

## A Compilation Research on Biopesticides in Agricultural Primary Products

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### Abstract

The increasing global emphasis on sustainable agriculture and environmental safety has led to the growing adoption of biopesticides as alternatives to chemical pesticides. This review provides a comprehensive analysis of biopesticides used in various agricultural primary products, highlighting their types, modes of action, and benefits and limitations. Biopesticides, derived from natural materials such as plants, microorganisms, and natural substances, are categorized into microbial pesticides, biochemical pesticides, and plant-incorporated protectants (PIPs). Case studies from different regions illustrate the effectiveness of biopesticides in controlling pests and diseases in crops like corn, tomatoes, cotton, grapes, soybeans, apples, and potatoes. Despite their environmental and health benefits, challenges such as variable efficacy, slower action, and regulatory barriers persist. Advances in formulation technology, genomics, and biotechnological innovations are enhancing the efficacy and market acceptance of biopesticides. The integration of biopesticides into sustainable agriculture practices, including Integrated Pest Management (IPM), underscores their pivotal role in future pest management strategies. This review underscores the potential of biopesticides in promoting eco-friendly pest control and sustainable agricultural practices.

**Keywords:** biopesticides, sustainable agriculture, microbial pesticides, pest management, Integrated Pest Management (IPM).

## 1. Introduction

Nowadays, a huge interest in organic agriculture and horticulture in order to produce high-quality and toxin-free food has been rising. This trend is due to fear of dangerous residues on food from chemical pesticides. Numerous biopesticides are at our disposal to protect crops. Biopesticides are naturally occurring substances that are intended to control pests. They are favored over chemical pesticides for the protection of plants as they are believed to have lesser threat and to be more sound for human and environmental health [1]. Agriculture faces significant challenges in managing pests and diseases that threaten crop productivity and food security. Traditionally, chemical pesticides have been the mainstay in pest control strategies. However, the adverse effects of chemical pesticides on the environment, human health, and non-target organisms have prompted the search for more sustainable alternatives [3]. The use of biopesticides in agriculture and plantation has gained a global market, and their demand has increased massively over the years. The biopesticides market reached an estimated 2.5 billion US dollars and is on an accelerating trajectory, ensuring future growth with the continuous involvement of large and small players. This is mainly due to consumer awareness of the ecological implications of pesticides, the rise in awareness about the quality of crop production, and the realization that biopesticides are eco-friendly [2].

Biopesticides are naturally occurring substances that control pests (biochemical), microorganisms that might control pests (microbial), and genetically modified plants designed to control pests (plant-incorporated protectants) [4]. They lessen the exertion of pesticides for the prevention of insects and other harmful organisms. They have a lesser threat and are more fit for human health as well as for environmental sustainability. Biopesticides, derived from natural materials such as animals, plants, bacteria, and certain minerals, have emerged as a promising solution. This essay provides a comprehensive review of biopesticides in agricultural primary products, including their types and the latest findings in the field [5]. Also, the essay discusses the various aspects of biopesticides such as bacterial toxins, vectors, fungistatic berries, natural regulatory proteins, RNAi agents, etc. [6].

The essay provided is a synthesis research of general knowledge about biopesticides and recent trends in their development and use.

## 2. Types of Biopesticides

Biopesticides are broadly categorized into three main types: microbial pesticides, biochemical pesticides, and plant-incorporated protectants (PIPs) [4]. (Fig.1)

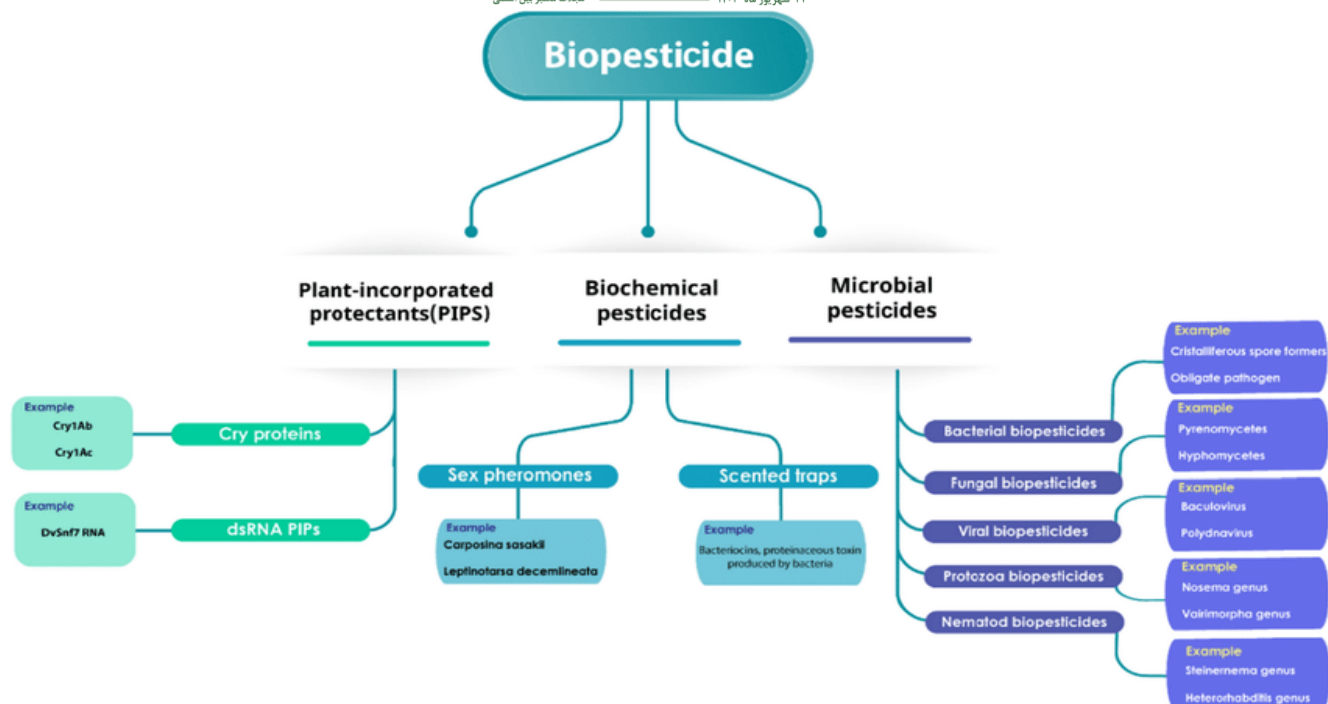


Figure.1: Classification of biopesticides with examples [7]

## 2.1. Microbial Biopesticides

Microbial pesticides contain microorganisms (e.g., bacteria, fungi, viruses, or protozoans) as active ingredients. These microorganisms either directly target pests or produce substances that inhibit pests. Common examples include:

*Bacillus thuringiensis* (Bt): Bt is a bacterium that produces toxic proteins face to specific insect larvae. Bt is one of the most widely used microbial agents in biopesticides. It produces crystal proteins (Cry and Cyt toxins) that are fatal to specific insect larvae when ingested, disrupting their gut cells and leading to death. It is one of the most widely effective against pests such as the European corn borer and tomato hornworm and is utilized commonly as a microbial biopesticide.

*Beauveria bassiana*: This entomopathogenic fungus infects and kills a variety of insect pests by penetrating their cuticle and proliferating inside them. This fungus acts as an entomopathogen, infecting and killing a wide range of insect pests. It penetrates the insect cuticle and proliferates inside, eventually causing death [8].

*Trichoderma spp.*: These fungi are used for their antagonistic properties against plant pathogens, producing enzymes and secondary metabolites that inhibit harmful fungi and bacteria [9].

*Metarhizium anisopliae*: Another entomopathogenic fungus, *Metarhizium* infects insects through their cuticle and grows internally, leading to the death of the host. It is effective against various insect pests [8].

*Pseudomonas fluorescens*: This bacterium produces a range of antimicrobial compounds that suppress plant pathogens. It also promotes plant growth and induces systemic resistance in plants [10].

*Streptomyces spp.*: These soil-dwelling bacteria produce antibiotics and enzymes that inhibit the growth of plant pathogens. They also play a role in decomposing organic matter and enhancing soil health [11].

*Bacillus subtilis*: Known for its ability to produce a variety of antimicrobial compounds, *B. subtilis* is used to control a broad spectrum of plant pathogens, including fungi, bacteria, and nematodes [12].

*Nucleopolyhedroviruses* (NPVs): These viruses specifically infect insect pests, causing disease and death. They are highly specific to their host species, making them a targeted biopesticide option [13].

*Azadirachtin*: Derived from the neem tree, although not a microbial product, it is often included in biopesticides for its insecticidal properties. It disrupts the growth and reproduction of insects [14].

These microbial products are crucial for developing biopesticides due to their specificity, effectiveness, and reduced environmental impact compared to conventional chemical pesticides.

## 2.2. Botanical Biopesticides

Plant-Incorporated Protectants or PIPs are pesticidal substances produced by plants that have been genetically modified. The genetic material from certain pest-resistant microorganisms is introduced into the plant's genome. A prominent example is Bt crops, where genes from *Bacillus thuringiensis* are inserted into crops like corn and cotton to produce insecticidal proteins [14].

## 2.3. Biochemical Biopesticides

Biochemical pesticides include naturally occurring substances that control pests by non-toxic mechanisms. They include insect pheromones, plant extracts, and other natural compounds. Examples include:

**Neem Extracts:** Derived from the neem tree, azadirachtin is a potent insect growth regulator and feeding deterrent [5].

**Insect Sex Pheromones:** These chemicals are used to disrupt mating patterns of insects, thus reducing their populations [4].

## 3. Modes of Action

### Modes of Action in Agricultural Biopesticides

Agricultural biopesticides represent a pivotal shift in pest management strategies towards more sustainable and environmentally friendly practices. Unlike chemical pesticides that often rely on broad-spectrum toxicity, biopesticides utilize a variety of modes of action that target specific pests with minimal impact on non-target organisms and the environment [5]. Understanding these modes of action is crucial for the effective application and integration of biopesticides into modern agricultural systems. This section explores the primary modes of action in agricultural biopesticides, highlighting the mechanisms by which they control pest populations.

As mentioned earlier, biopesticides are derived from natural sources, including microorganisms (bacteria, fungi, viruses, and protozoa), biochemicals (plant extracts, pheromones, and other naturally occurring substances), and genetically modified plants that produce pesticidal substances. These biopesticides work through various modes of action to manage pest populations. The effectiveness of biopesticides lies in their specific interactions with target pests, which can range from disrupting physiological processes to inducing lethal infections [1].

### Microbial Biopesticides

Microbial biopesticides utilize living organisms or their by-products to suppress pest populations. The modes of action for microbial biopesticides include infection, toxin production, competition, and induced resistance.

#### 3.1. Infection

Many microbial biopesticides work by infecting and killing pests. For example:

***Bacillus thuringiensis* (Bt):** This bacterium produces crystal (Cry) and cytolytic (Cyt) toxins that are ingested by insect larvae. Once inside the gut, these toxins bind to specific receptors on the gut lining, causing cell lysis and death. Bt is particularly effective against caterpillars, beetles, and mosquitoes. (fig.2)

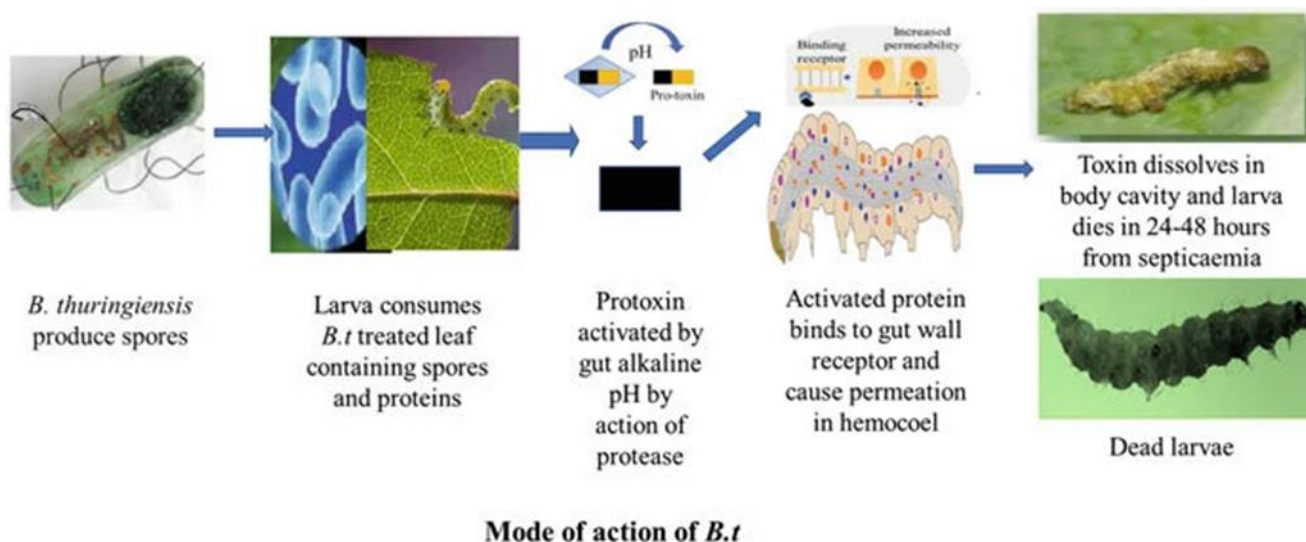


Figure.2: Mode of action of Bt. [15]

***Beauveria bassiana*:** An entomopathogenic fungus, *B. bassiana* infects insects through their cuticle. The spores germinate and penetrate the insect's exoskeleton, proliferating inside and ultimately killing the host [4].

#### 3.2. Toxin Production

Certain microbial biopesticides produce secondary metabolites that are toxic to pests:

*Streptomyces spp.*: These soil-dwelling bacteria produce antibiotics and other toxic compounds that inhibit the growth of plant pathogens and nematodes [8] . Fig.3

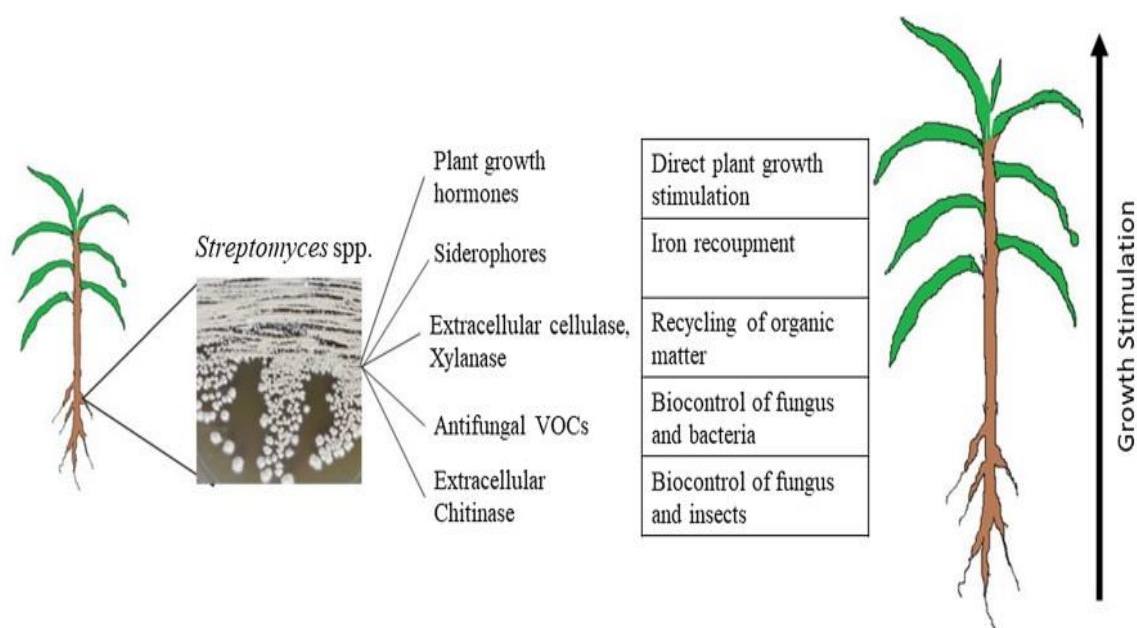


Figure.3: Different roles of secondary metabolites from *Streptomyces spp.* in plant growth stimulation [16]

### 3.3. Competition

Microbial biopesticides can outcompete harmful microorganisms for resources and space, thereby suppressing their growth:

*Trichoderma spp.*: These fungi compete with plant pathogenic fungi for nutrients and space in the rhizosphere. They also produce enzymes that degrade the cell walls of pathogens [5].

### 3.4. Induced Resistance

Some microbial biopesticides enhance the plant's own defense mechanisms:

*Pseudomonas fluorescens*: This bacterium induces systemic resistance in plants, enhancing their ability to fend off a wide range of pathogens [17].

### 3.5. Biochemical Biopesticides

Biochemical biopesticides include natural substances that control pests through various non-toxic mechanisms, such as disrupting hormonal balances, acting as repellents, or interfering with the pests' reproductive systems.

#### 3.5.1. Hormonal Disruption

Certain biochemical biopesticides disrupt the hormonal balance of pests:

**Azadirachtin**: Derived from neem tree seeds, azadirachtin interferes with the molting process of insects, inhibiting their growth and development [18].

#### 3.5.2. Repellents and Antifeedants

Some biochemicals act as repellents or antifeedants, discouraging pests from feeding on plants:

**Capsaicin**: Extracted from chili peppers, capsaicin acts as a repellent to many insects and animals [19].

#### 3.5.3. Mating Disruption

Insect pheromones are used to disrupt mating behaviors, reducing pest populations over time:

**Sex Pheromones**: Synthetic versions of insect sex pheromones are used in traps or released into the environment to confuse male insects, preventing them from locating females and thereby reducing reproduction rates [20].

**Plant-Incorporated Protectants (PIPs)**: PIPs are genetically modified crops that produce their own pesticidal substances. These biopesticides work by incorporating genes from pest-resistant organisms into the plant's genome, enabling the plant to produce specific proteins that target pests.

**Production of Insecticidal Proteins**: Bt crops, such as Bt corn and Bt cotton, have been genetically engineered to produce Bt toxins, which are effective against specific insect pests. These toxins function in the same way as those produced by the bacterium *Bacillus thuringiensis*, binding to receptors in the gut of the insect and causing cell lysis and death [21].



RNA Interference (RNAi): RNAi technology is used to silence specific genes in pests, leading to their death or reduced virulence. For example, genetically modified plants can produce RNA molecules that match the genetic sequences of essential pest genes, interfering with their expression and ultimately controlling the pest population [4].

#### 4. Benefits and Limitations of Biopesticides

##### Benefits of Using Biopesticides

###### 4.1. Environmental Safety

Biopesticides are typically less harmful to the environment than chemical pesticides. They are often specific to the target pests, which means they have minimal impact on non-target species, including beneficial insects, birds, and aquatic organisms. This specificity reduces the risk of ecological disruptions and helps maintain biodiversity [4][1].

###### 4.2. Human Health

Because biopesticides are derived from natural sources and are generally non-toxic, they pose fewer risks to human health compared to chemical pesticides. They are less likely to leave harmful residues on crops, reducing the potential for pesticide exposure through food consumption [1].

###### 4.3. Resistance Management

The use of biopesticides can help manage pest resistance. Chemical pesticides often have a single mode of action, making it easier for pests to develop resistance over time. Biopesticides, however, may work through multiple mechanisms, making it more difficult for pests to adapt. This can prolong the efficacy of pest control measures [22].

Biopesticides support sustainable agricultural practices by reducing the dependency on synthetic chemicals. They can be integrated into Integrated Pest Management (IPM) programs, which combine biological, cultural, mechanical, and chemical control methods to manage pests in an environmentally and economically sustainable manner [23].

###### 4.5. Soil Health

Many biopesticides, especially microbial ones, can improve soil health by promoting beneficial microbial activity. For example, *Trichoderma* spp. not only control plant pathogens but also enhance root growth and nutrient uptake, contributing to overall soil fertility and plant health [24].

##### Disadvantages of Using Biopesticides:

###### 1. Variable Efficacy

One of the main drawbacks of biopesticides is their variable efficacy. Environmental conditions such as temperature, humidity, and UV radiation can affect their performance. For instance, the effectiveness of microbial biopesticides like *Bacillus thuringiensis* can be reduced by high temperatures and sunlight.

###### 2. Slower Action

Biopesticides often act more slowly than chemical pesticides. While chemical pesticides can provide rapid knockdown of pest populations, biopesticides might take longer to show effects. This slower action can be a disadvantage in situations where immediate pest control is necessary.

###### 3. Shorter Shelf Life

Biopesticides, especially microbial ones, generally have a shorter shelf life compared to chemical pesticides. They may require special storage conditions to maintain their viability and effectiveness, which can complicate their use and distribution [25].

###### 4. Limited Spectrum

Many biopesticides have a narrow spectrum of activity, targeting specific pests. While this specificity is beneficial for minimizing non-target effects, it can also be a limitation when dealing with multiple pest species. Farmers may need to use a combination of biopesticides or integrate them with other control methods to achieve comprehensive pest management.

###### 5. Regulatory and Market Barriers

The development, registration, and commercialization of biopesticides can be challenging due to stringent regulatory requirements. The process can be time-consuming and expensive, which may limit the availability of biopesticide products in the market. Additionally, there can be limited awareness and acceptance among farmers, who may be more familiar with chemical pesticides.

###### 6. Production and Consistency Issues

The production of biopesticides, particularly microbial ones, requires maintaining the consistency and quality of the biological material. Variations in production processes can lead to inconsistencies in the efficacy and performance of the

biopesticide products. Ensuring quality control and standardization is essential but can be technically demanding and costly.

**Table 1.** The various disadvantages of conventional chemical pesticides over biopesticides [4]

Conventional Chemical Pesticides	Biopesticides
Synthesised or produced from artificial/chemicals	Use naturally occurring compounds derived from living organisms for the production
They cause environmental pollution and are not eco-friendly	They do not cause environmental harm
Harmful to nontarget organisms	Do not cause harm to nontarget organisms
Cost ineffective	Cost efficient and cheaper, compared to chemical fertilisers
Microorganisms develop resistance gradually as the application increases	Pests do not develop resistance
High market value	Not preferred in the market
Contaminate water and soil	Cannot contaminate water sources
Lead to bioaccumulation	Do not lead to bioaccumulation

## 5. Case Studies of Biopesticide Use in Different Crops

### 1. Corn (Maize)

Biopesticide Used: *Bacillus thuringiensis* (Bt)

Pest Controlled: European Corn Borer (*Ostrinia nubilalis*)

Case Study:

Location: United States

Details: Bt corn was developed to express Cry proteins derived from *Bacillus thuringiensis*. These proteins are toxic to the larvae of the European corn borer, a major pest that can cause significant yield losses. Farmers in the Midwest region have widely adopted Bt corn, resulting in reduced reliance on chemical insecticides. Studies have shown that Bt corn has effectively reduced corn borer populations and increased yields. Additionally, the targeted action of Bt proteins has minimized impacts on non-target species and beneficial insects [26].

### 2. Tomatoes

Biopesticide Used: *Beauveria bassiana*

Pest Controlled: Whiteflies (*Bemisia tabaci*)

Case Study:

Location: Spain

Details: Tomato growers in the Almería region of Spain have integrated *Beauveria bassiana* into their pest management programs to control whiteflies, a common and destructive pest. *Beauveria bassiana* spores attach to the cuticle of whiteflies, germinate, and penetrate the insect body, leading to death. The use of this biopesticide has reduced whitefly populations significantly, decreasing the need for chemical insecticides. Field trials have demonstrated that *Beauveria bassiana* can be effectively combined with other biological control agents, such as predatory insects, to enhance overall pest management [27].

### 3. Cotton

Biopesticide Used: Bt Cotton (*Bacillus thuringiensis*)

Pest Controlled: Bollworms (*Helicoverpa spp.*)

Case Study:

Location: India

Details: Bt cotton has been genetically engineered to express Cry proteins that are toxic to bollworms. The introduction of Bt cotton in India has led to substantial reductions in bollworm infestations and increased cotton yields. Farmers have reported fewer applications of chemical insecticides, resulting in cost savings and lower environmental impact. Studies have also indicated improvements in the health of farm workers due to reduced pesticide exposure. The success of Bt cotton has contributed to India's emergence as one of the leading cotton-producing countries [28].

### 4. Grapes

Biopesticide Used: *Trichoderma harzianum*

Disease Controlled: Powdery Mildew (*Uncinula necator*)

Case Study:

Location: Italy

Details: In the vineyards of Tuscany, Italy, grape growers have adopted *Trichoderma harzianum* to combat powdery mildew, a fungal disease that affects grape quality and yield. *Trichoderma harzianum* is applied as a soil amendment and foliar spray, where it competes with and inhibits the growth of the powdery mildew pathogen. Field trials have shown that the use of *Trichoderma harzianum* can significantly reduce the incidence of powdery mildew, leading to healthier vines and better grape production. The biopesticide has also been found to enhance plant vigor and root development.

5. Soybeans

Biopesticide Used: *Bacillus subtilis*

Disease Controlled: Root Rot (*Phytophthora sojae*)

Case Study:

Location: Brazil

Details: Brazilian soybean farmers have faced challenges with root rot caused by *Phytophthora sojae*. *Bacillus subtilis*, a bacterium known for its antifungal properties, has been used to protect soybean plants. *Bacillus subtilis* colonizes the root zone and produces antimicrobial compounds that suppress the root rot pathogen. Field studies have demonstrated that *Bacillus subtilis* can reduce disease incidence and improve plant health. The use of this biopesticide has also promoted root growth and nutrient uptake, contributing to higher yields [29].

6. Apples

Biopesticide Used: *Pseudomonas fluorescens*

Disease Controlled: Fire Blight (*Erwinia amylovora*)

Case Study:

Location: United States (Washington State)

Details: Apple orchards in Washington State have been impacted by fire blight, a bacterial disease that can devastate apple trees. *Pseudomonas fluorescens*, a bacterium with antagonistic properties against *Erwinia amylovora*, the fire blight pathogen, has been used to manage this disease. *Pseudomonas fluorescens* colonizes the plant surfaces and produces antibiotics that inhibit the fire blight bacteria. Field trials have shown that applying *Pseudomonas fluorescens* as a preventive measure can reduce the incidence of fire blight, leading to healthier apple trees and improved fruit quality [30].

7. Potatoes

Biopesticide Used: *Bacillus thuringiensis* var. *tenebrionis*

Pest Controlled: Colorado Potato Beetle (*Leptinotarsa decemlineata*)

Case Study:

Location: Canada

Details: The Colorado potato beetle is a major pest of potato crops in Canada. Farmers have utilized *Bacillus thuringiensis* var. *tenebrionis* to manage beetle populations. This specific strain of Bt produces a toxin that targets the digestive system of Colorado potato beetle larvae. Application of Bt has resulted in significant reductions in beetle infestations, lowering the need for chemical insecticides. This biopesticide has helped potato farmers achieve better pest control and maintain sustainable agricultural practices [31]. The name of the agent, the studied plants, and the treated disease, and their mechanism of action are summarized in Table 2.

**Table 2.** The name of the agent, the studied plants and the treated disease and their mechanism of action

	Biopesticide Used	Target Plant	Disease Controlled	References
1	<i>Bacillus thuringiensis</i> (Bt)	Corn (Maize)	European Corn Borer ( <i>Ostrinia nubilalis</i> )	[26]
2	<i>Beauveria bassiana</i>	Tomatoes	Whiteflies ( <i>Bemisia tabaci</i> )	[27]
3	Bt Cotton ( <i>Bacillus thuringiensis</i> )	Cotton	Bollworms ( <i>Helicoverpa spp.</i> )	[28]
4	<i>Trichoderma harzianum</i>	Grapes	Powdery Mildew ( <i>Uncinula necator</i> )	[29]
5	<i>Bacillus subtilis</i>	Soybeans	Root Rot ( <i>Phytophthora sojae</i> )	[29]



6	<i>Pseudomonas fluorescens</i>	Apples	Fire Blight ( <i>Erwinia amylovora</i> )	[30]
7	<i>Bacillus thuringiensis</i> var. <i>tenebrionis</i>	Potatoes	Colorado Potato Beetle	[31]

## 6. Latest Findings in Biopesticides

The field of biopesticides is dynamic, with continuous research and development leading to new products and improved efficacy. Some of the latest findings include:

### 1. Enhanced Formulations and Delivery Systems

Recent advances in formulation technology have improved the stability, shelf-life, and efficacy of biopesticides. Microencapsulation, nano-formulations, and bio-based carriers are being used to enhance the delivery and persistence of biopesticides in the field.

### 2. Genomic and Biotechnological Innovations

Advances in genomics and biotechnology have led to the identification of new microbial strains and genes with pesticidal properties. CRISPR-Cas9 and other gene-editing technologies are being utilized to enhance the effectiveness of biopesticidal organisms and develop new PIPs with broader pest resistance [32][33].

### 3. Integration with Sustainable Agriculture Practices

Biopesticides are increasingly being integrated into broader sustainable agriculture practices such as Integrated Pest Management (IPM). Combining biopesticides with cultural, mechanical, and biological control methods can lead to more effective and environmentally friendly pest management strategies [34].

### 4. Regulatory and Market Trends

The regulatory landscape for biopesticides is evolving, with many countries developing frameworks to support their registration and commercialization. Consumer demand for organic and sustainably produced food is also driving the growth of the biopesticide market. According to market analysis, the global biopesticides market is projected to grow significantly in the coming years, reflecting increasing acceptance and adoption by farmers [36][37].

## 7. Wide Used Biopesticides

Among the various microbial products used in biopesticides, bacteria, and fungi are the most commonly utilized. They are widely adopted due to their effectiveness, specificity, and the range of pests and diseases they can control. Viruses, while effective, are more specialized, and protozoa are less frequently used in comparison.

Bacteria:

1. *Bacillus thuringiensis* (Bt): This is the most widely used bacterial biopesticide. Bt-based products are extensively applied in agriculture to control a wide range of insect pests, especially caterpillars.
2. *Bacillus subtilis*: Commonly used to manage fungal diseases in plants by producing antimicrobial compounds.
3. *Pseudomonas fluorescens*: Used for its broad-spectrum antimicrobial properties and ability to induce systemic resistance in plants.

Fungi:

1. *Beauveria bassiana*: A popular fungal biopesticide used to control various insect pests through direct infection.
2. *Metarhizium anisopliae*: Frequently used against insects, penetrating their cuticle and proliferating internally.
3. *Trichoderma spp.*: Widely used for their antagonistic properties against plant pathogens, enhancing plant health and soil quality.

Viruses:

1. *Nucleopolyhedroviruses* (NPVs): These are specific to certain insect pests and are effective biocontrol agents, though their use is more specialized compared to bacterial and fungal biopesticides.

Protozoa:

Protozoa are less commonly used in commercial biopesticides compared to bacteria, fungi, and viruses. Their application is more limited and not as widespread in agricultural practices.

## 8. Examples of Crops Protected by Biopesticides

## 1. Corn (Maize)

Pest Controlled: European Corn Borer

Biopesticide Product: Dipel (active ingredient: *Bacillus thuringiensis* var. *kurstaki*)

## 2. Tomato

Pest Controlled: Tomato Hornworm

Biopesticide Product: Javelin WG (active ingredient: *Bacillus thuringiensis* var. *kurstaki*)

## 3. Cotton

Pest Controlled: Bollworms

Biopesticide Product: Biobit (active ingredient: *Bacillus thuringiensis* var. *kurstaki*)

## 4. Soybeans

Pest Controlled: Soybean Aphid

Biopesticide Product: *Beauveria bassiana* strain GHA (marketed as Mycotrol)

## 5. Grapes

Disease Controlled: Powdery Mildew

Biopesticide Product: Serenade (active ingredient: *Bacillus subtilis*)

## 6. Wheat

Pest Controlled: Root Rot

Biopesticide Product: *Trichoderma harzianum* (marketed as RootShield)

## 7. Potatoes

Pest Controlled: Colorado Potato Beetle

Biopesticide Product: Novodor (active ingredient: *Bacillus thuringiensis* var. *tenebrionis*)

## 8. Apples

Disease Controlled: Fire Blight

Biopesticide Product: BlightBan A506 (active ingredient: *Pseudomonas fluorescens*)

## 9. Rice

Pest Controlled: Rice Weevil

Biopesticide Product: Green Muscle (active ingredient: *Metarhizium anisopliae*)

## 10. Cucumbers

Disease Controlled: Fusarium Wilt

Biopesticide Product: RootShield (active ingredient: *Trichoderma harzianum*)

## 9. Conclusion

Biopesticides represent a crucial component of modern sustainable agriculture, offering effective pest control while minimizing environmental and health impacts. The diverse types of biopesticides, including microbial, biochemical, and plant-incorporated protectants, provide multiple mechanisms for managing pests and diseases in crops. Recent advancements in formulation technologies, genomics, and biotechnological innovations have further enhanced the efficacy and adoption of biopesticides. As regulatory frameworks and market trends continue to evolve, biopesticides are poised to play a central role in achieving sustainable agricultural productivity and food security.

The diverse modes of action employed by agricultural biopesticides offer effective and environmentally sustainable alternatives to conventional chemical pesticides. By understanding these mechanisms, farmers and agronomists can better integrate biopesticides into pest management strategies, reducing reliance on synthetic chemicals and promoting healthier ecosystems. As research and technology continue to advance, the development and adoption of biopesticides are likely to increase, contributing to the sustainability and resilience of agricultural systems worldwide.

Moreover, biopesticides offer numerous benefits over chemical pesticides, including environmental safety, human health protection, resistance management, and support for sustainable agriculture. However, they also present challenges such as variable efficacy, slower action, shorter shelf life, and limited spectrum of activity. Despite these disadvantages, the integration of biopesticides into pest management strategies is crucial for reducing the reliance on chemical pesticides and promoting a more sustainable and resilient agricultural system. Ongoing research and technological advancements are likely to address some of the current limitations, enhancing the effectiveness and adoption of biopesticides in the future.

Eventually, case studies illustrate the diverse applications and benefits of biopesticides in various crops, highlighting their potential to enhance pest and disease management while promoting environmental and human health. Indeed, biopesticide products are derived from various microorganisms and are targeted to manage specific pests and diseases effectively, offering sustainable alternatives to chemical pesticides in agriculture.

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