical deposits in these crops cultivated for human use [31]. Synthetic pesticides include active ingredients that are absorbed and retained by plants after application. People are suffering from chronic health issues due to the high concentration of harmful chemical deposits in these crops cultivated for human use [32].

3. Biopesticides

The need for biopesticides has been increased significantly in recent years, particularly in developing countries, due to restrictions placed on the use of some synthetic pesticides, such as organophthaloids, organochlorines, carbamates, and organophosphates, among other things. Synthetic pesticides are not only harmful to pests and diseases at the time of application, but they also have the potential to contaminate plant crops, posing a threat to human health, animal welfare, and environmental health. Synthetic pesticides are used to control pests and diseases in agriculture. In agriculture, synthetic pesticides are used to manage pests and illnesses that are introduced via the soil. As reported by the Environmental Protection Agency, synthetic pesticides are also harmful to both people and animals. They are also bad for the health of the ecosystem. When it comes to biochemistry, chemical pesticides are characterized by alterations in the signaling system, inhibition of enzymes, pH shifts, disruption of electrolytic balance, osmotic and membrane breakdown, pH gradients across membranes, and other characteristics. They also generate free radicals and other toxic compounds, which have the potential to damage proteins and DNA, as well as cause tissue degeneration, among other undesirable effects [14]. A wide range of diseases has been linked to the use of synthetic pesticides, including Parkinson's disease and neurotoxicity, type 2 diabetes, endocrine disruption, many cancers, and obesity, among others. Parkinson's disease is the most well-known of these disorders. It has been shown that the use of synthetic pesticides is linked with the development of these diseases, which may be due in part to the mechanisms of action of these chemicals, as well as the increasing exposure of individuals to these chemicals over time [33–35]. Despite the fact that it is regrettable, the majority of pesticides now in use are being phased out at a rapid rate, which is a good trend in the industry. On the other hand, pesticides that are still in use continue to accumulate in the human body with every meal that is eaten. In addition, employees who have been exposed to pesticides have been observed to get drunk as a result of the pesticides they have been exposed to over the course of their shift [36]. Natural pesticides offer many benefits over synthetic pesticides, the most significant of which is that they are less harmful to the environment and human health. However, this does not mean that they should be utilized recklessly or without consideration for the repercussions of their actions. Even if certain products have been authorized for use as biopesticides, it is conceivable that they may cause health issues among members of the general population. Large quantities of copper, which is an essential nutrient in the diets of both mammals and plants, have the potential to be poisonous to both humans and animals and hazardous to aquatic life if eaten over an extended period of time. There is also concern about toxic plant species, microalgae, and algae such as *Microcystis aeruginosa*, *Chrysanthemum* spp., *Gracilaria coronopifolia*, and others that are harmful because their appearance may be similar to that of hazardous compounds such as cyanide, among other things, and they are difficult to identify [13, 14].

As the name implies, biopesticides are pesticides that include active ingredients formed by microorganisms or natural materials rather than synthetic chemicals. They are used to control insects in a variety of circumstances and are referred to as “biopesticides.” Pesticides derived from plants are divided into three categories: (a) microbial biopesticides, which are microorganisms that are effective against diseases and insects; (b) botanical biopesticides; and (c) plant-incorporated protectants. Microbial biopesticides are microorganisms that are effective against diseases and insects. Microbial biopesticides are microorganisms that have been shown to be efficient against many illnesses and insects in the field. A microbial biopesticide is a bacterium that is effective against a wide range of diseases and insect species, including fungi [10].

3.1 Microbial biopesticides

The presence of fungus is associated with insect damage. *Metarhizium anisopliae* and *Beauveria bassiana* are two forms of entomopathogenic fungi that may be found in the environment and are both harmful to insects. According to the World Health Organization, as soon as *B. bassiana* spores come into contact with the body of an insect host, they begin to develop, penetrate the cuticle, and multiply within the insect host, eventually killing the insect host and spreading to other insects in the surrounding area. *B. bassiana* is a fungus that can cause death in insects. As the body ages, it produces a white mold that spreads new spores into the surrounding environment, leading the environment to become more contaminated as a result of the pollution. A host insect becomes infected when the spores of the fungus *M. anisopliae* come into touch with the insect’s body, causing the spores to sprout and the hyphae that emerge to pierce the insect’s cuticle, causing the insect to succumb to the infection. It then begins to spread throughout the insect’s body, resulting in the insect being infected within a few days after first becoming exposed to the fungus. In order to prevent the development of soilborne diseases, microorganisms such as *Pseudomonas* and *Trichoderma* have been extensively employed as biopesticides for many years, and they are still being utilized in this capacity today [37]. According to the University of California, Berkeley, a filamentous fungus such as *Trichoderma* may be found growing on organic materials such as rotting wood, soil and other organic materials. Many *Trichoderma* species, including *T. virens*, *T. viride*, and *T. harzianum*, have been found to have strong biocontrol capability. Many other competing methods for resources have been discovered to have biocontrol potential, including mycoparasitism, which is caused by the release of cell wall-degrading enzymes such as proteases, chitinases, and glucanases, among other things. The antibiotic compounds heptelidic acid and harzianic acid, as well as alamethicins, glisoprenins, tricholin and antibiotics, 6-pentylpyrone, peptaibols, viridin, and massoilactone, can all cause antibiosis. Heptelidic acid and harzianic acid are two of the most commonly encountered antibiotic compounds. Infections caused by bacteria are treated using the antibiotic heptelidic acid, which is produced by bacteria and used to treat infections caused by other bacteria [38].

Trichoderma is effective against a wide range of pathogenic fungi, including *Candida albicans*, *Phytophagthora*, *Fusarium*, *Sclerotia*, and other pathogenic fungi, in addition to *Candida albicans*. Cotton crops are affected by *Fusarium* wilt disease, caused by the fungus *Fusarium* sp., while other crops, such as maize, are affected by *Rhizoctonia* sp. and *Pythium* sp. As a consequence of using this technique, the development of cucumber resistance to the anthracnose disease caused by the fungus *Colletotrichum* sp. was aided. *Pseudomonas aeruginosa* weakened infections are characterized by the release of various derivatives and antibiotics such as pyoluteorin (Plt), 2,4-diacetylaminoglucinol (DAPG), phenazine-1-pyrrolnitrin (Prn),

carboxylic acid (PCA), or the development of systemic resistance (ISR) [39]. When it comes to developing microbial biopesticide formulations, microorganisms such as algae, bacteria, and fungus must be incorporated if the usage of these pesticides is to become more generally accepted. According to the International Biopesticide Trade Association, the biopesticide industry is experiencing an outbreak of bacteria, particularly among *Bacillus thuringiensis* species, which are commonly used to control insect infestations in plantations and are now being transported across multiple countries [40]. Whenever parasites eat this bacterium, it creates a toxic endotoxin that attaches itself to the stomach of the insect and causes holes to develop, resulting in anion imbalances in the insect's body, insensitivity of the insect's digestive system, and eventually, the insect's death. According to industry standards, these pesticides are usually regarded as less toxic to birds, mammals, and non-target insects than conventional insecticides, and as a result, they are believed to be less damaging to the environment. Microalgae as biopesticides, despite this, have been proven to be helpful in the prevention and control of the spread of a wide variety of plant-borne diseases. Many studies have demonstrated this bacterium's ability to produce a diverse range of bio-compounds, including terpenes and growth regulators, as well as phenolic chemicals and other molecules. These studies have all demonstrated this bacterium's ability to produce these compounds, as well as its potential to produce other molecules. Terpenes, growth regulators, phenolic compounds, and other molecules are among the substances studied [41, 42].

3.2 Biochemical biopesticides

Non-toxic biochemical pesticides are natural insecticides produced by animals, plants, and insects. They do not damage the creatures that produce them. They are employed to manage pests without killing them. These chemicals may assist in growth and development by attracting or repelling pests (pheromones) and acting as plant growth regulators (PGR). It's difficult to tell whether a biopesticide is hazardous since so few countries have committees to test metabolites.

As a consequence, evaluating a biopesticide's safety is difficult [43]. Since their discovery, Auxin-type PGRs have been hailed as one of the most effective herbicides and biological control agents on the market. And for a good reason. It is generally recognized as one of the most efficient herbicides and biological control agents on the market today. Consider the difference in action selectivity between marijuana and PGR. Marijuana has a more selective effect, perhaps due to its fast detoxification process. Low concentrations of these chemicals promote cell elongation, biofertilizer activity, cell division, and cell growth. Dense doses cause weeds to get intoxicated and exhibit developmental abnormalities such as impaired respiration, carbon absorption, and transpiration. In the end, these anomalies harm weeds' circulatory systems and membranes, leading to their demise [14].

3.3 Botanical biopesticides

When applied to crops, pesticides (chemical compounds and plant extracts) are used to prevent the growth of pests (including insects) of various types. Pesticides are used to limit, halt, or otherwise manage pests of many kinds, including insects. Some ways in which plant security may be achieved include the utilization of a variety of secondary metabolites produced from plant sources such as essential oils, phenolics, and terpenes, among other things [44]. The non-persistence of essential oils in the environment, along with the fact that they are non-toxic to animals, has led to their being widely regarded as one of the most efficient agricultural pesticides presently available. As acaricides and insecticides, these compounds have the

potential to be utilized in the environment, where they may also be used to inhibit the growth of fungus and bacteria. When essential oils are applied to plant cultures, the anti-oxidant properties of the oils protect the plants from pro-oxidants found in proteins and DNA, which cause cytotoxicity, the formation of reactive oxygen species, as well as the breakdown of cell membranes and organelles in the microorganisms that infect the plants [45]. However, the effectiveness of a biological pesticide can be affected by several factors, including the mist of the substance harvested, the method of extraction used to obtain this type of biopesticide, and the age of the plant from which the oil will be collected. The toxicity of a biological pesticide can also be affected by several factors, including the phenological age of the plant from which the oil will be collected. Although agricultural pesticides have many advantages, their use has been restricted for a variety of reasons, including their inability to maintain stability over time, the complexity of the extracted combination, extraction techniques, or formulation of the active component, as well as difficulties encountered during the purification process [46].

There are a number of plants that have been recognized as intrinsic sources of agricultural pesticides, as described in **Table 1**. The pests that are targeted by the insecticides contained in those plants are also included in the table. The ethanolic plant extracts of ginger (*Zingiber officinale*), turmeric (*Curcuma longa*), pepper (*Capsicum frutescens*), lemon (*Citrus limon*), and garlic (*Allium sativum*) have been shown to significantly inhibit the growth of *Fusarium oxysporum* sp., *Alternaria*

Plant	Host	Target pest	Reference
<i>Allium sativum</i>	Human and animal sp., <i>Oryza</i> sp., <i>Gossypium hirsutum</i> , Stored grain products; <i>Vigna unguiculate</i> , <i>Brassica oleracea</i>	<i>Colletotrichum</i> sp., <i>Bacillus subtilis</i> , <i>Salmonella senftenberg</i> , <i>Staphylococcus aureus</i> , <i>Staphylococcus epidermidis</i> , <i>Sitotroga cerealella</i> , <i>Spodoptera littorals</i> , <i>Tenebrio molitor</i> , <i>Callosobruchus maculatus</i> , <i>Plutella xylostella</i> , <i>Brevicoryne brassicae</i>	[47–49]
<i>Azadirachta indica</i>	<i>Vigna unguiculate</i> , <i>G. hirsutum</i> , <i>Solanum tuberosum</i> , <i>Triticum</i> sp., <i>Brassica</i> sp., <i>Prunus salicina</i> , <i>Lycopersicon esculentum</i> , <i>Capsicum chinense</i> , <i>Cardamomum</i> sp.	<i>Aphis craccivora</i> , <i>Aphis gossypii</i> , <i>Amrasca devastans</i> , <i>Myzus persicae</i> , <i>Sitobion avenae</i> , <i>Lipaphis erysimi</i> , <i>Bemisia tabaci</i> , <i>Sciothrips cardamomi</i> , <i>Rhizopus</i> sp., <i>Aspergillus</i> sp., <i>Monilinia fructicola</i> , <i>Trichothecium roseum</i> , <i>Pythium aphanidermatum</i> , <i>Alternaria alternata</i> , <i>Helminthosporium</i> sp., <i>Vibrio cholerae</i> , <i>B. subtilis</i> , <i>Meloidogyne javanica</i> , <i>Meloidogyne ingognita</i>	[50–52]
<i>Tagetes</i> spp.	<i>Gladiolus grandifloras</i> , <i>Leucadendron</i> , Human and animals sp., <i>B. oleracea</i>	<i>Fusarium oxysporum</i> , <i>Klebsiella pneumoniae</i> , <i>B. brassicae</i> , <i>Plutella xylostella</i> , <i>Mamestra brassicae</i> , <i>Meloidogyne incognita</i>	[53, 54]

Plant	Host	Target pest	Reference
<i>Thymus vulgaris</i>	<i>Gallus gallus domesticus</i> , <i>Triticum aestivum</i> , <i>Solanum lycopersicum</i> , <i>Citrus aurantium</i> , <i>Cajanus cajan</i> , <i>G. hirsutum</i>	<i>Xanthomonas vesicatoria</i> , <i>Escherichia coli</i> , <i>Salmonella typhimurium</i> , <i>Diaphorina citri</i> , <i>Megalurothrips sjostedti</i> , <i>Eloidogyne incognita</i> , <i>Helicotylenchus dihytera</i> , <i>Pratylenchus brachyurus</i>	[55–57]
<i>Cinnamomum zeylanicum</i>	<i>Zea mays</i> , <i>Pinus densiflora</i>	<i>Botrytis cinereal</i> , <i>Penicillium expansum</i> , <i>Aspergillus oryzae</i> , <i>Fusarium solani</i> , <i>E. coli</i> , <i>S. aureus</i> , <i>B. subtilis</i> , <i>S. typhimurium</i> , <i>Bursaphelenchus xylophilus</i> , <i>Meloidogyne</i> sp.	[58, 59]
<i>Curcuma longa</i>	<i>T. aestivum</i> , <i>Prunus persica</i> , <i>B. oleracea</i> , <i>S. lycopersicum</i> , Human sp., Animal sp.	<i>Tribolium castaneum</i> , <i>Bactrocera zonata</i> , <i>Trichoplusia ni</i> , <i>Alternaria solani</i> , <i>Streptococcus pyogenes</i> , <i>Streptococcus mutants</i> , <i>Ralstonia solanacearum</i> , <i>E. coli</i> , <i>Listeria monocytogenes</i> , <i>B. subtilis</i>	[60, 61]
<i>Zingiber officinale</i>	<i>S. lycopersicum</i> , <i>Arachis hypogaea</i> , <i>Coffea</i> sp., <i>Mangifera indica</i> , <i>Oyza sativa</i> , <i>B. oleracea</i> , <i>Clarias gariepinus</i>	<i>Aspergillus parasiticus</i> , <i>E. coli</i> , <i>Salmonella typhi</i> , <i>T. castaneum</i> , <i>Drosicha mangiferae</i> , <i>Trichoplusia binotalis</i> , <i>Necrobial rufipes</i> , <i>Dermestes maculatu</i>	[62, 63]

Table 1.
The potential plant compounds as botanical pesticides and respective target pests.

solani, *Rhizoctonia solani*, *Pythium ultimum*, and *Lycopersicum* sp. [64]. Regarding growth inhibition, turmeric (*Curcuma longa*) has been shown to be the most effective herb, with results against *Alternaria solani* reaching up to 73 percent effectiveness. *In vitro* studies have demonstrated that the herbs *Rosmarinus officinalis*, *Rhus coriaria*, and *Eucalyptus globulus*, among others, effectively inhibit the development of the pathogen *Pseudomonas syringae* tomato [65]. A study conducted in a greenhouse showed that the *Eucalyptus globulus* tree was very efficient in reducing the bacterial specks of tomato (*Pseudominas syringae* p.v. tomato) to a degree of as much as 65% when cultivated in a greenhouse. In one research, when juvenile root-knot nematodes (*Meloidogyne* sp.) were exposed to extracts of the *Nerium oleander* at a 5 percent concentration and the extracts were applied topically, the mortality of the worms increased. When treated with extracts of *A. sativum*, *Eucalyptus* sp., *Azadiractha indica*, *Cinnamomum versicolor*, *Zingiber officinale*, and *Nerium oleander* at a concentration of 10 percent, the mortality rate of insects on second-stage juveniles ranges between 65 and 100 percent, and when treated with a concentration of 20 percent, the mortality rate ranges between 65 and 100 percent [66].

4. Limitations of biopesticides

Because of a number of factors, biopesticides are not widely utilized as a pest and disease management alternative, despite the fact that they offer many benefits, including the preservation of the environment and the safety of food for human consumption. For the component compounds to be effective in field settings, high dosages of the compounds are required [67]. The emerging evidence revealed that the biopesticides isolated from plants have to face more challenges regarding activity because they are extracted from plants that also contain several other bioactive compounds that could change their chemical properties. Moreover, the utilization of organic compounds as a solvent for the extraction of pesticides is involved in environmental pollution through their disposal. It was also found that biopesticides have a short shelf life that is associated with a high biodegradability rate. In addition to botanical pesticides, microbial pesticides could prove to be better pesticides for a limited type of pest in the field, but they only showed activity against one type of pest, that is one of the biggest disadvantages of microbial pesticides. Furthermore, other environmental factors such as desiccation, heat, light, and UV reduce the activity of microbial pesticides, resulting in continuous crop destruction [68].

The number of bioactive compounds present in plants and the kind of habitat in which they develop is influenced by the environment in which they are grown. Furthermore, the diversity of plants and their differences have an impact on the amount and kind of active chemicals contained in them, resulting in differences in how they respond to illnesses [69]. The quality of plant extracts, on the other hand, varies depending on the extraction method employed. It may be difficult to get the appropriate active and inert components ratios during the formulation process in certain instances. Aside from that, there are no established processes for preparation or assessment of efficacy, especially in field situations when time is of the essence [70]. However, although *in vitro* studies provide positive results, field outcomes are often inconsistent, in part due to the short shelf life of source materials and, in certain instances, the low quality of source materials and preparation methods. In order to use predatory biopesticides effectively, it is essential to do a thorough assessment of the host crops and their dispersal capacities. A manual application may be prohibitively expensive on small acreages because of the time commitment required to guarantee adequate crop coverage and exposure length. In order for products to be registered, data on chemistry, toxicity, packaging, and formulation must be supplied, which is not always the case in the pharmaceutical business [71].

5. Nanotechnology

From 1959 to 1960, developments in nanotechnology and nanoscience have been made to explore the synthesis and role of nano-particles prior to using them for different biomedical applications. Norio Taniguchi, a professor at Tokyo University of Science, made several successful attempts to synthesize nanometer-sized semiconductors in 1974. Later, it laid the foundation for research to perform experimentation on different types of nano-particles and nanocomposites. Nano-particles are found naturally in plants such as algae in the form of superoxide nano-particles and insects in the form of nanostructures. Nano-particles can be synthesized through physical, chemical, and biological methods [72].

Nano-particles fabricated via physical, chemical, and biological methods are classified by their chemical composition. Nanoparticles in the form of metals such as Cu, Fe, Zinc, Au and in the form of oxides such as ZnO, CuO, AlO, in the form of

semiconductors such as ZnS, CdS, ZnSe, carbon-based nano-particles in the form of graphene, diamond, fullerenes, in the form of silicates such as nano clays, in the form of nano-particles based on dendrite with long chains of fibers [73]. Different nano-particles are divided into different dimensions on the basis of their application in different biomaterials. The one-dimensional object possesses thin layers and fine surfaces. Second-dimensional possesses the wires with excellent flexibility and long tubes. Third-dimensional materials can be synthesized from metal oxides through physical and biological methods. These dimensions of the nano-particles have different applications in the fields of agriculture, medical, pharmaceuticals, pest management, and different industrial sectors [72].

5.1 Nano-biopesticides

Nano-biopesticides are attractive due to their tiny size, high surface-area-to-volume ratio, stability, enhanced efficacy, better solubility, mobility, and decreased toxicity. Nano-biopesticides are also suggested because of their low toxicity (see **Figure 1**). Chemical pesticides are directly applied to plants can possess toxins released by air into the food chain and cause environmental issues. To control these issues, pesticides with formulations of nano-particles such as micelles and nano-composites reduce the chances of both environmental and health issues. Similarly, clay-based nanotubes deliver pesticides to control pests [75].

Like nano-fertilizers, nano-biopesticides are contained in carriers that enable for regulated release of active ingredients to accomplish desired effects in a given environment. Stiffness and penetrability are two properties enhanced by adding nano-biopesticides to biopolymers. Crystallinity, thermal stability, solubility, and

Figure 1.
The importance of nanotechnology for the formulation of nano-based biopesticides. This figure is reproduced from Lade et al. [74].

biodegradability are also enhanced [76, 77]. When nanomaterials were applied to the soils, nano-biopesticides containing nanomaterials resulted in the growth of mutualistic microorganisms that promote the plants' activities [17]. Sometimes, toxicity can be induced by coatings of silver-based nano-particles that could be reversed by biocompatible coatings, thus increasing the chances of seed germination in plants. Recently, nano-emulsions, nano-encapsulates, nanocontainers, and nano-cages have been reported as some nano-pesticide delivery techniques with different functionalities for plant protection [77].

Further research shows that cationic polymers may bind to polyanionic surfaces of bacteria, disrupt cell membranes, and kill pests. In agriculture, plants may be treated with biopesticides, such as nano-biopesticides, which can decrease microbial resistance, whereas chemicals applied directly to plants are unable to suppress a wide range of bacterial growth. Tertiary ammonium groups may be found in nano-particles as lengthy amino acid chains. Depending on their structure, these groups may attack various pests and illnesses, including bacteria. Because of their high activity in a wide variety of environmental and chemical conditions, polymers with quaternary ammonium groups in their chains are widely used [78]. Many polymers with this characteristic have been found and researched throughout time. For example, amphiphilic copolymers, functionalized cationic polycarbonates, poly(amidoamines), polyethylenimine, poly(methyl methacrylates), amino celluloses and chlorinated cellulose acetates are now available [78–80].

Essential oils (EOs) are highly volatile secondary metabolites found in many higher plants and flowers and certain fruits and vegetables. In addition to their traditional uses in medicine and cosmetics, a new study indicates they represent a major natural source of ecologically friendly pesticides. Essential oils are often used to treat gardening plants to keep insects and bees out of the garden. Invertebrates become neurotoxic when their nervous systems are suppressed of GABA and acetylcholine esterase (ACE) [81]. This 2007 research evaluated the anti-pest effects of plant extracts, essential oils, their purified components, and plant-based nano-formulations, as well as their modes of action. Temperature, light, and oxygen supply all have an impact on the EO's integrity. Researchers found that encapsulating flaxseed in gelatin and Arabic capsules may improve effectiveness by up to 84 percent, preventing the production of certain oxidants that stimulate the growth of some insects [82]. Sagiri *et al.* [83] summarized many techniques for encapsulating vegetable oils, including associated production processes, antimicrobial applications, insecticide/pesticide/pest repellent formulations, and antimicrobial applications. Purslane mustard, according to the manufacturer, is efficient against *Sitophilus granaries* and other grain-feeding insects. Using nanotechnology to control weevils and other pests improved their efficiency by about 7%, 21%, and 98%, according to prior research [84].

A variety of plants with nano-emulsions of ECs can be used to control the larval infections of different insects. These plants are *Tagetes minuta*, *Ageratum conyzoides* and *Achillea fragrantissima* used to control the growth of *Callosobruchus maculatus*. These nano-emulsions can be applied to kill or inhibit the growth of eggs and larvae in the form of fumes with treatment ranges from 16.1–40.5 $\mu\text{L/L}$ air and 4.5–243 $\mu\text{L/L}$ air, respectively [85]. The encapsulation of EOs can be performed through the use of nano-particles composed of liposomes and solid lipids. Encapsulation of EOs can be carried out through inverse gelation and oil emulsion [86]. Encapsulation of EOs through liposomes is helpful against microbes by protecting the cell membrane from the effects of EOs [87]. However, different types of nano-particles are used for pest management. Microparticles are also used to stabilize the effects of EOs. The encapsulation of carvacrol was performed with

a diameter of 0.5 μm with the cell wall of *Saccharomyces cerevisiae* to control the larvae of *Rhipicephalus microplus* and LC50 formulations of about 0.71 mg/mL. The cell wall of *Saccharomyces cerevisiae* appears more helpful in maintaining the low volatility of encapsulated carvacrol that maintains the acaricidal activity up to 60 hours [88].

5.1.1 In vitro nano-biopesticides bioassay

Nano-biopesticides can be tested against a specific pest in order to check their efficiency before applying them in different crops. Nano-biopesticides can be synthesized through the active pesticidal compounds and combinations of different nanomaterials such as zinc oxides, silver oxides, and aluminum oxides [89]. The toxicity of nano-biopesticides can be measured through the minimum inhibitory concentration that employs the agar well diffusion method. Filter paper is usually coated with the outer surface of nano-biopesticides, and oral feeding directly applies to the target pest. The concentration of dead and alive pests can be precisely measured after 40 days of feeding [90].

5.1.1.1 Pupicidal activity

The pupicidal activity of nano-biopesticides is helpful in preventing the attack of pupae of different insect groups. It can be measured after applying the nano-biopesticides applied to the pupae of the target insects. This activity strongly measures the mortality rate after one day, which depends on the concentrations of nano-biopesticides. The work of Sivapriyajothi *et al.* [91] shows that nano-particles from the extraction of *Leucas aspera* show pupicidal activity in the concentration values (LC 50 and LC 90) for killing the larvae of mosquito vectors such as *Aedes aegypti*.

5.1.1.2 Larvicidal activity

The larvicidal activity of nano-biopesticides can be measured by the leaf disc method by introducing them into the leaf, and concentrations of larvae can be determined after 96 hours. Some plants show larvicidal activity, such as leaf extract of *Ambrosia arborescens* which is helpful for larvae of some pests in concentrations such as LC50 = 0.28 ppm and LC90 = 0.43 ppm [92].

5.1.1.3 Anti-feeding activity

The anti-feeding activity of nano-biopesticides can be measured by applying them to the leaf disc of pest food. The one-third-instar larva is introduced to the leaf, and the condemnations of leaf eaten by larvae can be measured every 24 hours. Anti-feeding activity has been observed about 92.4% in *Helicoverpa armigera* by applying silver-based nano-biopesticides [93].

5.1.2 In vivo nano-biopesticide treatment

Nano-biopesticides can be applied to plants in the right concentration in order to protect them from seasonal diseases. These concentrations (LC 50 and LC 90) aid in the identification of specific larvae, insets, and bee attacks. Nano-biopesticides are also applied in changing environments such as temperatures, humidity, and environmental stresses. In these conditions, nano-biopesticides are directly applied

in the form of sprays to protect the plants from pest attacks. Therefore, the use of nano-biopesticides has become the most effective method in controlling the attack of animal vectors and disease-transmitting pests.

5.1.3 Activity against stored grain pests

Pests of stored grains are among the most difficult to manage in an agricultural system because of their large size [94]. Recently, it has been shown that alumina, silica, SiO₂, zinc, and silver nano-particles have a substantial anti-pest effect against a range of pests when combined with other chemicals [95]. According to the researchers, when sprayed on plants or crops, nano-emulsions have been shown to be efficient in deterring the attack of insects that cause harm to grains that have been stored for extended periods of time. The researchers discovered that nano-biopesticide emulsions effectively prevented the spread of the *Tribolium castaneum* fungus in one of the case studies they conducted [96]. In this study, oil/water emulsions of *P. anisum* essential oil (14 percent, v/v of the total coarse emulsion), ethanol (3 percent, v/v), and Tween 80 (3 percent, v/v), which together represented 20 percent (v/v) of the total coarse emulsion, as well as various components, were used. The emulsions were properly mixed and kept at 86°C for 1 hour. Separating the mixture from the water was accomplished by centrifuging it at 10,000 g for 15 minutes (which made up 80 percent of the mixture). A technique known as photon correlation spectroscopy was used to evaluate a variety of characteristics such as conductivity, zeta potential of the emulsion, and polydispersity index. Contact and digestion techniques on the insects in the medium were used to assess the insecticidal activity of the *P. anisum* emulsified with nano-particles. During the testing against the insects in the medium, the researchers discovered that the *P. anisum* emulsion incorporating nano-particles proved to be very effective. Different concentrations of nano-emulsions can be prepared by acetone in 50 mL bottles containing the 20 g mash grains. The positive and negative controls as emulsions of *P. anisum*. Different groups of 20 beetles were properly made in the sex ratio of 1:1 and then transferred to 50 mL bottles containing the treated and control grains, and each concentration was recorded as three replicates. The mortality rate was carefully recorded after treatments with 3-day intervals till 12 days, while on the other hand, the mortality rate with essential oil containing the beetles was recorded at intervals of 48, 72, and 96 hours. Those insects that were survived and were attached to grain were removed. F1 progeny were recorded 60 days after insect infestation to avoid generation overlaps, as elaborated by Tofel *et al.* [97]. Standard procedures were used to determine the LC 50 values that were used to control the attack of beetles and to understand the morphological changes associated with the nano-emulsions.

6. Methods for nano-suspensions preparations

Creating nanosuspensions may be accomplished using two distinct approaches, which are referred to as the bottom-up approach and top-down technology. The bottom-up approach is the more traditional way of creating nanosuspensions. In order to achieve top-down drug particle reduction, a number of techniques such as high-pressure homogenization and media milling are used. Following the bottom-up approach, pesticides (that are to be converted into nanosuspension) are solubilized in a suitable organic solvent and precipitated with the aid of a suitable stabilizer that has been dissolved in an antisolvent as a result of this solubilization and precipitation (often water). Methods such as precipitation, microemulsion, and melt emulsification, to name a few, are among the most often used in this method, and they are

described in more detail below [98, 99]. The following are some of the most important methods for the production of nanosuspensions, which are described below.

6.1 High pressure homogenization method

The advantage of this method is the production of pesticides that are poorly soluble in water via the use of high-pressure homogenization. Successful completion of this procedure depends on completing three essential steps: In the first stage, a finely powdered medication is dispersed in a suitable stabilizer solution, resulting in a pre-suspension that is then subjected to further treatment after being stabilized. The pre-suspension is homogenized at a low pressure throughout the following procedure to guarantee consistency. Finally, but certainly not least, it is homogenized at high pressure for about 10 to 25 cycles, or until the desired size is achieved. Despite this, this method is only suitable for the production of highly concentrated nanosuspension formulations rather than diluted nanosuspension formulations since the pesticides must be micronized before they can be delivered to the field [99, 100].

6.2 Precipitation and homogenization methods

It has been shown that when exposed to high temperatures, precipitated plant extract nano-particles may crystallize and transform into microparticles. Greater energy pressures are thus required to homogenize them in order to avoid the development of microparticles. Because of their crystalline structure, these particles, which may be completely amorphous, completely crystalline, or slightly amorphous in nature, may cause bioavailability and long-term stability problems when used in pesticide formulations. It is necessary to homogenize the precipitated nanosuspension before it can be used to maintain the particle size achieved during precipitation. This method also has the benefit of being able to be used to produce pesticides that have low solubility in both organic and aqueous solutions, which is advantageous in both cases [101].

6.3 Media milling method

In this method, the plant extracts are exposed to an ultra-fine grinding medium, which results in the production of extract particles of a nanometer or smaller diameter. As a consequence of the contact of extracted particles with the milling medium, higher energy shear forces are produced throughout the milling process. This provides the required energy input to induce the microparticles to burst into nano-particles during the operation. For many days, milling material, which may consist of extract, a stabilizer, and water or another appropriate buffer, is rotated at a faster speed than the rest of the milling chamber and spun at a slower speed than the rest of the milling chamber [102].

6.4 Precipitation method

When the plant extract is dissolved in an organic solvent of choice, it is dried, which is referred to as precipitation. The surfactant is mixed with water (antisolvent), which also includes surfactant, to create a cohesive combination in order to achieve cohesiveness in the final organic phase of the reaction (aqueous phase). It is feasible to oversaturate the plant extract by adding the prepared organic phase to the aqueous phase in a fast manner (organic solvent to antisolvent). As a consequence, ultrafine particles are produced in large quantities (crystalline or amorphous). This process involves, among other things, the creation of nuclei as well as the growth of

crystals, depending on the temperature. A high nucleation rate combined with a slow crystal development rate is required to do this since a stable solution with a smaller particle size than is presently accessible cannot be achieved without doing so [103].

7. Delivery of nano-biopesticides

Any nano-effective formulation in real-world applications depends on effective distribution. Environmentally friendly use of water, fertilizers, and pesticides is possible using nano-sensors and smart delivery systems (see **Figure 2**). Using satellite pictures of their fields in combination may allow farm managers to identify agricultural pests and collect evidence of stress caused by high heat, floods, or drought. Nanomaterials and GPS will be combined with satellite images of fields to produce a more realistic environmental model. Using this technology, farmers can now change agricultural inputs automatically. So, nano-sensors in the field may be able to detect plant viruses and soil nutrients, allowing for more precise crop management. Pesticide use and contamination will be minimized when slow-release nano-biopesticides contained in nano-particles are delivered to their targets [105]. Another alternative is to utilize a nano-barcode, a new technology that may be used to check the quality of agricultural products. Cornell University researchers used supermarket barcodes to create a low-cost, efficient, quick, and simple method for decoding and detecting diseases and illnesses. The technique was developed using grocery barcodes. These tiny probes or nano-barcodes may be scanned with a microscope using self-folding branching DNA constructs. It is feasible to detect a disease biomarker on agricultural goods or on the farm using a fluorescent color ratio. Because nano-barcodes and pathogen biomarkers are so compatible, any fluorescent-based device capable of detecting infection or illness should be able to recognize them. This continuing study's goal is to create a portable on-site detector that non-experts may utilize [106]. Auxins, plant hormones, are important in root development and seedling establishment

Figure 2.
The schematic diagram of delivery of nano-biopesticides to crop for pest management. This figure is reproduced from Lade and Gogle [104].

in both young and mature plants. Purdue University researchers have created an auxin-detecting nano-sensor that may be used to detect it in the environment. The interaction of auxin with biosensors produces a signal that can be monitored and used to detect the amount of auxin present at different locations along the root's length. Another method is to use mathematics to see whether neighboring cells absorb or release auxin at different rates. This advances auxin research by allowing scientists to better understand how plant roots adapt to their surroundings. This study's findings may help improve agricultural research in the future [107].

Using a micro- or nano-emulsion may enhance nano-biopesticide solubility, kinetic stability, optical transparency, and bioavailability while decreasing emulsion size and viscosity [108]. Despite not being intended for agricultural usage, a nano-permethrin formulation free of artificial polymers and stabilized with natural plant surfactants was shown to be an efficient larvicide. Developing nano-particles that act as a coating or protective layer for conventional nano-biopesticides and fertilizers may also be a future research topic. According to the National Science Foundation, nano-clay materials provide high aspect ratio interaction surfaces for encapsulating "agrochemicals such as fertilizers, plant growth stimulants, and insecticides" [109]. Incorporating silver nano-particles into electrospun polyacrylonitrile fibers is intriguing due to the possible antibacterial characteristics. This method may be used to entrap an active biopesticide or a nano-biopesticide for use in soil-applied pesticides or insecticides. To kill the soilborne bug, an electrospun nanofibrous mat loaded with nano-biopesticides is electrospun into the soil and subsequently removed [110].

8. Mechanism of action of biopesticides

Biopesticides have a variety of distinct modes of action that are distinct from one another and may be used in various settings, including agriculture. Through a variety of mechanisms, including parasitism, antibiosis, and predation, among others, microorganisms generate pesticides that are harmful to humans and animals. Botanical pesticides have been shown to be very effective since they kill insects while also interfering with the development of diseases. Prey is killed as a result of the attack by being parasitized or poisoned, which leads them to die as a result of the attack. Pests are attracted to the treatment area as a consequence of the application of the treatment, which results in the pests being killed or sterilized (see **Figure 3**). Extracts from plants belonging to the Asteraceae family have been reported to inhibit hyphal growth and induce structural modifications in the mycelia of plant pathogenic fungi [112]. *Asteraceae* plants contain compounds such as flavonoids, coumarin alkaloids, and terpenoids, leading to absolute fungal toxicity. Some compounds lead to changes in the cell wall as well as the morphology of cellular organelles [113]. As a result, when bioactive chemicals come into contact with fungal cell membranes, they may induce partitioning and penetration, which will allow the contents of the cell to escape via a hole created by this partitioning. In addition, it has been shown that the separation of the cytoplasmic membrane induced by plant bioactive substances results in the destruction of intracellular components and the growth of cells, ultimately resulting in the death of the cells [114].

There are different types of biopesticides, including sabadilla, pyrethrum, azadirachtin, and fluoroacetate that show different mechanisms of action against pests. For example, the alkaloid toxin of sabadilla significantly caused the loss of nerve cell membrane mechanism by affecting the nerve cell membrane of insects. It was found that sabadilla could kill most insects immediately after its use, but a few could survive up to few days in a state of paralysis before dying [115]. In addition,

Figure 3.
The general mechanism of action of nano-biopesticides for pest insect management. This figure is reproduced from Mossa, [111].

the emerging evidence revealed that a low dose of pyrethrins significantly causes the immediate death of insects. For humans and warm-blooded animals, pyrethrins are not toxic. Allergic responses to humans, however, are frequent. It may cause a rash, and inhaling the dust can lead to headaches and illness. By altering the process of sodium and potassium ion exchanges in insect nerve fibers, pyrethrins exert their deadly effects by inhibiting the normal transmission of nerve impulses. The insecticides containing pyrethrin work very quickly and produce paralysis in the insects very quickly. But many insects can swiftly metabolize (break down) pyrethrins in spite of their acute toxicity. However, piperonyl butoxide (PBO) and pyrethrin could be used as combined therapy against these insects [116].

A recently reported study revealed that administration of azadirachtin to third instar larvae significantly reduces food consumption compared to control [117]. But, its antifeedant activity surely depends on the insect species and dose concentration [118]. It was reported that the inhibition of feeding behaviors after azadirachtin dose from stimulation of deterrent receptors was coupled with sugar receptors that lead to food restriction, starvation, and bad nutrition [119]. Recently, various studies have demonstrated the weight loss behavior of azadirachtin in different insects, including *Spodoptera eridania*, *Periplaneta americana*, *Drosophila melanogaster*, and *Helicoverpa armigera* [117, 120]. The pesticide mechanism of action of fluoroacetate is well known; it was reported that after ingestion of fluoroacetate by insects, it converted into fluoroacetyl-CoA and after that, into fluorocitric acid. However, the structure analogue (fluorocitric acid) to citric acid blocked the activity of an enzyme that was involved in the conversion of citric acid to cis-aconitic acid resulting in the energy production method being stopped. Due to the accumulation of citric acid inside the cell, the concentration of α -ketoglutaric acid, calcium, and glutamic acid reduced that resulting affected the nervous system of the insect because the nervous system is very sensitive to these acids, especially glutamic acid which is an essential neurotransmitter [115]. When bugs are exposed to insecticides such as allicin, which may be found in garlic bulbs (*A. sativum*),

they suffocate and die. When applied to insects, allacin acts by interfering with the neurotransmitter receptors in their nervous systems. Suffocation is caused by substances such as allacin. Phytotoxins and terpenoids biochemically interact with insects via hydrophobic and ionic interactions. In addition, a large number of proteins are targeted and destroyed, resulting in physiological failure and degeneration. Plant extracts and essential oils include a range of compounds that may interact with an insect's nervous system and coordination, resulting in the insect's death as a consequence of the disruption produced by this contact [121].

9. Environmental sustainability of nano-biopesticides

Nano-biopesticides are eco-friendly, possess biodegradation properties, and are transported to the different parts of plants. Due to their bioavailability in the plant system, they are helpful in understanding the interactions and behavior of different pests that tack on crops. Spraying silver nano-particles with combinations of aloe vera extract and silver nitrate is helpful to control the growth of pests such as *H. armegera*. Formulations of biopesticides through nanotechnology help to control the harmful pests that attack crops [122]. Nano-biopesticide applications in plants not only control pests but also control environmental pollution by reducing the risks of accumulations of toxic metals in plants, which are helpful in cleaning the environment. For example, the delivery of zinc-based nano-biopesticides to roots protects the plants as they exhibit high efficiency compared to the toxic chemicals directly applied to plants. Nano-biopesticides are also helpful in the bioremediation process by degrading toxic compounds [123, 124].

Nano-biopesticides are biodegradable and transported to the different tissues of pants. Some studies have shown that soil applications of nano-biopesticides under optimum conditions are helpful for the degradation of toxic metabolites that are produced in plants. These metabolites cause the accumulation of toxic metals. It leads to an increase in the chances of death of plant tissues. On the other hand, traditionally used chemicals also increase the chances of death of plant tissues due to

Figure 4.
The general process of formulation of nano-fertilizer to commercialization. This figure is reproduced from Lengai and Muthomi [128].

cellular toxicity in some cells. Therefore, the use of nano-biopesticides in environmental applications is much more reliable than other chemical compounds [125]. Nano-biopesticides reach the soil by activating the microbial activities that increase the chances of useful bacterial activities in plants such as mycorrhizal association.

Nano-biopesticides play an important role in maintaining environmental sustainability by replacing traditionally used chemicals in the form of sprays. The use of nano-biopesticides to control the pests also maintains the ecological chain. Nano-biopesticides for land conservation ensure the maximum yields and maintain the farming system. So, nano-biopesticides are also helpful for improving soil quality and increasing food yields under different cultivations. Other applications are found in crop protection by controlling pests and other animals such as bees and birds through sustainable development [126, 127]. The representation of the process of formulation of nano-biopesticides to fully commercialization is presented in **Figure 4**.

10. Future perspectives

Nano-biopesticides are used in the control of pests in order to prevent their action in agriculture sectors. These bio-pesticides will be helpful in targeting the different pests in more effective ways by reducing the chemical compounds in order to make profitable and environmentally friendly production. Due to unclear molecular mechanisms and sites of action to the target of the action, research progress for pest control in agriculture is slow [129]. Recent studies show that applications of nano-biopesticides are effective in controlling pests by replacing the traditionally used chemical compounds. These nano-biopesticides have fewer side effects as compared to directly applied chemical compounds. Nano-biopesticides have great potential to release active ingredients that are helpful in maintaining the different problems associated with agricultural systems, such as eutrophication. Although nano-biopesticides are widely used in different crops to control pests, their utilization in humans and animals remains unclear as they have entered into the food chain. More study is needed to characterize and formulate newly developed nano-biopesticides for controlling the different varieties of pests by ensuring no side effects on humans through the food chain [130].

As the world population increases rapidly, the feeding of humans will reach approximately 9 billion by 2050. It requires lots of nano-biopesticides to kill the pests and for the storage of food for long periods of time. It will be an emerging approach towards pest management that maintains environmental sustainability with fewer toxic effects on human health. The use of nano-biopesticides is also helpful in maintaining the nutrient balance in crops, minimize the risks to food security, and accumulating hazardous materials [131]. Nano-biopesticides have been extensively used in the agricultural fields for pest management or arthropod attack, but they possess chemical formulations that contain nano-particles that lead to toxicity concerns and health issues. These nano-biopesticides need to be standardized internationally to reduce their toxic effects on crops and the food chain. The use of nano-biopesticides in agriculture looks promising, but more research is needed in order to understand their toxic nature and monitor their application time to soils [132].

11. Conclusions

Approximatively, 25% of the world's food yield is destroyed each year by the attack of pests. According to recent studies, using synthetic pesticides has been related to an increase in some illnesses, including Parkinson's disease, neurotoxicity,

type 2 diabetes, endocrine disruption, various malignancies, and even obesity. Insecticides produced from microorganisms or natural compounds are known as biopesticides. Due to their eco-friendliness, great efficacy, and few side effects, nano-biopesticides have gained in popularity over conventional pesticides over recent years. Biologically active pesticide compounds (APCs) may be produced in two ways: either by extracting APCs from plants and combining them with nano-particles or by inserting them into a polymer. As a result of their nano-size, high surface area/volume ratio, durability, enhanced effectiveness, greater solubility, mobility, and low toxicity, nano-biopesticides are superior to chemical pesticides. Biopesticides inhibit pathogen's growth by altering their cellular structures and morphology and exhibit neurotoxicity on insects. As a result, nano-biopesticides are environmentally benign and have biodegradation characteristics; they assist in cleaning the environment by reducing the danger of harmful metal buildup in plants. However, the use of nano-sensors and nano-based smart delivery systems could help in the efficient use of agricultural, natural resources such as water, nutrients, and chemicals through precision farming. Moreover, it is recommended to use a nano-barcode, which is a novel method to monitor the quality of agricultural products.

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