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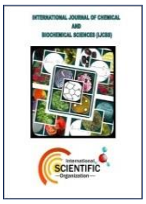

Biopesticides: A Green Substitute to Chemical Pesticide

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Abstract

Chemical pesticides have played a significant role in agriculture for a long time, efficiently reducing pests and boosting crop yields. However, because of its widespread use, there have been reports of harmful effects on human health and the environment. There has been an increase in interest in researching safer and more sustainable pest control solutions over the past several decades. Biopesticides have emerged as an effective alternative to chemical pesticides, with various advantages in terms of efficacy, environmental impact, and human health. They are obtained from natural sources and have the capacity to control pests through naturally occurring mechanisms. They can target pests without affecting the ecosystem because of their short residual periods, which decrease the possibility of bioaccumulation. Another advantage of biopesticides is their potential to be incorporated into long-term agricultural operations with other pest management techniques such as organic farming, crop rotation, and biological control approaches to create a more comprehensive and environmentally friendly pest management plan. Some of the barriers to their widespread use include limited availability, higher pricing compared to chemical pesticides, and variances in performance against pests. Continuous research, funding, and stakeholder participation are required to make biopesticides more effective, economical, and accessible, as well as to provide a more resilient and sustainable agricultural system in the future.

Keywords: Biopesticides, Chemical pesticides, Sustainable Agriculture, Nano-Biopesticides, Nano-emulsion

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1. Introduction

Chemical pesticides have been used often in agriculture to safeguard crops against weeds, illnesses, and pests. Chemical pesticides are widely used, however, this has resulted in a number of environmental and health problems [1]. The overuse of chemical pesticides has caused the emergence of pests that are resistant to them, pollution of the soil and water, and the eradication of non-target creatures. As a result, there is an increasing interest in creating biopesticides as alternatives to chemical pesticides [2]. Biopesticides, often known as naturally occurring pesticides, have gained popularity as an alternative to synthetic pesticides for the protection of plant harvests. Biopesticides classified as biochemical biopesticides, botanical biopesticides, or microbial biopesticides, depending on their origin. They can be derived naturally or from living organisms. The growth, feeding, development, or reproduction of a pest or pathogen are just a few of the ways that biological pesticides can effectively decrease pest populations [3]. Non-toxic techniques involving biochemical pesticides can effectively control pests. Biopesticides release endotoxins and enzymes that destroy the cell walls of pests, and they can also introduce viruses to infect the pests. Additionally, these compounds have the capability to impact the development and growth of pests, such as plant growth regulators (PGR) and pheromones that either attract or repel pests. [4]. Some nations establish committees to decide which metabolites fit the criteria for biochemical pesticides because it is still difficult to identify whether biopesticides are hazardous. Since their discovery, PGRs of the auxin type have become one of the most popular and effective biological control agents. When compared to marijuana, plant growth regulators (PGR) exhibit selectivity of action due to the plant's quicker detoxifying process [3].

Biopesticides, derived from natural sources, are effective in controlling pests and diseases. Biopesticides have several advantages over chemical pesticides, including low toxicity, biodegradability, and target specificity. Biopesticides are also effective in controlling pests that are resistant to chemical pesticides [5]. The search for effective and sustainable pest control strategies continues in the ever-changing area of agriculture. The negative effects of chemical pesticides on the environment and human health have sparked interest in alternative remedies. The use of nano biopesticides is one such promising invention. These cutting-edge compositions combine the power of nanotechnology with the advantages of biopesticides, revolutionizing pest control and crop protection [6]. Nano-biopesticides are a potentially effective and efficient method of using biopesticides in pest management. Using the power of nanotechnology, these innovative formulations improve the efficiency and distribution of biopesticide active ingredients. The nanoscale particles used in these formulations provide a variety of benefits, including improved stability, longer activity, and targeted pest delivery. Nano-biopesticides, due to their small size, may more efficiently penetrate the pest's protective barriers, resulting in greater effectiveness [6]. Furthermore, the controlled release features of nano-biopesticides allow for continuous and regulated release of the active components, optimizing efficacy while decreasing environmental exposure. Nano-biopesticides, which make use of nanotechnology developments, provide a highly efficient and accurate method of utilizing biopesticides, resulting in sustainable and environmentally friendly pest management strategies [7]. In contemporary agriculture, biopesticides are a promising alternative to chemical pesticides. They offer an attractive alternative to traditional pest management methods due to their low danger to human health, environmental friendliness, and compliance with sustainable agricultural techniques. To further improve the effectiveness, cost, and accessibility of biopesticides and ensure a more sustainable and resilient agricultural system for the future, stakeholders must continue to research, invest, and collaborate [1].

2. Exploring Pesticides: An Overview, Historical Context, Effects

Pesticides are synthetic or biological substances used to prevent, suppress, or eliminate pests that can harm crops, animals, or people. They are frequently used in home gardening, public health, and agriculture to stop the spread of illness and boost output. This article gives a general overview of the many kinds of pesticides, their applications, and the hazards related to their usage [2]. Even since the dawn of human civilization, humans have been at war with their insect adversaries. Farmers have historically relied on a variety of Indigenous traditional knowledge to guard against pest damage to stored grain goods. Around the world, a number of crop-specific storage methods have been created to preserve the food's quality and quantity until it is consumed or moved someplace else. Farmers created a variety of traditional grain storage buildings utilizing locally accessible raw materials such as cow dung, bamboo, straw, wooden planks, mud, and bricks [8]. It was also typical to employ plant components or plant extracts as natural pesticides. It was the discovery of nicotine, rotenone, derris dirt, and pyrethrum coming from N. tabacum (L) (Solanaceae), D. elliptica (Wall.) Benth. (Fabaceae), and Asteraceae, accordingly, in the 1850s, that resulted in the wide-scale use of botanical extracts as insecticides. Pyrethrum, an insecticide based on pyrethrin isolated from the flower heads of C. cinerariifolium, is highly efficient against a variety of insect pests, including moths and larvae. To prevent stored goods from being harmed by insects in both temperate and tropical regions, it has been utilized internationally. Other plant preparations and extracts have also been discovered to operate against insect pests [9]. A novel substance created in 1939 by Swiss scientist Paul Muller fundamentally altered the future of agricultural workers all over the world. A new age of synthetic pesticides began when Muller created di-chlorodiphenyl trichloroethane (DDT). In the course of World War II, many troops and civilians perished from illnesses spread by insects, including typhus and malaria [8].

3. Types of Pesticides

Pesticides classified as insecticides, fungicides, rodenticides, nematicides, avicides, herbicides, acaricides, and molluscicides, among other things. Each type of pesticide targets specific pests and has unique properties that determine its effectiveness [10]. Insecticides are used to control insects and other arthropods that can damage crops and spread diseases. They are systemic or contact, according to how they work. Systemic insecticides are absorbed by plants and travel throughout the plant, making them toxic to insects that feed on them. Contact insecticides kill insects upon contact and are applied directly to the pests or their habitat [11]. Weeds and undesirable plants are managed with the aid of herbicides. Their chemical makeup and manner of action are used to categorize them. For instance, the broad-spectrum herbicide glyphosate works against a variety of plants by preventing the synthesis of vital amino acids [12]. Fungicides are used to control fungal diseases in plants. They are divided into two categories based on how they work, either preventatively or therapeutically. Preventive fungicides are applied to plants before they are infected to prevent the growth and spread of fungi. Rodenticides are used to control rodents like rats and mice. They are classified based on their mode of action, which can be either anticoagulant or non-anticoagulant. Anticoagulant rodenticides inhibit blood clotting, leading to internal bleeding and death. Non-anticoagulant rodenticides act as nerve toxins, causing paralysis and death [13]. In figure 1 the effect of pesticides on human health is illustrated.

Pesticides are chemicals that are used to control pests and illnesses in crops as well as protect public health. While pesticides have provided major benefits, such as higher crop yields and a lower frequency of vector-borne diseases, their uncontrolled use has also had harmful environmental and health consequences [10]. In figure 1 the effect of pesticides on human health is illustrated.

4. Biopesticides Unveiled: Overview, Types, Pros, Cons, Limitations, and Role

Pesticides known as "biopesticides" come from organic sources, including plants, microbes, and other biological components. They are employed to manage pests in domestic gardening, public health, and agriculture. Biopesticides are typically safer and more ecologically friendly than traditional pesticides, which frequently include synthetic chemical compounds that can have detrimental effects on the environment and human health. We shall examine what biopesticides are, how they operate, and their advantages and drawbacks with this introduction to them [4]. Biopesticides come in a wide variety of forms, and they can be divided not distinct categories based on the sources from which they are extracted and the molecules or compounds they are made of. Following is a list of the categories [15].

Microbial pesticides are created by microorganisms that may directly or indirectly manage pests, such as bacteria, fungi, and viruses. For instance, the insecticide Bacillus thuringiensis (Bt), which is based on bacteria, is frequently used to manage caterpillars and other pest insects [16]. Viruses, fungi, and bacteria are examples of microorganisms that can be used as microbial biopesticides. These biopesticides have the ability to kill or impede the growth of the pests they are intended to control, either directly or indirectly [17]. A bacteria found in soil called Bt makes crystal proteins that are poisonous to a variety of insect pests. It is one of the most often used microbial biopesticides and works well to get rid of pests like beetles, caterpillars, and other critters [18]. A fungus called *B. bassiana* affects a variety of nuisance insects. It functions by growing within the insect and sticking to its exoskeleton, where it finally kills the bug. It works well to get rid of pests, including aphids and thrips [19]. Another fungus that affects a variety of insect pests is *M. anisopliae*. Like *B. bassiana*, it kills pests by growing inside of them after adhering to their exoskeletons. It works well to get rid of pests like termites and mites [20]. A bacterium called P. fluorescens creates a number of compounds that are poisonous to a variety of insect pests. It works well to get rid of pests like aphids and white flies [21]. A safe and dependable biopesticide, baculoviruses are viruses that infect insects. They function by infecting the insect with a sickness that finally kills it. Baculoviruses are useful for eradicating pests like beetles and caterpillars [22].

These plants that have undergone genetic modification generate pesticides. The PIPs produce proteins that are harmful to pests to defend the plants from attack. The utilization of Bacillus thuringiensis proteins to create PIP by genetic engineering is a classic illustration of this. The Bacillus thuringiensis toxin is host-specific and can kill within a brief period, typically 48 hours. It is harmless to humans, other living things, the environment, and vertebrates [23]. PIPs, or plant-incorporated protectants, are a powerful and safe substitute for conventional chemical pesticides. They function by creating pesticide-producing proteins that are common in agriculture and hazardous to pests. PIPs provide various benefits over conventional pesticides and have undergone rigorous research and regulatory assessment to verify their safety and performance [17]. A class of pesticides known as biochemical pesticides is created from organic materials like hormones, pheromones, plant extracts, and other naturally occurring molecules. These insecticides are an efficient and safe substitute for chemical pesticides since they function by interfering with the biochemical processes of pests [24]. These pesticides are thought of as an ecologically benign alternative to chemical pesticides since they are frequently sourced from plants and other organic materials. These biochemical insecticides come in many forms [25]. The neem tree, *Azadirachta indica*, is a plant that produces a substance called azadirachtin, which is frequently used to control insect pests. It is effective on mites, soft-bodied insects, and plant pathogens and is not hazardous to mammals or pollinators. Azadirachtin prevents the production and elimination of molting hormones, causing impotence in adult female bugs and partial ecdysis in juvenile insects. Another result appears to be that its antifeedant activity prevents insect attack [25-26]. Pyrethrins are an insecticide made from the dried petals of *Chrysanthemum cineraria* folium that quickly take down insects and cause them to become hyperactive and convulse. Pyrethrins have a similar method of action to commercial chemical pesticides, primarily affecting the neurotoxic voltage-gated sodium channels in the axons of neurons that inhibit action potentials [25]. Rotenone, extracted from plant species belonging to the genus Lonchocarpus, is an important insecticide that blocks the electron transport chain and prevents energy production by acting as a mitochondrial toxin. The celandine-type alkaloids found in sabadilla, which is generated from the seeds of *Schoenocaulon officinale*, are comparable to pyrethrins and alter the activity of nerve cell membranes, resulting in paralysis and death [25]. Ryania, a slow-acting abdominal toxin, is made from the stem of the *Ryana speciosa* plant and includes the alkaloid ryanodine, which prevents calcium from being released into muscle tissue. Because insects do not instantly stop eating after consuming it, the effect it has is not instantaneous but rather delayed. Chemical pesticides may be effectively replaced with plant-based biochemical pesticides, which are also safer for the environment [25-26].

Insect growth regulators (IGRs) include organic or inorganic substances that prevent insects from growing and maturing normally, which causes their demise. IGRs are an efficient substitute for chemical pesticides that can have broader and more damaging impacts on non-target creatures and the environment because they specifically target stages of bug growth and development [27]. There are three main types of IGRs: These stop the production of chitin, a crucial element of the exoskeleton of insects. The insect dies because it is unable to molt or create a new exoskeleton without chitin. These mimic the action of juvenile hormone, which is responsible for regulating the transition from one developmental stage to the next in insects. By preventing the insect from transitioning to the adult stage, JHMs disrupt normal development and ultimately lead to death [28]. These mimic the action of ecdysone, a hormone that triggers molting in insects. By causing the insect to molt prematurely or at abnormal times, ecdysone agonists disrupt normal development and ultimately lead to death. Several IGRs have been identified and evaluated for their effectiveness as biopesticides, including diflubenzuron, methoprene, pyriproxyfen, and tebufenozide. These IGRs have been shown to be effective against a wide range of insect pests, including mosquitoes, flies, and various crop pests [29]. These biopesticides rely on chemical cues such as insect pheromones or other signals that alter insect behavior. Animals, especially insects, emit a series of chemical molecules known as pheromones to interact with other members of their own species. To manage insect populations, chemical signals like these can be used as biopesticides. One method involves drawing a lot of insects from the mating and feeding populations and eradicating them using mass traps. For instance, ambrosia and pine bark beetles have been effectively mass trapped in British Columbia to lessen damage to wood in newly cut boards and raw logs. Similar to codling moths, a significant pest of apples and pears, and yellowjackets, which harm ornamental plants, mass trapping has been successful against both of these pests [30]. Another strategy includes preventing pest populations from reproducing, which has been particularly effective with agricultural moth pests. To reduce the density of pest populations, synthetic pheromones are sprayed onto crops to produce phony odor plumes that draw males farther away from females who are ready to mate. In certain instances, this technique has been so successful at eradicating pests locally [31]. The codling moth, an important pest of pears and apples, is one example of the successful application of pheromones for pest management. By preventing male codling moths from mating, artificial pheromones lower the number of eggs deposited by female moths, which in turn lowers the pest's population density [32].Like this, ambrosia beetles and pine bark beetles can be mass-trapped to prevent harm to trees. Pheromones are superior to conventional pesticides in a number of ways, including their high specificity and low toxicity. However, elements like temperature, wind, and the presence of competing scents can have an impact on how effective they are. Additionally, the cost of pheromones tends to be higher than that of other pesticides, which may restrict their use [31].

Oils constitute some of the most powerful and secure substitutes for synthetic fungicides and insecticides that have been utilized as pesticides for millennia. Biopesticides classification is given in Figure 2. These include oils produced from plants and animals, as well as oils distilled from petroleum (sometimes described as horticultural or mineral oils). Most oil-based insecticides are used to control insects, but they frequently also contain fungicidal characteristics. All oil-based products possess a similar mechanism of action, regardless of source or kind. On contact, insecticidal oils cause damage to cell membrane structure or function, which results in the immediate death of insects. Neem oil is one example of a plant oil that contains sulfur compounds and may be more fungicidal than petroleum oils [33]. Oil-based insecticides must be applied directly to the insect since they have little residual action. To battle plant fungal diseases, oils are typically applied preventively before infection. To obtain desirable degrees of control, oils may need to be applied repeatedly. Oils work well against arthropods with soft bodies. The most typical insects they are used to combat include mites, aphids, white fly larvae, thrips, mealy bugs, and scale insects [34].

5. Advantages of Biopesticides over Chemical Pesticides

There are numerous benefits associated with using biological pesticides as opposed to chemically produced goods. Biopesticides are produced in an eco-friendly and sustainable way from naturally existing raw materials. Biodegradable insecticides are available. They break down rapidly and don't have a bad effect on groundwater or surface water [34]. They are non-toxic to creatures other than the targets, such as beneficial insects and fauna. Biopesticides have great species specificity, making it less probable that they would damage species outside the target. By doing this, the danger of damaging beneficial insects and the development of pesticide resistance are decreased[35]. They boost plant physiology, resulting in larger and more colorful fruits, as well as crop quality and production by avoiding insect damage. In order to control insect resistance and prolong the useful life of conventional pesticides[25-36].

They have better efficacy at lower concentrations, are purported to be less hazardous, more selective in attacking undesirable biological targets, degrade more quickly, and have less of a negative environmental impact. They can be employed as an active part of IPM to decrease the use of traditional chemical pesticides while maintaining excellent crop yields. However, in order to employ biopesticides efficiently, one must have extensive knowledge of pest management [32]. Biopesticides must be the preferred element in the execution of programs for managing resistance in IPM-related initiatives. They purportedly have fewer harmful side effects, are less toxic, are more selective in their attack on undesirable biological targets, are more effective at lower doses, and degrade more quickly [25]. Due to its significant effects, the agrochemical sector is switching from chemical to botanical products. Both the demand for and awareness of foods devoid of chemicals are growing. Customers are increasingly willing to pay more for goods grown organically without the incorporation of chemicals than the standard costs [25-34].

6. Limitations of Biopesticides

As a result of their high specificity, biopesticides may necessitate a precise identification of the pest, but they also have the potential to be advantageous since they are less likely to damage species other than their intended target [34]. Because of their sluggish rate of action, biopesticides are inappropriate if a pest epidemic poses an urgent threat to a crop [34]. Since some biopesticides are living creatures that suppress pests by proliferating inside or close to the target pest, biopesticides have varying degrees of efficiency due to the impacts of numerous biotic and abiotic variables[34]. It is possible that biopesticides are less accessible than chemical pesticides. This is due to the possibility that they would be harder to create and that there would be less demand. This may make it more difficult for farmers to get to them when they're needed [25]. The effectiveness of biopesticides may be limited by the fact that they frequently have a shorter duration of effect than chemical pesticides. This might pose a particular issue in regions with seasonal pests or those where significant stretches of time pass between attacks [37]. When it comes to managing agricultural pests, biopesticides are just as effective as synthetic pesticides. Natural goods are also environmentally beneficial because they are quickly biodegradable and do not harm the environment. Because consumer tastes and preferences change over time and are influenced by the need for food grown organically, biopesticides are acceptable substitutes for synthetic pesticides [38]. Figure 3 gives a comparison between limitations and benefits of biopesticides.

7. Role of Biopesticides in Sustainable Agriculture

It is safe to apply biopesticides to fresh fruits and vegetables since they have short pre-harvest intervals. Additionally, they have a narrow field of attack, so they do not harm helpful organisms like natural enemies. Their usage encourages sustainable pest control, which helps to support sustainable agriculture. They are effective in modest doses. The development of insect resistance is not a result of using natural pesticides. Since they are present in the natural environment and some of them are utilized for other purposes like food and feed, their raw materials are readily available, making them cheap to get [39]. Due to their lack of toxicity, biopesticides are products that are safe for both the applicant and the consumer. As a result, biopesticides may be effectively included in integrated pest management (IPM), which contributes to a decrease in the quantity of chemical pesticides necessary to manage agricultural pests. Because they break down fast, natural goods are safer for the environment. The applicant's safety is ensured by the extremely small re-entry intervals of natural pesticides. Through the introduction of significant microbial species, biopesticides are also utilized to decontaminate agricultural soils [40].

8. Role of Biopesticides in Integrated Pest Management (IPM)

The term "Integrated Pest Management" (IPM) refers to a comprehensive strategy that combines several crop protection techniques with thorough insect and natural predator monitoring. The fundamental tenet of IPM is that a variety of activities may be combined to make up for the shortcomings of individual practices [41]. Not eradicating pest populations is the goal; rather, it is to keep them under control so that they don't cause financial losses [42]. Integrated pest management (IPM) employs a variety of techniques. Use of synthetic chemical pesticides with excellent selectivity and minimal danger, such as synthetic insect growth regulators. Creating agricultural cultivars with full or partial pest resistance through breeding the use of farming techniques like crop rotation, intercropping, or under sowing[43]. Use of physical techniques, such as mechanical weeders. use of natural compounds such as Semiochemicals or plant extracts that are biocides. Biological control using naturally occurring enemies such as predatory insects, mites, parasitoids, and microbial pathogens against invertebrate pests as well as microbial antagonists of plant infections and microbial pathogens of weeds Making use of decision support technologies to assist farmers in choosing the most financially advantageous way to use pesticides and other control measures [41].

9. Mode of Action of Biopesticide in Crops

9.1. Bacillus thuringiensis (Bt)

The Bt gene encodes for a protein class known as cry proteins (or delta-endotoxins). Bacillus thuringiensis, which is also the name of the gene, produces these cry proteins. The Bt gene is used to allow crops to produce these cry proteins [44]. The cry proteins produced by the Bt gene poison certain insect pests. When insects consume plant parts carrying cry proteins, the proteins bind to specific receptors in the insect's stomach lining [44]. Figure 4 explains the insertion of Bt gene into plant. Once coupled to the receptors, the cry proteins produce holes or channels in the stomach lining of the insect. This weakens the stomach's integrity, allowing gut contents to leak and causing injury to the insect's digestive system [45]. Disruption of the digestive system of an insect has several undesirable repercussions. Among the consequences are nutrient deficiency, paralysis, and death. Cry proteins are very specific to specific insect groups and have no effect on non-target organisms such as humans, animals, or beneficial insects [44]. When agricultural plants express the Bt gene and make cry proteins, they gain the ability to defend themselves against specific insect pests. Certain pests, such as caterpillars, lose their ability to feed on agricultural plants, resulting in less crop damage and increased crop yield [45]. The use of Bt crops has been demonstrated to bring environmental benefits when compared to standard pesticides. Bt crops target pests accurately, reducing the need for broad-spectrum chemical pesticides, which may kill non-target species and disturb ecosystems [45].

9.2. Trichoderma for Fungal Disease Control

Trichoderma colonizes plant roots and the surrounding soil, competing with pathogenic fungi for nutrients and space. Trichoderma prevents the development and establishment of pathogenic fungi by effectively using available nutrients and occupying space, thereby lowering their pathogenicity Trichoderma has mycoparasitic activity, which allows it to parasitize and attack other fungi, especially plant-harmful species. Trichoderma destroys the cell walls of target fungi by producing numerous hydrolytic enzymes and metabolites, resulting in their disintegration and death [46]. Trichoderma synthesizes and secretes a variety of secondary metabolites, including antibiotics, which are poisonous to many plant diseases. These bioactive chemicals disrupt pathogenic fungi's critical metabolic processes, preventing their growth and development [47]. Trichoderma activates the plant's defensive systems through ISR, a complex signaling route. This activation increases the synthesis of defense-related chemicals in the plant, strengthening its resistance to fungal diseases. ISR offers long-term, broad-spectrum protection against a wide range of fungal illnesses [47]. In addition to disease control, Trichoderma has a good impact on plant growth and development. It increases root development by increasing nutrient intake, notably phosphate solubilization. Trichoderma also generates plant growth hormones such as auxins, cytokinin, and gibberellins, which promote healthier, more robust plants that are better able to fight fungal diseases [46]. Trichoderma species are very adaptable to a wide range of environmental circumstances, including varied soil types and climates. This versatility allows their survival and efficacy as biocontrol agents across a wide range of cropping systems, making them a useful tool for long-term disease management [47].

9.3. Azadirachtin for Pest and Disease Control

Azadirachtin disrupts insect growth by interfering with molting and metamorphosis. It inhibits the formation of ecdysone, a hormone required for insect molting. This disturbance stunts larval development and disturbs the insect's life cycle [48]. Azadirachtin has antifeedant properties, which prevent insects from feeding. It lowers their feeding activity when they encounter or ingest Azadirachtin-treated plants. This might result in insect pests starving or losing fitness [49]. Azadirachtin possesses insect repellent properties. It deters them from congregating or feeding on treated areas or plants. This helps to safeguard crops by keeping harmful insects at bay. Insect Reproduction Interference: Azadirachtin interferes with insect reproduction. It has an impact on their mating patterns, fertility, and the survivability of their eggs and progeny. Azadirachtin helps to manage pest insect populations by interfering with their reproductive ability [48]. Azadirachtin possesses insect repellent properties. It deters them from congregating or feeding on treated areas or plants. This helps safeguard crops by keeping harmful insects at bay. Insect Reproduction Interference: Azadirachtin interferes with insect reproduction. It has an impact on their mating patterns, fertility, and the survivability of their eggs and progeny. Azadirachtin helps to manage pest insect populations by interfering with their reproductive ability). Azadirachtin modulates insect feeding behavior, generating changes in feeding preference and acceptance. This disturbance in feeding habits might impede the insect's capacity to collect essential nutrients, resulting in stunted development and survival [49].

10. Nano technology and biopesticides

Using nanotechnology of some biological agents can increase the efficiency against pests while lowering their toxicity toward people and the environment and minimizing losses from physical deterioration. This done by encapsulating the chemicals in nanoparticulate systems, which may aid in the creation of safer, less toxic biopesticides with improved active agent stability. Nanoparticles can help protect neem oil from degradation, ensuring its prolonged effectiveness against pests. However, the impact of nanoparticles on the environment and the toxicity towards components of the agroecosystem is not yet well understood. Additionally, there is still a lack of comprehensive knowledge regarding the variables involved in risk assessment. Despite considerable commercial use, the technology is still in its infancy, raising questions about release rates, storage stability, and cost efficiency. However, nanobiotechnology holds promise for the development of formulations that can increase the potency and stability of natural products, deliver molecules in a controlled manner to the site of action, reduce the risk of toxicity to organisms other than the intended target, and prevent the degradation of the active ingredient by microorganisms [50]. Engineered nanoparticles offer the potential to lessen the harmful effects of pesticides on the environment while simultaneously enhancing their transport and effectiveness. Different nano-formulations can be used to regulate the release of pesticides, enabling the targeted treatment of certain pests or regions and lowering the necessary pesticide dosage for desired results [6]. Surfactants are combined to generate a two-phase dispersion system called a nano-emulsion, in which the active ingredients (AIs) are dissolved in both the oil and water phases [51]. Due to the 20–200 nm nanometer-sized droplets that give this system its kinetic stability, it may be described as either transparent or translucent [52-53]. Poorly water-soluble pesticides are transformed into tiny oil droplets by the oil-in-water (O/W) dispersion method, which dramatically increases the bioavailability and effectiveness of the pesticides [7-54]. Furthermore, compared to conventional pesticide formulations, nano-emulsion greatly reduces the usage of organic solvents and surfactants, which has attracted the attention of researchers in recent years [55-56]. The use of nano emulsions for pesticide administration is illustrated. They created a nano-emulsion solution for their investigation that contained esterified vegetable oils, the herbicide glyphosate isopropyl amine, and 41% (w/w) ecologically friendly surfactants [55-56]. Abamectin (Abm)-loaded nano-emulsion by combining 2% Abm, 5% castor oil polyoxyethylene, and 7.5% hydrocarbon solvent that complied with the Food and Agriculture Organization's (FAO) quality indicators (Feng, Chen et al. 2020). The nano-emulsion had a number of benefits over conventional oil/water emulsions (EW) and microemulsions (ME), including a smaller dynamic contact angle on cabbage leaves, stronger insecticidal action, and decreased cytotoxicity. The most popular method utilizes high-energy emulsification, and although a stable nano-emulsion of pesticides may be easily created, the oil phase and emulsifiers may still pose a hazardous concern [56-57]. Green nano-emulsion of -cypermethrin by combining the non-ionic surfactant polyoxyethylene 3-lauryl ether (C12E3) with the renewable methyl ester of fatty acids (methyl laurate) as the oil phase and "green surfactant" alkyl polyglycolide as the mixed surfactant [56].

Pesticides Active ingredients (AIs) are encased in an assortment of nanomaterials and delivered gradually over time in nano-encapsulation, a cutting-edge delivery method [58]. Encapsulating AIs in nanomaterials can protect them against early deterioration brought on by photolysis, hydrolysis, biodegradation, and other mechanisms [59]. Additionally, leaching and volatilization can prevent unnecessary losses from happening, enhancing their efficacy [60]. The encapsulation system may also display sustained release behavior, prolonging the control time, or may have stimulus-responsive release features for precise control thanks to the rational design of nanomaterials [56-61-62]. Nano encapsulation of biopesticides is explained in Fig. 7. Pesticides can be nano-encapsulated using a variety of nanomaterials, including organic substances (synthetic and natural polymers) [63-64], lipids [65], plant-derived nanoparticles [66-67] (Chariou et al., 2019; Chariou & Steinmetz, 2017), and inorganic materials (silica, carbon, calcium, and clay-based nanoparticles, etc.) to carefully encapsulate the active ingredients (AIs) [61]. This technique increases the bioavailability of AIs and extends their useful lifetimes while protecting them from deterioration and losses [64]. A lot of research has been done on polymer-based nanoencapsulation because of its exceptional biocompatibility and biodegradability. Insecticidal action can be increased by encapsulating hydrophobic or hydrophilic Ais (active ingredients) via lipid-based nano-encapsulation.
The mobility or spread of nematicides in soil can be increased by plant virus nanoparticles, providing crops with improved protection against plant-parasitic nematodes [66]. Large surface areas, variable pore sizes, high loading capacities, and superior biocompatibility make inorganic materials, including silica and calcium carbonate, suitable pesticide carriers [68].

After being encapsulated in these materials, active ingredients exhibit dramatically improved controlled release qualities and anti-photolysis capabilities. The effectiveness of the encapsulated AIs is further increased in practice by managing the pore structures [68]. (Y. Gao et al., 2020). Natural nano-clay that has been changed by a high-energy electron beam (HEEB) and graphene oxide that has been embellished with copper selenide nanoparticles are two examples of inorganic materials with unique forms or architectures that can limit the encapsulated AI loss. But there are still problems to be solved, including physicochemical instability and acid monomers produced by polymer degradation that cause AIs to disintegrate [56-69]. Niosomes and liposomes are flexible drug delivery systems that can contain a variety of phospholipids or non-ionic surfactants [70-71]. They can accept both hydrophilic and lipophilic medications by encasing them in their cavity or attaching them to their bilayer. Additionally, these vesicles can serve as pesticide delivery vehicles. In another study, the commonly used herbicide paraquat's toxicity was reduced using photo-responsive and user-friendly vesicles. Paraquat was only released in response to UV or sunshine exposure [56-72]. Examples of nano vesicles are discussed below in Table 1.

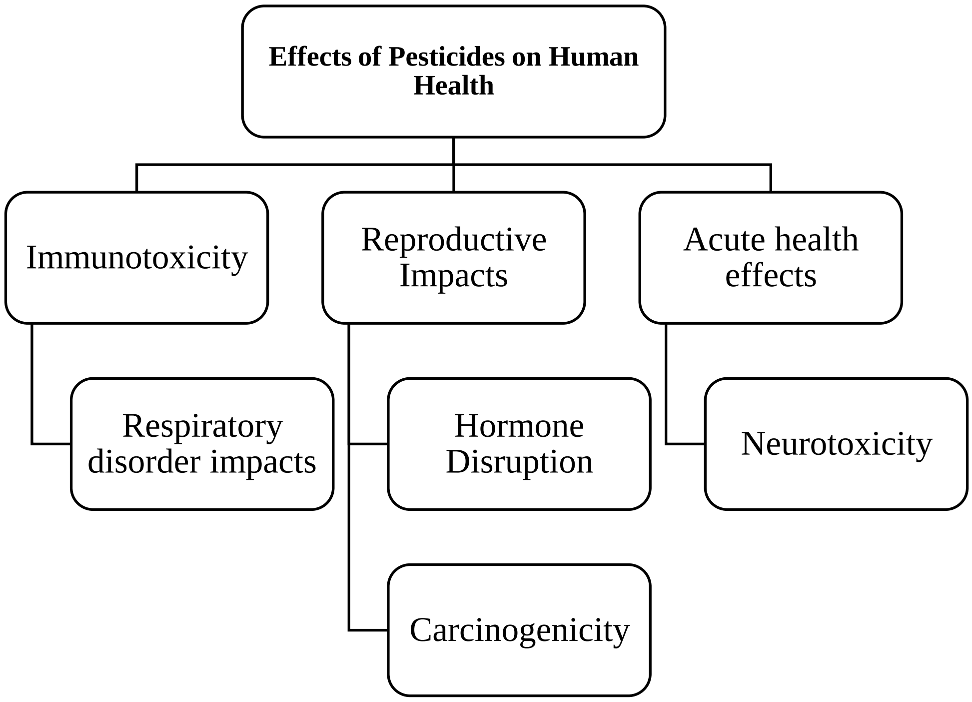

Figure 1: Pesticides Effects on Human health [14].

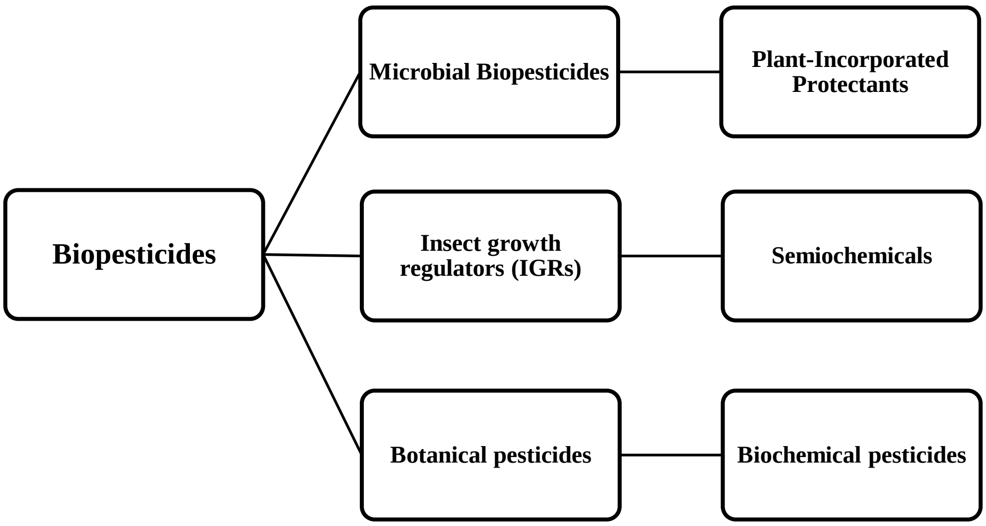

Figure 2: Classification of Biopesticides

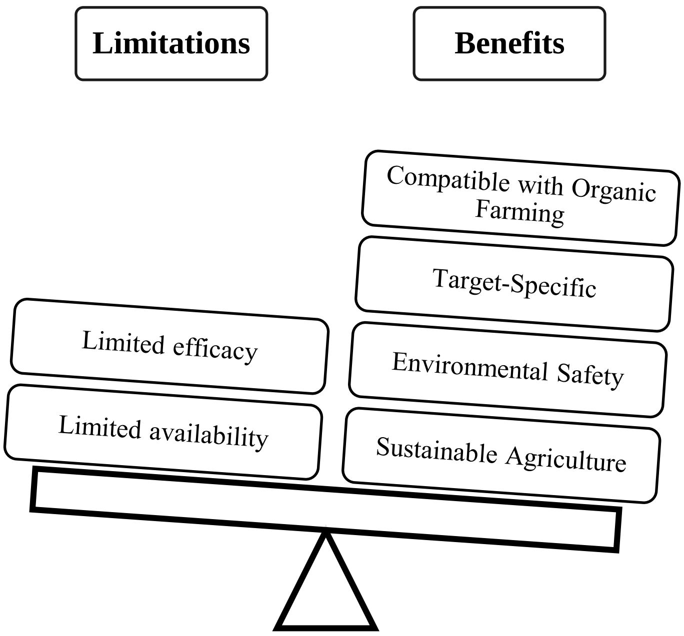

Figure 3: Comparative view of Biopesticides

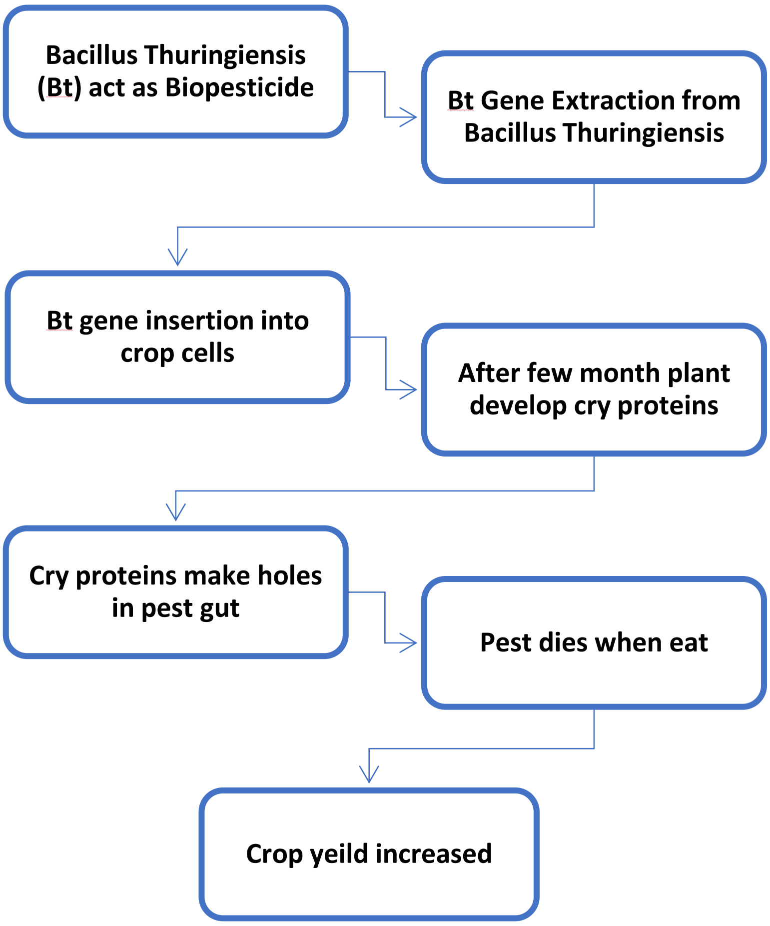

Figure 4: Schematic diagram depicting Bt Mode of Action

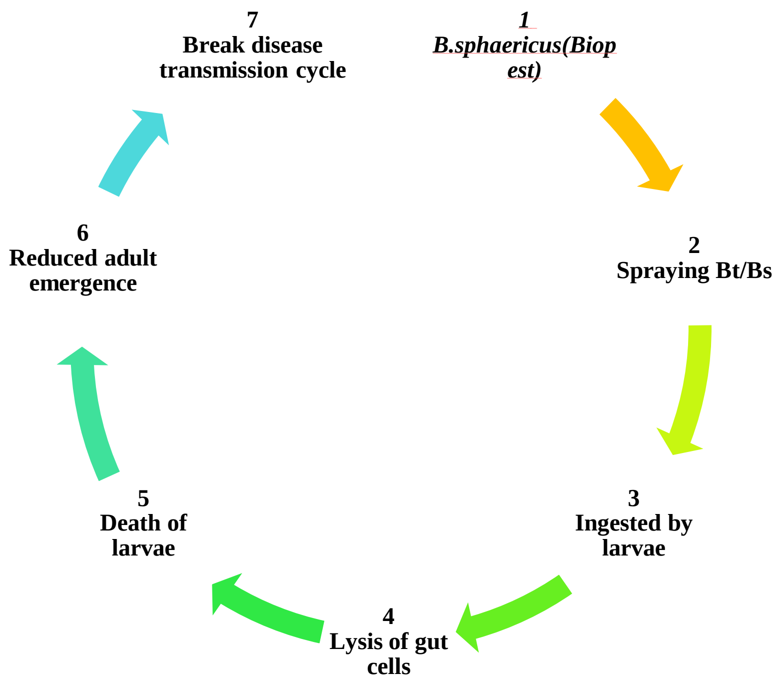

Figure 5: Schematic diagram of Mode of action of Bs

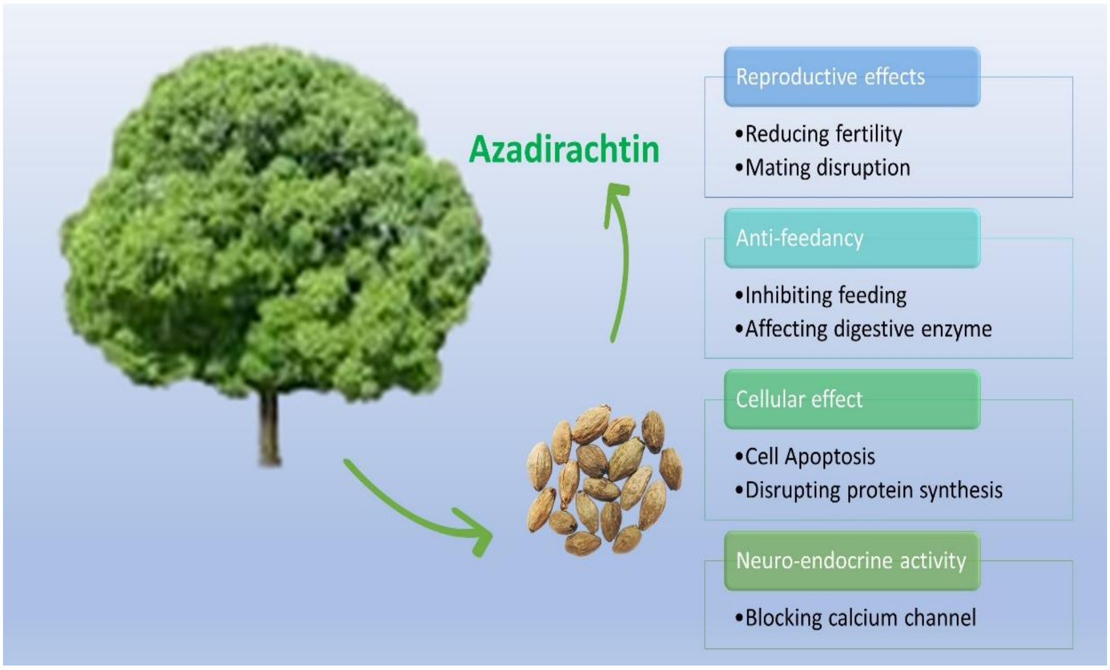

Figure 6: Azadirachtin Effects on Pests(Neem Tree.png was used from clipartkey uploaded by Mysin Website Link : http://www.clipartkey.com?downpng/oiiRhm-neem-tree-png-apple-tree-png-hd/)

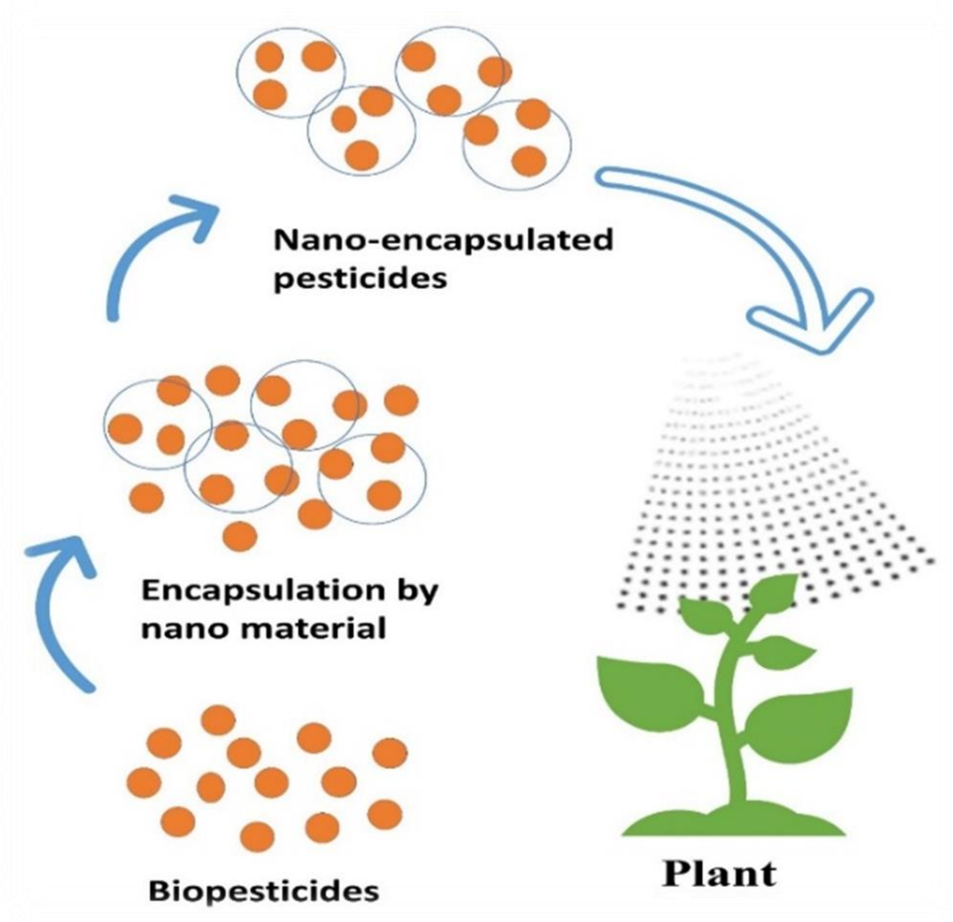

Figure 7: Nano encapsulation of Biopesticides

Table 1. Nano-vesicles.

Nano-vesicle	**Target**	**References**
Cellfectin	*Spodoptera frugiperda*	[73]
Qiagen	*Aedes aegypti*	[74]
Lipofectamine	*Spodoptera frugiperda*	[75]

11. Current Status of Biopesticides

Due to a number of disadvantages, such as expensive production processes, low storage stability, effectiveness issues, vulnerability to environmental conditions, and others, the use of biopesticides is restricted in comparison to synthetic chemical pesticides. Even though formulation changes can help with some of these issues, other obstacles to their commercialization include inadequate quality control, a short shelf life, limited awareness, and greater costs. There are now 700 active ingredient products and 175 registered biopesticides available worldwide; however, only 12 have been registered in India. Currently, plants can be protected by Bt, *T. viride*, *Metarrhizium*, *B. bassiana*, nuclear polyhedrosis virus, and neem, with Bt being the most popular biopesticide [17]. However, new tactics are required when resistance to Bt-based products starts to develop. Vegetable oils and other naturally occurring chemicals like azadirachtin have also been investigated for use as biopesticides. In several nations, including China and Japan, pathogen-based biopesticides have been utilized to manage pests. These include insect viruses and microbial insecticides [17]. The creation of biopesticides has significantly improved over the past ten years thanks to developments in techniques including molecular biology, genetic engineering, and protein engineering. As a result, the field is receiving more attention, which has significant social and economic advantages [76-77]. Due to their better qualities, biopesticides are currently a popular study issue in biotechnology institutes and businesses. As a result of their increased use, they are displacing very harmful pesticides from the market [78-79]. In recent years, the output of chemical pesticides has decreased by 2% annually, while the output of biopesticides has increased by 20% annually [76-77]. In China, demand for biopesticides peaked in 2005 at 145,000 tons, with total sales estimated to be worth between 0.8 and 1 billion yuan [76]. More than 122 biochemical pesticide active components, such as floral attractants, plant growth regulators, insect development regulators, repellents, and pheromones, have been registered by the Environmental Protection Agency [78].

The use of pesticides has given rise to growing public anxiety about their possible negative effects, even though they were created under strict control to guarantee a minimal impact on human health and the environment. This has sparked a hunt for safer agricultural methods and goods. There are also fewer chemical pesticides on the market globally because of the issues with pesticide resistance and the removal of some pesticides for commercial or regulatory reasons. As a result, the Integrated Pest Management (IPM) strategy must be used to stop the agro-ecosystem from degrading as a result of intensive farming [80]. Genetic research advances have made it possible to isolate genes that are efficient against certain pests, and these genes are now being utilized to manage plant diseases and insect pests that affect crops. Utilizing biopesticides in agricultural and public health initiatives has several advantages since they do not have any residual effects, which is a major worry for consumers, especially when it comes to fruits and vegetables. The effectiveness of biopesticides can be on par with conventional pesticides when used as a part of IPM. Due to its benefits related to environmental safety, target-specificity, effectiveness in extremely tiny doses, natural decomposition, and appropriateness in IPM, interest in biopesticides is rising. To minimize environmental contamination, biopesticides are therefore one of the most promising options. They can also replace some of the potentially harmful substances [81].

Although biopesticides have long been recognized as having the potential to support sustainable agriculture, interest in them has increased considering the rising demand for safe and wholesome organic food. While the use of agrochemicals is necessary to fulfill the constantly increasing needs for food, feed, and fodder, there are chances for biopesticides to be utilized as a part of IPM in certain crops and specialized regions. The market for biopesticides is being driven in part by the increased demand for agricultural products free of residue, the expansion of the organic food industry, and the convenience of registration compared to conventional pesticides. Along with the need to boost agricultural productivity without too heavily depending on chemical pesticides, there are also growing concerns for biodiversity preservation and the risks to some endangered species [81]. The creation of biopesticides has mostly been based on the development of chemical pesticides, which do not fully take advantage of the beneficial biological characteristics of biological agents. Environmentalists seek narrow-spectrum treatments based on strains from the region of usage, despite commercial pressure from the manufacturing side to produce broad-spectrum products based on a single strain that can control a variety of pests on various crops. Biopesticides have been kept on the market with little to no environmental harm, if any, in order to satisfy these conflicting needs [80].

12. Commercialization of Biopesticides

Plant-based biopesticides are highly sought-after in areas including gardens, homes, greenhouses, parks, and organic agriculture. Consumer worries about food safety as well as environmental preservation are what fuel this desire. New biopesticides are required to address this expanding need, and prospective sources include agricultural waste materials, easily accessible plants, and historically utilized species. A novel biopesticide is commercialized after being screened, isolated, identified, and evaluated for active chemicals. Commercializing these products offers a number of difficulties, including the need to find and develop novel microbial strains, scale up manufacturing, and standardize performance testing, despite the biopesticide market's ongoing expansion. With the emergence of prospective biopesticides like baculoviruses in the horticulture sector, biopesticide companies have the chance to develop safer alternatives to conventional pesticides. However, in vivo manufacturing could be expensive, which would restrict its application to large farms. Production costs may be reduced by integrating innovative capability and technology, such as an integrated pest management program. Overall, there is significant economic potential for biopesticides, particularly those used to treat plant diseases, and it is essential to continue doing research and development in this field to raise production and preserve the environment [17]. Natural materials are often investigated for effectiveness against target pests in both laboratory and field settings before being commercialized as biopesticides. Techniques including gas chromatography-mass spectrometry (GC-MS), high-performance liquid chromatography (HPLC), and thin layer chromatography (TLC) are used to identify active chemicals [82-83]. Stabilizers and carrier materials are included to improve the active compounds' application and durability. The formulation process seeks to promote application, efficiency, and stability while minimizing degradation brought on by environmental elements including heat, water, and acids. Petroleum distillates, maize starch, talc, clays, and water are examples of typical carrier substances. To increase the efficiency of the chemicals, emulsifiers like soap are also used. Neem and pyrethrum are two plant-based biopesticides that have been successfully developed and sold for use in agriculture. Microorganisms like Bacillus and Trichoderma have also been developed and commercialized [38-84].

Particularly for bioinsecticides, bio fungicides, and bio nematicides, the need for biopesticides is rising quickly on a global scale. The market is being driven by both the rising demand for organic food and residue-free agricultural products as well as the quicker registration of biopesticides compared to conventional pesticides. Due to strict pesticide restrictions and rising demand from organic growers, Europe is predicted to see the quickest market growth in 2012. North America, which accounted for 40% of worldwide consumption in 2011, is the market that dominates the world. The US market is now estimated to be worth around $205 million, but by 2020, that value is predicted to rise to over $300 million [78]. A considerable market for biopesticides exists in Asia, notably in China and India [85]. Collaboration between businesses and research institutions is necessary for the strategic and forward-looking goal of developing the biopesticides sector. Agricultural productivity may profit from the cohabitation of biopesticides and chemical pesticides, even if they cannot yet fully replace the latter. Accelerating the actual implementation of scientific findings and fostering extensive industry growth are imperative. As the mega-economies of China and India increase their usage of biopesticides, the Asian market represents a large potential for biopesticides. In terms of integrated pest management, biopesticides have received a lot of attention and are often used in addition to chemical pesticides. Biological pest control has long been promoted as an alternative to chemical pesticides. Biopesticide applications have a promising future, but it is important to regulate their usage since certain products may pollute the environment or damage natural enemies or other living things. However, biopesticides will contribute more to the battle against ailments, insects, and other agricultural pests, and they are expected to take center stage in the future of the pesticide sector [78].

13. Future of Biopesticides

The desire for environmentally friendly agricultural treatment solutions is boosting the market for biopesticides worldwide. The market is being further stimulated by the promotion of eco-friendly goods for use in agriculture by various governments. Additionally, the industry is being driven by the rising demand for organic food and urban consumers' increased knowledge of the negative impacts of chemically farmed raw foods [34]. Customers are prepared to pay more for goods produced organically. The market is expanding in part due to the rise in the usage of bio-control seed treatment methods and the rising price of conventional pesticides and fertilizers. Another factor boosting the growth of the biopesticide market is the trend toward sustainable approaches to increasing crop yields [86]. Another major aspect is the preference for environmentally friendly pest management techniques over traditional techniques. Biopesticides provide a number of advantages, including improved action effectiveness, sustained crop protection, and focused insect population activity [81].

14. Conclusions

In conclusion, the growing use of chemical pesticides in public health and agriculture has had harmful effects on the environment and has contributed to the emergence of pesticide-resistant illnesses and pests. Because of their low toxicity and natural nature, biopesticides have gained popularity as a sustainable solution. These biopesticides are classified as microbial, biochemical, or plant-incorporated protectants, depending on their efficacy against pests and illnesses. They function very effectively with integrated pest management (IPM) strategies. Biopesticides are also recognized for their low toxicity and environmental friendliness. However, the biopesticide industry has a variety of challenges, including high manufacturing costs, low stability, and occasionally insufficient effectiveness in specific environments. Despite these obstacles, the business is expanding, and the development of innovative methods such as nano-biopesticides shows promise. However, it is critical to thoroughly assess any potential environmental implications of such items. Overall, biopesticides serve a key role in achieving sustainable agricultural and public health goals by removing chemical residues from food and the environment, encouraging a healthier and more sustainable world.

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