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REVIEW ARTICLE

Natural pesticides for pest control in agricultural crops: an alternative and eco-friendly method

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Abstract

Biological pesticides are pesticides derived from natural materials such as bacteria, plants, and minerals that are applied to crops to kill pests. Biopesticides are targeted, inexpensive, eco-friendly, sustainable, leave no trace, and are not associated with the production of greenhouse gases. It contributes significantly to the agricultural bio-economy's sustainability. The advantages to the ecosystem provided by many significant biological resources justify the incorporation of biopesticides in Integrated Pest Management (IPM) programs. Through advancements in research and development, the use of biopesticides has significantly reduced environmental contamination. The development of biopesticides promotes agricultural modernization and will surely result in a gradual phase-out of chemical pesticides. Although synthetic pesticides have positive effects on crop yield and productivity, they also have some negative impacts on soil biodiversity, animals, aquatic life, and humans. In general, synthetic pesticides make the soil brittle, decrease soil respiration, and reduce the activity of some soil microorganisms, such as earthworms. Pesticide buildup in bodies of water can spread from aquatic life to animals including people, as their biomagnification can cause fatal diseases like cancer, kidney disease, rashes on the skin, diabetes, etc. Biopesticides, on the other hand, have surfaced and have proven to be quite beneficial in the management of pests and are safe for the environment and hence have emerged as very useful in the control of pests with a lot of merits. The present review provides a broad perspective on the different kinds of pesticides. We analyzed suitable and environmentally friendly ways to improve the acceptance and industrial application of microbial herbicides, phytopesticides, and nano biopesticides for plant nutrition, crop protection/yield, animal/human health promotion, as well as their potential integration into the integrated pest management system.

Keywords

Bioeconomy; Bacteria; Biopesticides; Eco-friendly pesticide; Microorganisms; Sustainable Agriculture

Introduction

Chemical substances known as pesticides are employed to get rid of weeds, rodents, fungi, and insects. Rodenticides, pesticides, fungicides, molluscicides, nematicides, plant growth regulators, and other substances are among them (1-3). It is typically used to prevent diseases spread by vectors and plays important roles in commercial and food-based industrial practices, such as the aquaculture sector, the agricultural sector, food processing, and storage, as well as crop protection and food preservation (4-5). When applied to an affected species as well as when they are disposed of, pesticides play a key role in entering the environment. After being discharged into the environment, insecticides can go through a variety of processes, such as migrations as well as degradation (6, 7, 8). Pesticides degrade in the environment, creating new compounds (9). Pesticides can spread by several methods, including surface absorption, percolation spray drift, volatilization, and runoff, from the location of the target to other sites in the environment or non-target plants (10). Chemicals can take many different forms, which shows how they behave differently in the environment. Although the widespread use of chemical pesticides significantly increased crop yield, it also brought about several serious problems for both human and animal health. Pesticides have been used for protection from pests but the fact is that only 1 percent of pesticides used could target the pests and the remaining cause contamination of soil, water, and air (11). Population growth and climatic changes are the key drivers of increased pesticide use (12-14) and future projections indicate increased worldwide pesticide production. Although pesticides are important for raising crop yields and producing affordable, high-quality food, their widespread usage has several detrimental impacts on the environment as well as human health (14). Pesticides are used to kill pests and manage weeds because of their chemical makeup, but they can also be harmful to other animals such as aquatic species, beneficial insects, birds, and non-target plants (15-17) exposure to many forms of environmental media, such as air (14, 15, 16) water, soil, and crops (18-19). Such chemical residues affect human health by contaminating the environment and food. Additionally, environmental degradation results from pesticide contamination spreading outward from the target plants. There are many ways that pesticides can spread, including through the air, wind currents, water, runoff, or leaching, along plants, animals, and people (20, 21).

Synthetic pesticides can enter the environment through a variety of channels, including vapor movement, haphazard storage, droplets drifting, deterioration, and leaching. When this happens, certain non-targeted plants are exposed, which reduces their capacity for photosynthetic energy and reduces their ability to produce seeds (22). Pesticides that are discharged into bodies of water have the potential to destroy marine life and pollute the water. Additionally, the accumulation of pesticides in aquatic systems may transfer from aquatic life to that of people and animals, and their bio-magnification may result in lethal diseases like cancer, kidney disease, skin rashes, diabetes, and other ailments (23-25). Since the middle of the 19th century, pesticides have been commonly used to control pests (26, 27) causing a widespread release of these xenobiotics into the environment (28). The frequent use of pesticides increases the risk of environmental pollution and the negative effects on biodiversity, food security, and water resources (29, 30). Pests, for example, insects, weeds, and plant diseases, are an ongoing challenge to agricultural producers. Oerke (31) reported that, globally, an average of 35% of potential crop yield is lost 8 Environmental Health Risk - Hazardous Factors to Living Species to preharvest pests. With the expected 30 percent increase in world population to 9.2 billion by 2050, there is a projected demand to increase food production by 70% according to Liu et al. (32). Even if non-pesticide technologies are crucial, insect control and food security strategies based on pesticides will still be needed in the future (32, 33). It is now vital to utilize organic insecticides (biopesticides), which are more readily available, environmentally friendly, and long-lasting due to the concerns associated with using synthetic pesticides. Affordably priced, environmentally friendly, specifically targeted, long-lasting, residue-free, and with no impact on the release of greenhouse gases, biopesticides have several advantages (34). Phytopesticides (35), microbial pesticides (36), and nanobiopesticides (37, 38) are a few different types of biopesticides that can be used. Microbial pesticides are specific in their actions, freely accessible without the need for costly chemicals, environmentally friendly, and free from long-term side effects, in contrast to synthetic pesticides (36, 39). In addition to having a variety of phytochemical components that give them different modes of action, phytopesticides also pose fewer health concerns for humans than synthetic pesticides because they don't release greenhouse gases into the atmosphere (35, 40). In comparison to synthetic pesticides, nanobiopesticides offer superior biocompatibility, targeted or controlled release, and pesticidal action (37, 38). In addition to damaging their plasma membranes, biopesticides can also function by inhibiting the translation of the pests' proteins and those of diseases. Although a few drawbacks have reduced their acceptability and commercial utilization, yet, biopesticides are highly specific in their target, have a short shelf life, are less persistent in the soil environment, and originate from sustainable raw materials, unlike synthetic pesticides (41). Some of the advantages of biopesticides that were listed above could also be considered their disadvantages. For instance, if the goal is to control multiple pests at once, the specificity of their approach towards pests may be a detriment. The fact that they have a short shelf life also makes them quickly degradable and less persistent in the natural world, but this becomes a drawback if the objective is to entirely eradicate the pests that are already there and stop their growth once biopesticides have been applied. It has become crucial to critically evaluate these virtues and shortcomings as well as potential solutions to address these apparent shortcomings.

The main objective of the present review paper is to explain the advantages of biopesticides over synthetic pesticides and how biopesticides can act as natural and eco-friendly methods to control pests in agriculture. This review examined the types of pesticides, effects, advantages, and disadvantages associated with both chemical insecticides and biopesticides. The main emphasis was on appropriate and sustainable strategies to boost the acceptance and industrial usage of microbial insecticides, phyto-pesticides, GM plants-based pesticides and nano-biopesticides over the nutrition, protection, and yield of crop plants, promotion of health of both animal and human and their potential incorporation into an integrated pest management system.

Methodology

In the present study, we have used a collection of databases indexed by Scopus and Web of Science, which are the most popular and novel databases available in the literature. Data analysis was performed on 58% of databases that were found in the literature indexes of Scopus and 30% of databases found in the literature indexes of Web of Science. A variety of pesticides are available nowadays but we mainly use biopesticides that are derived from plant extracts, microbes, genetically modified plants, and nanoparticles. A large number of databases related to these types of biopesticides have been collected and we have critically examined the production, formulation, commercialization, and market opportunities of biopesticides as well as their mode of action. Different databases of biopesticides derived from chemicals have been excluded as they are the most common and found in most literature reviews. The keywords used to collect our databases are described in the keyword section (after the introduction).

Results

3.1. Biopesticide- A historical perspective

A history of bio-pesticides can be traced back to the 17th century when plant extracts of nicotine were used as bio-control against plum beetles (44). As soon as 1835, when Agostine Bassi demonstrated the use of a white-muscadine fungus (*Beauveria bassiana*) in agriculture as biological pest control, it was discovered that the fungus could infect silkworms with a contagious disease. (42). A variety of studies were conducted about the use of mineral and plant oils as protective agents in the early 19th century. More studies of biopesticides came to light during the early 20th century's fast organizational growth in agricultural research (43). The first and most widely used bio-controls among them were *Bacillus thuringiensis* (Bt) spores. Shigetane Ishiwata, a Japanese researcher, discovered Bt from a sick silkworm in 1901. Japanese researcher Shigetane Ishiwata discovered Bt in an ill silkworm in 1901. After ten years, a sick flour moth caterpillar was responsible for its rediscovery by Ernst Berliner in Thuringen, Germany. *Bacillus thuringiensis* was designated as the type species of the pathogen Bt in 1911. The French started to employ Bt as a natural insecticide in the early 1920s. France created Sporeine in 1938, the first Bt substance that was sold commercially. Another plant-based product used widely during 1917 by the US Navy was pyrethrum extracts. For mosquito and house fly control, they mixed it with oil from kerosene and sprayed it. Two esters known as the compound Pyrethrin I and the compound Pyrethrin II are what provide pyrethrum its insecticidal abilities, according to a 1924 article by Swiss researchers Staudinger and Ruzicka. The Insecticide Act of 1968 states that just 12 different types of bio-pesticides are currently recognized in India thus far. Elcar, the first viral pesticide, was given a label in 1975 and Heliothis NPV acquired an exemption from tolerance in 1973. Though the type of bacteria *Bacillus thuringiensis* var. *israelens* (toxic to flies) initially came to light in 1977, the strain Tenebrion (toxic to beetles) was first isolated in 1983. The very first insect pheromone was authorized for use in bulk Japanese beetle trapping by the U.S. EPA in 1979. Other commercial successes from the 1980s and 1990s include using *Pseudomonas fluorescens* to prevent fire blight in orchards with populations of streptomycin-resistant pathogens and using the *Agrobacterium radiobacter* to prohibit crown gall disease on woody plants (44, 45). In organic fruit orchards, researchers started experimenting with kaolin clay in the 90s as an insect deterrent. It was made commercially available, particularly for use in organic systems, in 1999.

A comparable revolution has occurred in biological research for the prevention and treatment of plant diseases. Studies on the microbiology of soil and environmental issues led to the discovery of a large number of unique microorganisms that act as antagonists or hyperparasites of diseases and insect pests as early as the 20th century. Many of these were found to be helpful in large-scale inoculations in the field, but because of the quick acceptance of chemical pesticides at the time, few of them were developed for commercial use. In the 1980s and 1990s, products including *Agrobacterium radiobacter* for avoiding crown gall disease on woody plants and *Pseudomonas fluorescens* to reduce fireblight in orchards where streptomycin had been abused and pathogen populations were abundant were commercial successes. Public databases provide a lot of the active substances that are now permitted for usage in the United States. The most common biopesticides made and utilized in India are those based on neem, *Bacillus thuringiensis*, NPV, and *Trichoderma*.

3.2. Advantages of biopesticides

Biopesticides exert their inhibitory effects through multiple modes of action such as growth regulators, gut disruptors, metabolic poison, neuromuscular toxins, and non-specific multi-site inhibitors (46, 47). These multiple modes of action against targeted pests obliterate the chances of developing resistance as is common with chemical pesticides. The intensive use of conventional pesticides in industrial-scale farming over a long period, especially in the Green Revolution era, also created challenges such as pesticide-related pollution, post-harvest chemical consumption through bioaccumulation, biodiversity losses, and insurgence of secondary pests and elimination of natural/beneficial enemies. These negative consequences are not associated with the use of biopesticides. Thus, prohibitive restrictions are continually imposed on synthetic pesticides to reduce their numbers with time. For instance, there has been a reduction to 250 active ingredients of conventional pesticides in 2009 as opposed to more than 1,000 in 2001 while the entrance of new conventional pesticides into the market reduced from 70 in 2000 to 28 in 2012 (48). The direct result of the declining number of classical pesticides is the increased demand for biopesticides for some beneficial reasons. These benefits include but are not exclusive to, altering the course of pest resistance, low toxicity properties, complementary input to synthetic pesticides, ecofriendliness, specificity (thus have little or no negative impact on non-target organisms and humans), biodegradability, and little or no problem of post-harvest contamination, stability against abiotic stress (49, 50) and compatibility in integrated pest management (IPM).

3.3. Types of biopesticide

There are three categories of pesticides based on their extraction and the molecules or ingredients that make up each biopesticide viz. microbial biopesticides, biochemical pesticides, and GMO-based biopesticides. Other biopesticides like nano-biopesticides, myco-biopesticides, and RNAi are most importantly used for pest management processes (51, 52, 53). The properties of the biopesticide's source and constituent molecules have an impact on the processes through which it defends crops against disease attack (54, 55, 56).

3.3.1. Microbial pesticides

Microbial pesticides are compounds used to manage pests that are generated from microorganisms such as bacteria, fungi, viruses, protozoa, and algae (57). Toxic metabolites produced by microbes are used to kill and stop the spread of pests. Microbial pesticides are applied to the environment using a variety of techniques, such as an emulsion, an electrospraying system, a fluid bed, drying by spray extrusion, lyophilization, spray chilling, and coacervation (58). The most common bacterial genera, such as *Chromobacterium, Pseudomonas*, and *Yersinia*, and fungal genera *Lecanicillium, Hirsutella, Metarhizium, Paecilomyces, Beauveria, Paecilomyces, Verticillium*, and nematodes from the *Steinernema* and *Heterorhabditis* genera are utilized as biopesticides (59, 60) which are shown in Table 1.

Table 1. Microbial biopesticides and their pest control

SL. No.	Name of the pesticide	Constituent Microbes	Name of the plant species/ crops applied	Action against pest	Reference
1	NPV	Nucleopolyhedroviruses	Mulberry orchards, tea orchards, rubber orchards, sugar cane orchards, corn herbicide, vegetable gardens, cotton fields, ridges, roads	Lepidoptera Noctuidae, Mothidae, Fruit Mothidae, Leaf Rolleridae, Melymothidae, PlutellaXylostidae, Cephalididae, and Lepidopteridae.	(13)
2	NPV (AucaMNPV)	Imported cabbage worm (PiraGV) NPV (AucaMNPV)	Cabbage	*Artogeia (Pieris) rapae*	(61)
3	Plant Shield® HC Biological Foliar and Root Fungicide	*Trichoderma harzianum*;	Strawberry, Lettuce, Pea, Lima Bean, Bean, Ginseng, Lentil, Soybean, Bushberry	*Rhizoctonia* sp., *Pythium* sp., and *Fusarium* sp.	(62)
4	RootShield® Granules	*Trichoderma harzianum* Rifai strain T-22 and *Trichoderma virens* strain G-41,	Lettuce, Pea, Lima Bean, Bean, Ginseng, Lentil, Soybean, Bushberry	*Rhizoctonia* sp., *Pythium* sp., and *Fusarium* sp	(63)
5	Ballad® Plus Biofungicide	*Bacillus pumilus* QST 2808	Soybeans, Wheat, Rice, and potatoes	*Pucccinia* sp., *Erysiphe* sp. *Leveillula* sp, *Helminthosporium* sp,	(64)
6	Serenade® MAX™	*Bacillus subtilis* strain QST 713	Cherries, Cucurbits, Grapes, peppers, potatoes, tomatoes, and walnuts	*Pucccinia* sp., *Helminthosporium* sp, *Sclerotinia sclerotiorum, Erysiphe* sp. *Leveillula sp., Botrytis cinerea*	(64)
7	Serenade® ASO	*Bacillus subtilis* strain QST 713	cherries, cucurbits, grapes, leafy vegetables, peppers, potatoes, tomatoes, and walnuts	*Botrytis cinerea, Erysiphe* sp., *Microsphaera* sp, *Phyllactinia* sp, *Podosphaera* sp, *Sphaerotheca* sp, and *Uncinula* sp. *Sclerotinia sclerotiorum*, *Xanthomonas campestris* pv. *campestris* (Xcc)	(64)
8	Yield Shield® Concentrate Biological Fungicide	*Bacillus pumilus* GB34	Poaceae (e.g. maize, rice, wheat, barley, oat), Fabaceae (e.g. soybean, peanut, dry bean, alfalfa, chickpea, lentil, field pea), Solanaceae (e.g. tobacco, potato), Amaranthaceae (e.g. sugar beet), Brassicaceae (e.g. canola), Rubiaceae (e.g. coffee), Malvaceae (e.g. cotton), Tomato, tobacco, legumes, cucurbits, sweet potatoes and banana	*Rhizoctonia* and *Fusarium* sp.	(65)

9	Planter Box T-22™ HC and T-22™	*Trichoderma harzianum* Strain T-22,	Tobacco, potato, maize, rice, wheat, barley, oat, cucurbits, sweet potatoes and banana	*Rhizoctonia* sp., *Pythium* sp., *Fusarium* sp *Cylindrocladium* sp. and *Thielaviopsis*	(66)
10	SoilGard 12G3	*Trichoderm avirens* (formerly *Gliocladium virens*)	Pumpkin., Chili., maize, rice, wheat, barley, soybean, peanut, dry bean, alfalfa, chickpea, lentil, field pea	*Pythium* sp*., Rhizoctonia*, and root rots	(66)
11	Rhapsody®	*Bacillus subtilis* QST 708	*Geranium aglaonema, Delphinium sp., Roses, Rice, Turf, Sod, Lawns, Golf Cour, Bluegrass, Bentgrass*	*Xanthomonas* spp., *Pseudomonas delphinii, Botrytis cinerea, Rhizoctonia solani, Colletotrichum graminicola*	(67)
12	Actinovate® SP	*Streptomyces lydicus* WYEC 108	Pumpkin, pepper, maize, rice, wheat, barley, soybean, peanut, dry bean, alfalfa, chickpea, lentil, field pea	*Pythium* spp., *Rhizoctonia* spp., *Phytophthora* spp., *Fusarium* spp., *Verticillium* spp., *Phymatotrichum omnivorum,* and additional fungi that cause root decaying	(68)
13	Bio-Save® 10LP3	*Pseudomonas syringae* strain ESC 10	Apples, pears, lemons, oranges, or grapefruit after the fruit is harvested	*Rhizopus* sp.	(69)
14	AgriPhage™	Bacteriophages of *Xanthomonas* spp. and *Pseudomonas syringae* pv. *tomato*	Tomatoes and pepper	*Xanthomonas* spp., *Pseudomonas syringae* pv. *tomato*	(39)
15	*Btt*-Xd3	*Bacillus thuringiensis* var. *tenebrionis*-Xd3 (*Btt*-Xd3)	Cotton	*Aphis gossypii*	(70)
16	Bloomtime Biological™ 3 and Bloomtime Biological™ FD3	*Pantoea agglomerans* strain E325	Apples and pears	Fireblight (*Erwinia amylovora*)	(69)
17	Actinovate® SP	*Streptomyces lydicus* WYEC 108	Pumpkin	Soilborne pathogens: *Pythium* spp., *Rhizoctonia* spp., *Phytophthora* spp, *Fusarium* spp*.,* *Verticillium* spp., *Phymatotrichum omnivorum* and other root decay fungi. Foliar pathogens: *Podosphaer*a spp., *Botrytis* spp., *Sclerotinia* spp., *Monilinia* spp., *Alternaria* spp., *Peronospora* spp. and other foliar fungi	(68)
18	Contans® WG	*Coniothyrium minitans* strain CON/M/91-08	Snap beans, Lettuce	*Sclerotinia minor, Sclerotinia sclerotiorum*	(64)

3.2.2. Biochemical/herbal pesticides:

The majority of plant parts, including essential oils and extracts, have been successfully used to treat plant illnesses (70). They attract, drive away, stop breathing, locate host plants for specific pests, get rid of pest eggs and larvae, and kill pests that feed on plants (71, 72, 73). *Tribolium castaneum* (Herbst), a red flour beetle that decimates numerous crop species, has been reported to be controlled by essential oils from *Coleus aromaticus* Benth., *Hyptissua veolens* (L.), *Azadirachta indica, Ageratum conyzoides* L., and *Achillea* sp. (74,75). Various plant infections can be controlled by using additional plant parts such as bark, flowers, roots, leaves, peels, seeds, and buds (76). Botanical pesticides frequently contain secondary metabolites, such as phenols, resins, steroids, terpenes, alkaloids, flavonoids, and tannins have been reported to contain antifungal, antimicrobial, antioxidant, or insect-killing activities (77). Certain plant species are efficient against a particular type of pests because of the unique compounds they contain, which also dictate how they kill the targeted pests (78). Botanical pesticides comprise bioactive substances that work in several ways to control pests such as fungi, insects, nematodes, bacteria, and plant host tissues infected by viral infections (78). Depending on the botanical chemical and pest, the mechanisms of action may include repellence; suppression, breakdown of proteins, and other effects. Insects are paralyzed and killed by pyrethrum-based pesticides that damage their nerve cells. Additionally, neem-based insecticides that have anti-feed ant and repellent qualities cause abnormal molting, impede oviposition, and mess with the body's hormonal balance (78). Plant insecticides can inhibit the manufacture of cell walls, the structure of cell membranes, the activity of ATPases, sensing of quorum, pumping out efflux, and the development of biofilms (79,80). In *Tanzania*, extracts from four weed plants *Tephrosia vogelii*, *Tithonia diversifolia, Lippia javanica,* and *Vernonia amygdalina*, were utilized to manage insects in common bean. (81). Similar to this, another team of researchers conducted an experiment in which *Brevicoryne brassicae* was exposed to nine different aqueous plant extracts from the leaves, fruits, and flowers of nine plants. *Solanum pseudocapsicum* L. and *Solanum guaraniticum* A were found to be the most successful (82) which is shown in Table 2.

Table 2: Plant-derived biopesticides and their pest control

Sr.N.	Name of the pesticide/ plant extract	Constituent chemical	Name of the plant species/ crops applied	Action against pest	Reference
1	Azadirachtin	Tetranortripenoid, 1 H, 7H-naphthol (1,8, a-c; 4,5-b'c') difuran-5, 10a (8H) dicarboxylic acid	vegetables, fruits, herbs, and ornamental crop	aphids, scale, thrips, whitefly, leafhoppers, weevils	(37)
2	Rotenone	1,2,12,12a-tetrahydrochromeno[3,4-b] furo[2,3-h]chromen-6 (6aH)	Bean and Cucumber	Aphids, bean leaf beetles, cucumber beetles, leafhoppers, red spider mites	(83,84)
3	Ryania	9,21Didehydroryanodine	Potato, Onion	Onion thrips, Codling moths, silkworms potato aphids, corn earworms	(85)
4	Sabadilla	cevadine and veratridine	Lettuce and Cucumbers.	Grasshoppers, moths, armyworms, aphids, loopers, bugs.	(86)
5	Pyrethrum	Pyrethrin I, Cinerin I, and Jasmolin I and Pyrethrin II, Cinerin II, and Jasmolin II	Cabbage, vegetables, fruits	Caterpillars, aphids, leafhoppers, spider mites, bugs, cabbage worms, beetles	(87)
6	Essential oils	Aldehydes, fatty acids, phenols, ketones, esters, alcohols, nitrogen, and sulfur compounds	vegetables, fruits	Caterpillars, aphids, white flies Land snails.	(88,89)
7	Nicotine	Heterocycles pyridine and pyrrolidine,	vegetables, fruits	Aphids, mites, bugs, fungus, gnat, leafhoppers	(90)
8	d-Limonene Linalool	limonene,β-citronellal, linalool, pinene, β-caryophyllene, β-myrcene, terpinene, citral	vegetables, fruits	House crickets, paper wasps, aphids, mites, and fleas	(90)

3.2.3. Plant-incorporated Protectants (PIPs)

Plant-incorporated protectants (PIPs) are another class of biopesticides that are certain pesticidal constituents, produced by the crop plants from genetic material that was inserted into the plant genome. Because the genetic material taken from a naturally existing microbe has been successfully integrated into the nuclear material of these plants, they are essentially GM plants. Therefore, transgenic plants exhibit the typical traits of genetically modified organisms, they're able to eradicate pests. So far, many PIPs have been produced. The most frequent instances of them are transgenic plants that carry the cry gene (which produces a toxin from the Bt bacteria, *B. thuringiensis*). Several agricultural crops have been genetically modified and show traits of *B. thuringiensis*. This transformation, where a simple plant becomes a transgenic plant, is carried out via manipulation of biological or physical means. For example for transgenic Bt, crop plants that are to be modified are inserted with corresponding genes from the Bt bacterium by the use of recombinant DNA technology with the aid of *Agrobacterium tumefaciens*. This technology was originally applied in 1987 to genetically modify tomato plants. After this success, it was expanded to help many other economically significant crops, such as cotton and tobacco (91). *Bacillus* bacteria produce parasporal, proteinaceous, and crystal inclusion bodies, also known as cry toxins (85). According to Verma and co-researchers, these bodies can kill over 150 distinct types of arthropod insects (91). From Bt strains, many toxins are identified and reported, including a-exotoxin, b-exotoxin, c-exotoxin, louse factor exotoxin, mouse factor exotoxin, water-soluble toxin, Vip3A, and enterotoxin (30,92). Depending on its potency and receptor specificity, each toxin has its unique pesticidal properties (85) which are shown in Table 3.

3.2.4. Nanobiopesticides

According to Chaudhary and colleagues, nano biopesticides are biological protection items that are created utilizing nanotechnology to increase efficacy and lower the environmental burden of pesticides (101,102). To be activated by external stimuli or enzyme-mediated triggers, nanobiopesticides are made from nanomaterials and applied specifically fixed on a hybrid substrate (103, 104,). They are two - or three-dimensional nanostructures that are used to transport the active ingredients in agrochemicals. They can improve the solubility and bioavailability of agrochemicals in water and shield them from environmental deterioration. It also helps revolutionize the control of pathogens, weeds, and insects in crops (105). They are available in different forms, such as nano-gel, nano-encapsulation, nano-fibers, nano-sphere, etc. (106, 38). 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). Nanoparticles in recent years have been reported to be very helpful in agriculture (107). They have been employed as active components and carriers to stabilize many agrochemicals and their products from them include nanofertilizers, nanopesticides, etc. (104,105). For instance, pesticides from nanomaterials, such as magnesium oxide, magnesium hydroxide, copper oxide, and zinc oxide derived from aqueous extracts of *Chamaemelum nobile* flowers, *Punica granatum* peels, green peach aphid (GPA) and *Olea europaea* leaves have been reported when controlling insects (110, 111). Also investigated in the management of the cotton bollworm's causal agent, *Helicoverpa armigera*, were silver nanoparticles generated from the leaf extract of *Euphorbia hirta* (112). The ability of

Table 3 : Genetically modified plant genes and their resistance against pathogen/pest/insect

Sl.No	Name of the GM plant	Name of the gene that is inserted to confer protection	Name of the pathogen/pest/insect against which the plant is resistant	Reference
1	Castor	cry1AC	Lepidoteran-*Achaea janata Spodoptera litura*	(93)
2	Soybean	Cry14Ab-1cry 8 like	control certain lepidopteran pests of corn, Parasitic Nematode, Coleopteran- *Holtrichia panallele*	(94)
3	Pigeon pea	cry2Aa	Pod borer- *Helicoverpa armigera*	(94)
4	Chickpea	CryIIAa	Pod borer	(95)
5	Sweet Potato	cry1Aa	*Spodoptera litura*	(96)
6	Bt-Maize	Bt-gene	Kills Lepidoptera larvae, in particular, European corn borer.	(97)
7	Bt-Cotton	Bt-gene	Pathogenic Bacteria and insect pests *Helicoverpa armigera*	(98)
8	Tomato	cry1Ab	*Tuta absoluta*	(99)
9	Rice	cry2A	Leaf folder	(100)

copper oxide nanoparticles and zinc oxide nanoparticles to control *Alternaria citri*, a causative agent of citrus black rot disease in the plant has also been reported (113). The major interactions that occur between plants and nanoparticles have been studied using different techniques, which include fluorescence spectroscopy, microscopy, and magnetic resonance imaging (114). Nanobiopesticides' potency can be assessed based on their composition, charge on the surface, concentration, size, and physical and chemical alterations (105). By reducing the quantity and quality of agricultural products and foods, nanoformulations have prevented endemic pest infestation, plant damage, and economic loss (115). This is due to their critical role in decreasing the amount of active ingredient degradation, enhancing the solubility in water balance, and enhancing the biological availability of active ingredients.

3.2.5. Mycopesticide

Mycopesticides consist of fungi and fungi mobile components. Propagules which include blastospores, conidia, oospores, chlamydospores, and zygospores had been evaluated, at the side of hydrolytic enzyme mixtures (98). The position of hydrolytic enzymes especially chitinases within the killing process, and the viable use of chitin synthesis inhibitors are the top research regions which is shown in Table - 4.

3.2.6. RNA interference enabled pesticide technology

Pesticides with an RNA interference (RNAi) foundation work by using RNAi processes to suppress pest populations. They are thought to be eco-friendly and offer a possible substitute for traditional chemical pesticides. Double-stranded RNA (dsRNA), which is engineered to match the nucleotide arrangement of a target critical gene of the pest in question, is the active component in RNAi-based insecticides. This has an RNAi impact and inhibits various important biochemical/biological processes in the pest when it is ingested by the insect. dsRNA products are anticipated to be used for RNAi-based viral disease management in aquaculture, particularly in shrimp farming. The need for inexpensive dsRNA manufacturing is essential for the practical application of RNAi agents. Such RNAi-based products contain a molecule of RNA with a double-strand structure (dsRNA), which serves as the active component. As soon as the dsRNA is picked up into a cell with RNAi capability (4), it acts through the process of RNA interference (RNAi), which precisely suppresses the expression of the targeted gene in a nucleotide sequence-specific way (4,5). In other words, RNAi-based insecticides work by limiting the expression of a gene that is crucial for the target crop pest's existence through the RNAi effect, hence stifling the pest's critical biology and even resulting in its demise (6,7). These pesticides are also known as "RNA-induced gene silencing pesticides" for this reason. RNAi effects from topical dsRNA treatment have also been investigated to stop pathogens such fungus, viruses, and viroids from infecting and multiplying in plants (8,9,10,11,12).

The first benefit of utilizing RNAi-based insecticides as pesticides is that they virtually stop the growth of just the pest(s) that are being targeted. The RNAi-based insecticide should not harm unintended (non-target) insects since it is constructed with a nucleotide sequence that selectively inhibits the expression of the target gene in the pests to be killed or inhibited. This strategy is good for ecosystem biodiversity. Another benefit is that the insecticide's active ingredient, RNA, degrades rapidly in the environment due to its inherent chemical volatility and the bioecological community's widespread presence of nucleases (14, 15). In this context, however, it has recently been noted that a strong resistant pest has emerged as a result of genetic changes connected to the fundamental mechanism of RNAi activity (19); this is covered in more detail which is shown in Table 5.

Table 4 Mycopesticides and their action against pest

Sr. No.	Name of the mycoinsecticide	Mane of the fungi involved	Name of the plant species/crops applied	Action against pest	Reference
1	Vertalec*	*Verticillium lecanii*	cucumber	Hemiptera (Aphididae)	(116)
2	Melocont Pilzgerste	*Beauveria brongniartii*	*Melothria pendula*	Coleoptera (Scarabaeidae)	(127),(118)
3	Mycohit*, Vektor 25 SL,MeteHit***	*Conidiobolus thromboides*		Hemiptera (Aleyrodidae, Ortheziidae), Acari	(119)
4	Priority, PreFeRal*	*Paecilomyces fumosoroseus*	food and non-food crops, ornamentals, and tobacco	Hemiptera (Aleyrodidae)	(120)
5	BioCane Granules Biological Insecticide*	*Metarhizium anisopliae*	Rice	Coleoptera (Scarabaeidae)	(85)
6	Green Guard ULV*	*Metarhizium anisopliae* var. *acridum*	Beetroot, Beans	Orthoptera (Acrididae)	(121)
7	Ago Biocontrol Nomuraea 50***	*Nomuraea rileyi*	Food crops	Lepidoptera	(122)
8	Sporothrix ES*	*Sporothrix insectorum*	Rice and vegetables	Hemiptera (Tingidae)	(123)
9	Tri-Sin	*B. bassiana, M. anisopliae, I. fumosorosea*	Bean, Tomato		(124)
10	Bio-Power*	*Aschersonia aleyrodis*	Citrus	Coleoptera, Hemiptera Lepidoptera	(85)

Table 5 RNA interference enabled pesticide and their action against pest

Sl. No.	Silenced gen	Target crop	Target insect	References
1	TREH, ATPD,	Soyabean	Aphid	(125)
2	ECR gene	Potato	Colorado potato beetle	(126)
3	AchE-Acetylcholine esterase	Rice	Yellow stem borer	(127)
4	dvvgr dvbol	Maize	Corn root warm D. virgifera	(128)
5	hormone methyl transferase (JHMT)	Cotton Juvenile	*Helicoverpa armigera*	(129)
6	Chitinase gene-HaCHI	Tomato Tobacco	*Helicoverpa armigera*	(130)
7	dsRNA-Spray	Maize	Lepidopteran	(131)

3.3. Production, Formulation, Commercialization, and market of Biopesticides

3.3.1. Current Global Status of Biopesticides

The biopesticides' total production is 3000 tonnes per year, and their use is enhancing steadily by 10% every year (132, 133). Seiber in his study states that about 1400 biopesticide products are prepared and sold worldwide (134). Only 60 comparable products are offered in the European Union (EU) compared to over 200 biopesticides sold in the US market. About 45% of biopesticides were used and sold in the USA, Canada, and Mexico (NAFTA Countries). In comparison, Asia lacks biopesticides and uses only 5% of biopesticides sold globally (135, 136). The biopesticides market holds a pretty small share of the crop protection market of the world. The worldwide biopesticides market was approximately 3.5% ($1.6 billion) of the total pesticide market of the world in 2009 (137), which grew to 5% ($3 billion) (138). However, its rate of growth has shown an increasing trend in the past two decades. Approximately up to 2023, the yearly growth rate of biopesticides will rise to 8.64% and account for more than 7% ($4.5 billion) of the worldwide crop protection market (138). However, biological pesticides are still predominantly governed by the system created for pesticides that are chemical (139). Most nations have modified their policies to limit the use of chemical insecticides and promote biopesticides. Fewer biological pesticides have been registered in the European Union than in Brazil, the United States, China, and India due to the extremely drawn-out and challenging registration procedures there (140, 141). Due to poor foundations, high expenses, and governmental policies, Nigeria uses biopesticides infrequently (142). 327 biological pesticides were registered in China. A total of 237 bacterial biopesticides, including 181 derived from B. thuringiensis, were made from 11 different species of microorganisms (143). In 2002, total biopesticides, mainly B. thuringiensis, weresoldat1.5 million dollars in Kenya alone (144).

3.3.2. Current Indian status of biopesticides

For a long time, India has pioneered the biocontrol idea for plant diseases (145). To reduce the danger of loss after harvest in stored storage cereals, the neem plant (*Azadirachta indica, A. Juss*) and its byproducts, including extracts of the leaves, oil, and seed cake, have been employed as fertilizers (146, 147). The idea of IPM also emerged in the 1960s with a focus on the prudent use of insecticides in agriculture (148). Subsequently, when traditional pesticides failed to eliminate *Helicoverpa armigera, Spodoptera litura*, and other cotton pests in India, a significant technological advance in biocontrol resulted (149). Additionally, farmers are becoming more aware of the use of biopesticides, making them a very attractive alternative to chemical and synthetic insecticides (150). Biopesticides are registered and regulated under the Insecticides Act, of 1968 (151). The predicted yearly growth rate of biopesticides in India is 2.5 percent. The production of biological pesticides is comparatively lesser in India due to several difficulties at the industrial and policy levels. Less than 1 percent of biopesticides generated from plants are consumed in India and only 12% worldwide. The use of biopesticides has been encouraged by the National Farmer Policy 2007 for sustainable agriculture (152). According to the Insecticide Act of 1968, only twelve different types of biological pesticides have been registered in India, illustrating how different biopesticides are developed in various industries. The usage of biopesticides in India has increased dramatically over time, reaching 8847 and 8645 metric tonnes in 2019–20 and 2020–2021, respectively.

The Directorate of Plant Protection, Quarantine and Storage (DPPQS) reports that 361 biocontrol laboratories and devices are in use in India, although very few of them are concentrated on manufacturing (153). Records indicate, however, that during the past few decades, the consumption of biopesticides has increased in India(154). For instance, consumption of neem, one of the most widely used biopesticides in India, went from 83 metric tonnes (MT) in 1994–1995 to 686 MT in 1999–2000, while consumption of *Bacillus thuringiensis* (Bt) climbed from 40 to 71 MT during the same period (155). However, it was only a few years ago that the status committee on chemicals and fertilizers (2012–2013) throughout the fifteenth Lok Sabha submitted its file on the production and availability of pesticides in India. The committee reported that from 123 metric tonnes (MT) in 1994-1995 to 8110 MT in 2011-2012, the use of biopesticides has increased above and beyond expectations (156). According to information obtained from the Directorate of Plant Protection, Quarantine and Storage (DPPQS), the overall intake of biopesticides in India increased by 40% between 2014–2015 and 2018–2019 (157). According to statistics, Himachal Pradesh and Goa used the least amount of biopesticides—36 and 38 MT, respectively—while Maharashtra, West Bengal, and Karnataka used the most—5549, 4416, and 3478 MT, respectively (158). This information also explains why biocontrol programs in northern US states have a lower reach than those in the south. In the previous couple of years, the improvement of microbial biostimulants or biopesticides for reinforcing plant growth and disease eradication has emerged as an alternative, but a broader element of their application as biostimulant merchandise has remained in infancy, especially in developing nations (159).

So studies were initiated to discover the biocontrol capability of microorganisms to develop a price powerful and realistic control approach in augmenting sickness management. Evaluation of massive wide variety of soil samples collected from extraordinary components of the arid vicinity brought about isolation of native biocontrol seller's viz., *Trichoderma harzianum, T. longibrachiatum, Aspergillus versicolor, A. nidulans, Penicillium oxalicum, Bacillus firmus, B. tequilensis,* and *Streptomyces mexicanus* from one-of-a-kind agricultural structures. Those biocontrol marketers have proved their adverse capacity in laboratory exams. Within the subsequent step, their field efficacy on most generally grown crops, and bushes, and their impact on resident microflora was studied to verify whether or not any bioagent has an unfavorable impact on native organisms.

3.3.3. Commercialization of biopesticides

Commercialization of biopesticides is a multistep manner. Even though it is simple for any research organization to become aware of every location's particular biocontrol agent stress, it will be rather challenging to move it to an industrial level of manufacturing. Because any biocontrol agent must go through the same registration procedures as all chemical pesticides, which are arduous, expensive, and time-consuming. Farmers constantly look in their direction with skepticism since the effects of biopesticides are unpredictable. Once more, because microbial biopesticides are living organisms, several variables like temperature, moisture, pH, ultraviolet spectrum, and soil conditions harm their survival. The sellers and shops also are least endorsed to sell biopesticides because of less shelf-existence of the product, low earnings margin, and absence of normal demand amongst farmers. a lot of these together have led to restrained adoption of biopesticides by many of the farmers. But, the diffusion and use of natural and merchandise for pest and sicknesses and nutrient control in agriculture have increased in recent decades in India as a result of several reasons:

1) To "make sure environment sustainability" turned into one of the 8 Millennium Development desires (MDGs) of the united countries. All the countries inclusive of India are slowly transferring their national policies in the direction of renewable electricity assets and green technologies.

2) Self-sufficiency in food production: The country has attained self-sufficiency in food grain production due to the fact 1980's. This has enabled India to shift its awareness in the direction of satisfactory meal production while maintaining the amount of modern meal grain production degrees. India's modern agricultural policies are aimed toward sustainable control of herbal assets, sustainability of agriculture, enhancing farm earnings, and removing malnutrition. A few unproven technologies are being encouraged to eventually replace or lessen agriculture that uses a lot of chemicals.

3) Growing attention amongst customers: The increase in great of existence and profit ranges have enabled the city population to become greater conscious of the pleasant food products being fed through them. Healthy food and lifestyle have become a concern and numerous chemical loose foods are trendy utilizing this phase of society.

4) Increase in region underneath organic/chemical loose agriculture: there's growth in location beneath natural agriculture in India, which once more illustrates the shift toward reduction in the use of chemical fertilizers and pesticides as practiced in depth agriculture. The overall vicinity dedicated to organic agriculture in Asia changed to greater than 5.9 million hectares in 2019. There have been 1.4 million manufacturers, most of which have been in India.

3.3.4. Biopesticides Market

According to a Fortune Commercial Enterprise Insights report, a CAGR of 9.38 percent is predicted for the Indian biopesticides market, which is expected to increase from USD 69.62 million in 2022 to USD 130.37 million by 2029 (160). Another data from the World Market Analysis Forum (GMAF) unequivocally demonstrates that the global market for biopesticides topped USD 2.5 billion in 2021 and is expected to increase by more than 11% CAGR from 2022 to 2030 (161). Growing consumer demand for organic fruits and vegetables, along with advancements in farming technology, will drive market growth throughout the forecast period. Growing consumer preference for natural and organic foods as a result of the continued trend toward healthy living has favorably influenced the biopesticides industry over the anticipated timeframe. Biopesticides are pesticides that are unmistakably derived from plants, animals, minerals, and microbes. The global biopesticides market is expanding as consumers become more aware of the risks and health problems associated with eating food containing insecticides, such as respiratory problems, neurological damage, hypersensitive reactions, and many more. The increasing necessity to increase agricultural output because of the hastily growing population and reducing arable land region is assisting the biopesticides business call for. Further, growing agricultural improvement in international locations like Indonesia, Vietnam, India, Africa, and Malaysia is a major thing using the marketplace data. Agriculture plays an essential position in the monetary improvement of African and Asian locations, contributing around 47% of employment in 2021 across the area (162). Biopesticides are quite valuable for ecological and environmental stability in terms of crop safety. Additionally, speedy technological advancement by systematic and sizeable research has positively motivated industry penetration. Stringent rules to limit the pesticide residue in food products are creating new growth opportunities for biopesticide producers. To meet consumer expectations in the advanced economies of North America and Europe, the majority of food-exporting nations utilize biopesticides (163). However, the COVID-19 epidemic has resulted in low customer purchasing power and delivery chain disruption, which may limit the market's demand for biopesticides.

3.4. Mode of action of biopesticide

3.4. 1. Mode of action of fungal pesticides

As new findings are emerging periodically, various scientific studies are ongoing, and many others are still to come. Several questions have been raised, and different authors have identified various research gaps in very recent publications. Given these conditions, it is possible that the processes responsible for endophytic fungi's ability to combat insect pests through pathogenic activities have not been thoroughly explored (18,34). By encouraging the creation of plant defense chemicals, which have been characterized as having a variety of bioactivities and functions, endophytic fungi generally improve host protection against main pests (44). Because endophytic fungi produce secondary metabolites, plants with fungal endophytes show feeding deterrence or antibiosis over their major insect pests. The fecundity, fitness, and longevity of pests are indirectly impacted by colonized plants, which are less hospitable to herbivores (16, 37,). The ability of endophytic fungi from the genus *Beauveria* and *Metarhizium* spp. to synthesize a variety of secondary metabolites, some of which have been shown to have antifungal, antibacterial, and insecticidal effects, is well recognized. These compounds include bassianolides, bassianolone, beauvericin, and oosporein, which are synthesized by *B. bassiana*. Similar to these, important substances produced from *Metarhizium* spp. include destruxins, cytochalasins, serinocyclins, etc. (76). For instance, destruxin A (DA), a mycotoxin produced by M. anisopliae, has been shown to have insecticidal and immunosuppressive properties (31, 66). The fungus modifies the host's nutritional composition during the endophytic colonization of the plant to promote the generation of secondary metabolites.

3.4.2. Bacterial pesticides

They have a distinct method of operation, have a short residual effect, are environment friendly, are made from different species, which ensures sustainability in their production, are cost-effective, and it is easy to make mass production in vitro. They have nothing to do with greenhouse gas emissions. To kill an insect, Bt spores must be consumed by the vulnerable insect. Proteolytic enzymes in the alkaline stomach juice (pH 8–10) make the cry toxin active. The majority of cry toxins constitute 60–70 kDa pro-toxins that were once 130–140 kDa in size (80). The midgut epithelial cells' apical microvillar brush borders membrane contains specific receptors that the activated toxin binds to, creating pores that allow the toxin to enter and cause the cells to swell. Up until the time that the cells lyse and split from the midgut epithelium's basement membrane, the swelling persists. The insect becomes paralyzed and dies as a result of the alkaline digestive contents leaking into the hemocoel and raising the pH of the hemolymph (6). But according to Broderick and co-researchers, infection of the hemolymph and the insect's mortality are brought on by the naturally occurring microorganisms (*E. coli* and *Enterobacter*) in the gut penetrating the hemocoel via the damaged epithelium brought on by Bt toxins (86). The endospore plays a significant role in the insect's death in Bt-moderately sensitive insects like *Spodoptera* spp. by releasing toxins while it is vegetatively growing in the hemolymph (44). The insect or any living organism that does not have the receptors in gut epithelial cells is not killed by Bt(12).

3.4. 3. Mode of action of GM plant toxin

The Cyt toxin is also a protoxin, about 28 kDa, and is activated by the proteolytic enzymes in the midgut juice to become 24 kDa. The toxin then penetrates from peritrophic membrane and the epithelial cells which lyse and separate resulting in the insect's death (19). Lepidopteran insects have been used primarily to characterize the mechanism for the action of Cry toxins. As was previously mentioned, Cry toxins are commonly believed to lyse midgut epithelial cells of the target insect by creating pores in the cells' apical microvilli membrane (11,70,97). Nevertheless, it has been recently suggested that toxicity could be related to G-protein-mediated apoptosis following receptor binding (25). Crystal inclusion protoxins release cry proteins into membrane-inserted oligomers, which result in ion leakage and cell lysis. The alkaline environment of the stomach causes the crystal inclusions consumed by vulnerable larvae to dissolve, while the dissolved inactive protoxins are then broken down by midgut proteases to produce 60–70 kDa protease -resistant protein (58). Toxin activation involves the proteolytic removal of an N-terminal peptide (25–30 amino acids for Cry1 toxins, 58 residues for Cry3A, and 49 for Cry2Aa) and approximately half of the remaining protein from the C-terminus in the case of the long Cry protoxins. The active toxin then attaches to a certain receptor on the membrane that covers the brush border of the midgut epithelial columnar cells before penetrating the membrane (34, 27, 58). In microvilli of apical membranes, toxin insertion results in the development of lytic holes (159, 161). Cell lysis and destruction of the midgut epithelium later cause the discharge of cell contents, which gives spores a medium to germinate in, causing acute septicemia and insect deaths (47, 58). The processing of the toxins' N-terminal ends is one intriguing aspect of Cry toxin activation. Two?-helices in the N-terminal region of the Cry2Aa protoxin's three-dimensional structure were found to obstruct a portion of the toxin crucial in its interaction with its receptors (100). Moreover, it was discovered that a Cry1Ac mutant that retained the N -terminus end after trypsin treatment binds nonspecifically to M. sexta membranes and was unable to form pores on M. sexta brush border membrane vesicles

(BBMV) (35). Consequently, N-terminal end processing of Cry protoxins may unmask a domain II hydrophobic patch involved in toxin-receptor or toxin-membrane interaction.

Plant lectins have developed the capacity to interact negatively and interfere with the development and physiological processes of several insect species, giving rise to their entomotoxic qualities (94). The insecticidal activity of plant lectins against a diverse array of Coleoptera, Homoptera, Diptera, and Lepidoptera insect species is well documented in the literature. Numerous lectins show considerable resistance to insect gut proteolysis, favoring the contact between the lectin and the carbohydrate and, as a result, the lectin's toxicity. Some entomotoxins have a low potency when consumed directly by the insect as they do not efficiently enter the hemolymph to exhibit their insecticidal function. As a result, the entomotoxin-lectin fusion gives the fused protein the capacity to pass through the stomach epithelium of the target insect and enter the hemolymph without breaking down (89).

3.4. 4. Action of beneficial nematodes

Nematodes have different sites for finding their target insects. *Heterorhabditis baceriophora* uses an active cruiser strategy to search their host while *Steinernema carpocapsae* waits for the passing insects (ambushers). Nematodes rely on chemical cues, temperature cues, and touch or vibration to detect insect hosts. When they find their host they enter and kill it. Nematodes pass through several life stages. Infective third-stage juveniles in soil enter an insect through the natural opening of the host such as the mouth, anus, and breathing holes. After the first step, they enter into insect body cavity and release their bacteria. Then toxins produced by the bacteria kill the insects within a couple of days. These nematodes grow into adults, feed on the bacteria and the liquefying host, mature, reproduce, and produce progeny. Nematodes then depart from the deceased insects and look for an alternative insect host. Insects killed by *Steinernema tidaen* turn brown while *Heteror habdit* is killed insects turn red.

3.4. 5. Action of Viral biopesticide

When a larva consumes a virus, the occlusion body dissolves in the acidic stomach fluid and releases viral particles into the gut. The peritrophic membrane lining the midgut then binds viral particles. Nucleocapsids are released into the cytoplasm when the lipoprotein membrane of the virus combines with the plasma cell membrane of the cells that make up the gut wall. Viral gene expression starts once the nucleotide transfers virus DNA into the cell nucleus. The virus rapidly replicates and invades the host body with viral fragments. Late in the life cycle, these virus particles get occluded. When larvae die, they release a large number of occlusion bodies into the environment, where they spread the infection to new larvae. The larvae grow sluggish and unable to feed themselves after 2-4 days of viral ingestion. The epidermis becomes extremely brittle and prone to rupture at the advanced stage. The larvae wilt and their body parts transform into a fluidized mess of polyhedral and degraded tissue. Infected larvae continuously climb to the substrate's highest point just before they die and cling to it using their prolegs. They hang in a distinctive V form after passing away.

3.4. 6. Mechanism of action of nano-biopesticides

There are various kinds of biopesticides with various modes of action, including pyrethrum, azadirachtin, fluoroacetate, and sabdilla, which have varied effects on pests. For example, the alkaloid toxin of sabdillaca used the loss of nerve cell membrane. It’s found that sabdilla could kill most insects immediately after its use (39). Although pyrethrins are not poisonous, they instantly kill insects. For humans and animals, it’s not toxic. Pyrethrins alter the process of potassium and sodium ion exchange in insect nerve fibers, it’s causes inhibiting the transmission of nerve impulses. While azadirachtin has antifeedant activity and it causes reduced food consumption instead of control. According to reports, azadirachtin dosage stimulates deterrent receptors together with sugar receptors, which inhibits eating behavior and causes food limits, famine, and poor nutrition. Various studies have demonstrated weight loss in some insects such as *Spodoptera eridania*, *Periplaneta americana, Helicoverpa armigera,* etc (40). In plant extracts and some oils, a range of compounds is present that may interact with the insect's nervous system and coordination resulting death of insects by disrupting their life cycle.

3.5. Challenges and Future Perspectives

Biopesticides are an excellent alternative to chemical suppliers for farmers who require more reliable insecticides to protect their plant harvests. Yet, there are still a lot of obstacles in the way of biopesticide deployment, manufacturing, and enhancement. It is necessary to conduct further research in manufacturing, shipping, and systems to support the commercialization of biopesticides (163). Integrations between the public and commercial sectors might increase the production, advancement, and marketing of environmentally friendly alternatives to chemical pesticides in developing countries (147). Also, there is a need for more guidance from businesses, customers, and pesticide manufacturers (164). Creating rigorous regulatory frameworks to keep biopesticides affordable in underdeveloped countries is a major challenge. As a result, there are still certain limitations to the development of many biopesticides (63). By using more advanced "2nd" and "1/3" technology plants with more flexibility in IPM, it is possible to witness the "first technology" of transgenic vegetation carrying Bt genes. They include plant life that has many designed genes and inducible, tissue-specific expression structures. Since the early 1980s, scientific interest in mycoherbicide investigations has advanced faster in terms of the variety of weeds it controls and the potential diseases it investigates. Globally, both regulated and unlicensed mycoherbicide use has grown. Likewise, the mycoherbicidal era saw a sharp rise in the number of U.S.A. patents issued (64). Studies of organic manipulation marketers have significantly advanced as a result of new biopesticide initiatives that integrate fitness/

environmental issues with economic constraints for agrochemicals. The effectiveness and dependability of biopesticides may advance through the next era. Moreover, product prices continue to be unfavorable due to advancements in manufacturing production. Although there are still a lot of obstacles to overcome, some market predictions show that commercial biopesticide production is feasible. Bt production in particular is forecast to increase, but huge sales of bio-fungicides and bioherbicides are also envisaged (165).

Conclusion

Chemicals are widely used and have been around for a long time because natural goods are valuable commercially. These characteristics that lead to innovative processes are thought to exist in natural objects. It has been difficult to put the idea of natural biopesticides into practice and determine how they affect high-output displays, but there have been some significant results under conditions where some crop damage is acceptable. Recently, research plans have been carried out to improve shelf life, immediate death, biological scheme, field efficiency, dependability, as well as the impact of cost-of-living systems. Biopesticides are crucial to integrated pest control because they might avoid the use of harmful synthetic chemical pesticides in their stead. A sustainable alternative to conventional pesticides, biopesticides can preserve agricultural productivity while protecting the environment. A pest management strategy that effectively manages insect resistance is necessary to raise agricultural output. The most effective strategy to manage pests is to use biological methods or combine biological conventional methods. The use of biopesticides has expanded as a result of improvements in application techniques, eco-friendly alternatives, and less-priced options for many formulations. This makes it more logical to use biopesticides to control pests, especially as better cost-efficiency approaches reality shortly.

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Authors' contributions

MB wrote the paper. SKC designed the Review manuscript and improved the manuscript and Dewa Basnett wrote and corrected it.

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