

Lecture 10. Biopesticides and Biofungicides: Principles of Action, Advantages and Disadvantages, and Applications in Crop Production

Introduction

Modern crop production faces continuous losses caused by insects, fungi, bacteria, viruses, nematodes, weeds, and other harmful organisms. Conventional agriculture has traditionally relied heavily on synthetic pesticides to protect crops and maintain productivity. These products can provide effective and rapid control, but intensive or inappropriate use may contribute to pesticide resistance, residues in agricultural products, contamination of soil and water, and negative effects on non-target organisms. For these reasons, sustainable agriculture increasingly emphasizes biological approaches to crop protection. **Biopesticides** are pest-management products derived from microorganisms, naturally occurring biological substances, or other biological sources. **Biofungicides** are biological products specifically intended to suppress plant-pathogenic fungi and fungus-like organisms. Their activity can involve direct antagonism, competition for nutrients and ecological niches, production of antimicrobial metabolites, parasitism of pathogens, activation of plant defense responses, or combinations of these mechanisms. Biopesticides and biofungicides are especially important components of **Integrated Pest Management (IPM)**, where biological, cultural, genetic, physical, and chemical approaches are combined to maintain pest populations and disease pressure at acceptable levels while reducing unnecessary environmental impacts.

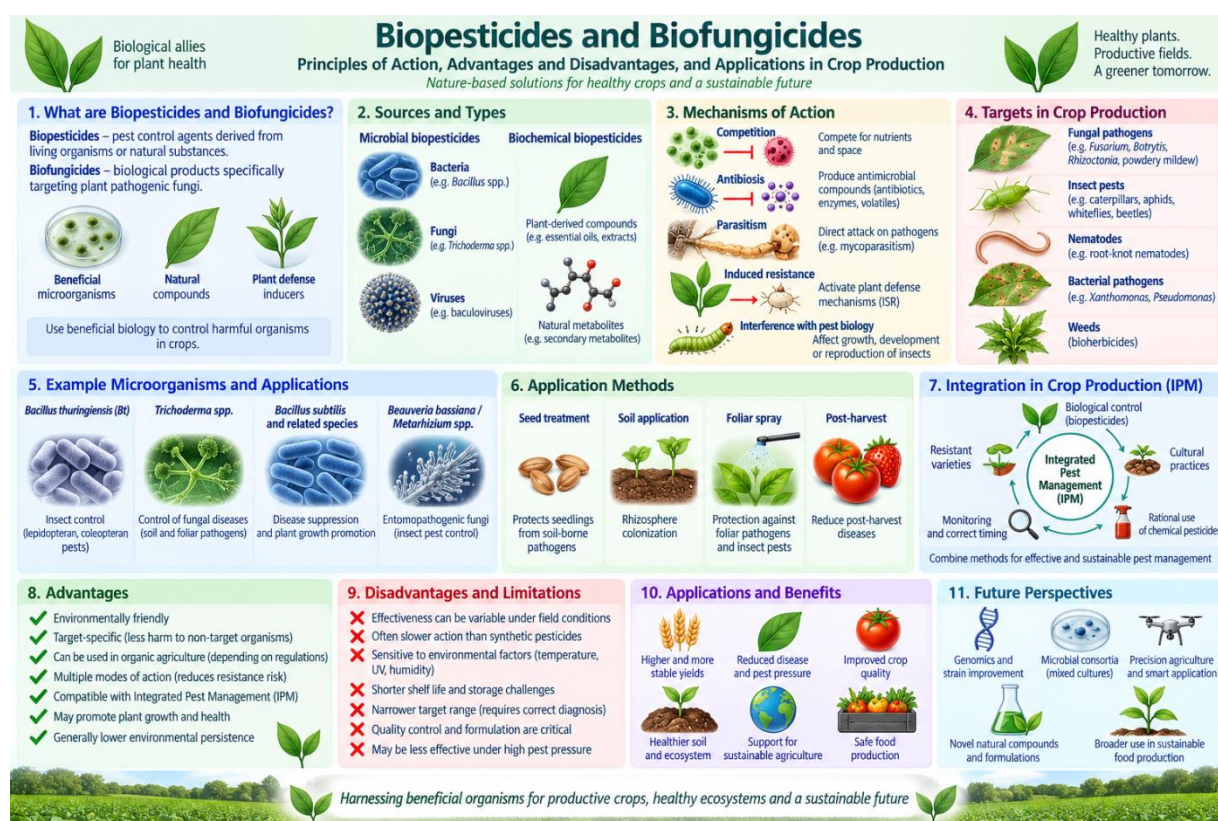


Figure 1. Graphical Abstract of Biopesticides and Biofungicides: Principles of Action, Advantages, Disadvantages, and Applications in Crop Production

Classification of Biopesticides and Biofungicides

Biopesticides represent a diverse group of products rather than a single type of pest-control agent. Microbial biopesticides contain microorganisms such as bacteria, fungi, or viruses whose biological activity suppresses particular pests or pathogens. Well-known bacterial examples involve strains of *Bacillus thuringiensis*, which produce proteins active against particular groups of insect pests. Other species of *Bacillus* and related bacteria can suppress plant pathogens through competition, antimicrobial compounds, and stimulation of plant defense mechanisms. Fungal biological-control agents include species belonging to genera such as *Trichoderma*, *Beauveria*, and *Metarhizium*. Their biological functions differ: some are primarily associated with antagonism against plant pathogens, whereas others are entomopathogenic fungi capable of infecting susceptible insects. Certain viruses can also function as highly specific biological insect-control agents.

Another important category consists of naturally derived biochemical substances that affect pest behavior, development, reproduction, or survival. Plant-derived compounds and signaling molecules can be used in pest-management strategies, although the regulatory definition of a biopesticide differs among countries. The source of a product alone does not determine its safety or effectiveness; biological activity, toxicity, environmental persistence, formulation, target specificity, and application conditions must all be evaluated. Consequently, biological pesticides should be assessed scientifically in the same way that other crop-protection technologies are evaluated.

Principles and Mechanisms of Action

The mechanisms of biological pest control are highly diverse. One important mechanism is competition. Beneficial microorganisms can colonize roots, leaves, or other plant surfaces and compete with pathogens for nutrients, space, and infection sites. If beneficial microorganisms establish themselves rapidly, they may reduce the ecological opportunities available to pathogens. Competition for micronutrients can also be important. Some microorganisms produce compounds called siderophores that bind iron efficiently, potentially reducing its availability to competing microorganisms.

Another mechanism is antibiosis, in which a beneficial microorganism produces biologically active metabolites that inhibit the growth or development of another organism. Various bacterial and fungal biological-control agents produce antimicrobial compounds, enzymes, volatile substances, or other metabolites capable of suppressing pathogens. The effectiveness of these compounds depends on concentration, environmental conditions, target organism, and interactions with other microorganisms. Biological control should therefore not be interpreted simply as replacing one chemical pesticide with one microbial compound; the living organism may interact dynamically with the plant, pathogen, and surrounding microbiome.

Parasitism and predation provide additional mechanisms. Some beneficial fungi can interact directly with pathogenic fungi, recognize their structures, grow around or along them, and contribute to their suppression. This phenomenon is commonly discussed as mycoparasitism in the context of fungal antagonists such as certain *Trichoderma* strains. Enzymes capable of degrading components of fungal cell walls can participate in these interactions. Entomopathogenic microorganisms use different mechanisms to infect susceptible insect hosts and ultimately reduce pest populations. Because biological interactions are often relatively specific, correct identification of the target pest or pathogen is essential for successful biological control.

Biofungicides and Suppression of Plant Diseases

Plant-pathogenic fungi and fungus-like organisms cause economically important diseases of roots, stems, leaves, flowers, fruits, and seeds. Biofungicides are designed to

reduce disease by interfering with pathogen establishment, growth, reproduction, or infection. Some biofungicides contain living microorganisms that colonize plant surfaces or the rhizosphere and establish a protective microbial community. Others act partly through metabolites or enzymes produced by the biological-control organism. Effective colonization can prevent pathogens from occupying the same ecological niche and can reduce the availability of nutrients required for pathogen development.

Species and strains of *Trichoderma* are among the most extensively studied fungal biological-control agents. They can interact with plant roots, compete with other fungi, produce biologically active metabolites and enzymes, and in some plant systems contribute to activation of defense responses. Certain strains of *Bacillus* are also important because they can form resistant spores, which can provide advantages for formulation and storage, and they produce diverse compounds associated with antagonistic activity. However, biological properties are often strain-specific. Two strains belonging to the same microbial species may differ considerably in their ability to colonize plants or suppress a pathogen. Selection and characterization of effective strains are therefore fundamental steps in the development of reliable microbial products.

Induced Plant Resistance

Biological-control microorganisms may protect plants not only by directly attacking pathogens but also by influencing the plant's own defense systems. Plants possess complex innate immune mechanisms that allow them to recognize potential threats and activate protective responses. Interactions with particular beneficial microorganisms can prepare, or “prime,” plants to respond more effectively to subsequent pathogen attack. This phenomenon is often associated with induced systemic resistance (ISR) and related defense responses.

Activation or priming of plant defense can influence signaling pathways, production of antimicrobial compounds, reinforcement of cell walls, expression of defense-related genes, and antioxidant responses. Because the effect depends on interactions among the microorganism, plant genotype, pathogen, and environment, results obtained with one crop or microbial strain cannot automatically be generalized to another system. Nevertheless, stimulation of plant immunity represents an important mechanism through which microbial biocontrol agents can contribute to crop protection.

Biopesticides Against Insect Pests

Biological control of insect pests is another major area of biopesticide application. *Bacillus thuringiensis* (Bt) is one of the best-known microbial insect-control organisms. Different Bt strains produce insecticidal proteins with activity against particular groups of insects. Their relatively specific biological activity can provide an advantage compared with broad-spectrum insecticides when an appropriate Bt strain and target pest are matched. Bt-based products have been used in agricultural pest management for decades, and genes encoding particular Bt proteins have also been introduced into some genetically engineered crops.

Entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium* species represent another important group. These fungi can infect susceptible insects and are used or investigated against various agricultural pests. Their effectiveness is influenced strongly by environmental factors such as temperature and humidity. This illustrates an important difference between many biological and conventional chemical pesticides: because microbial agents are living biological systems, environmental conditions can strongly influence their survival, reproduction, persistence, and effectiveness.

Biological Control and the Plant Microbiome

Plants live in close association with complex microbial communities. The rhizosphere, the region of soil directly influenced by plant roots, contains diverse bacteria, fungi, and other microorganisms. Leaves and internal plant tissues also support characteristic microbial communities. Collectively, these organisms form important components of the plant microbiome. Beneficial microorganisms can influence nutrient acquisition, growth, stress tolerance, and protection against pathogens.

Modern biological crop protection increasingly considers how introduced microbial agents interact with native microbiomes. A microorganism that performs effectively in laboratory culture may fail to establish itself in field soil because it must compete with an existing microbial community. Conversely, some introduced organisms may cooperate with native beneficial microorganisms. Understanding microbial ecology is therefore becoming increasingly important for designing effective biological-control strategies. Metagenomics, sequencing, and other molecular technologies can help characterize microbial communities and identify organisms associated with disease suppression or plant health.

Advantages of Biopesticides and Biofungicides

Biological crop-protection products can offer several important advantages. Many microbial agents show relatively high specificity toward their target organisms, potentially reducing effects on beneficial organisms when products are correctly selected and applied. Some biological agents can establish temporary populations on plant surfaces or in the rhizosphere and interact dynamically with the crop. Certain products have relatively low environmental persistence compared with persistent synthetic compounds, which may reduce long-term residues in some contexts. Biological products can also provide additional modes of action that are valuable in resistance-management programs.

Another important advantage is compatibility with sustainable agriculture and IPM. Biological products can be combined with crop rotation, resistant cultivars, sanitation, monitoring, biological conservation, and carefully selected chemical treatments. This can reduce dependence on a single pest-control mechanism. Biopesticides may also be suitable for some organic production systems, although whether a specific product is permitted depends on the relevant certification and regulatory framework. Their contribution to sustainability is therefore greatest when they are used as part of a scientifically designed management program rather than treated as universal replacements for all conventional pesticides.

Disadvantages and Limitations

Despite their advantages, biopesticides and biofungicides have important limitations. Their effectiveness may be more variable under field conditions because living microorganisms are sensitive to temperature, moisture, ultraviolet radiation, soil characteristics, plant developmental stage, and interactions with native microorganisms. Some products may act more slowly than conventional pesticides and may perform best when applied preventively or at relatively early stages of pest or disease development. This means that monitoring and correct timing can be especially important.

Storage and formulation can also be challenging because microbial viability must be maintained until application. Shelf life, transport conditions, compatibility with other agricultural products, and application technology can influence effectiveness. Biological agents can have relatively narrow target ranges, which is beneficial for specificity but means that accurate diagnosis of the pest or disease is essential. Production quality is another critical issue: microbial identity, concentration, purity, stability, and biological activity must be standardized. Finally, the term “natural” should not be interpreted as automatically meaning

harmless. All biologically active crop-protection agents require appropriate evaluation of risks to humans, animals, beneficial organisms, and the environment.

Development and Formulation of Microbial Products

The development of an effective microbial biopesticide begins with identification of microorganisms that show useful biological activity against a target pest or pathogen. Candidate strains are characterized genetically, physiologically, and functionally. Researchers evaluate their ability to suppress the target organism, survive under relevant environmental conditions, interact with the host plant, and maintain their properties during production and storage. Promising candidates must then be formulated into a stable product.

Formulation is particularly important because microorganisms must remain viable and active during storage, transportation, and application. Products may be formulated as liquids, powders, granules, seed treatments, or other forms depending on the microorganism and intended agricultural use. Formulations can help protect microbial cells or spores from environmental stresses and facilitate application. Quality control ensures that commercial batches contain the correct biological agent at an appropriate concentration and are free from unacceptable contamination. These production requirements demonstrate that microbial biopesticides are sophisticated biotechnology products rather than simply naturally occurring microorganisms applied directly to crops.

Application in Crop Production

Biopesticides and biofungicides can be integrated into crop production at different stages. Some products are used as seed treatments, where beneficial microorganisms are associated with seeds before planting. This strategy can help establish beneficial populations near developing roots. Other products are applied to soil or growing substrates to influence rhizosphere interactions and suppress soil-borne pathogens. Foliar biological products can be used on leaves and other aerial plant surfaces, while some treatments are designed for fruits or harvested agricultural products.

Successful application requires understanding the biology of the target organism and the biological-control agent. Preventive establishment may be more effective than attempting to suppress a severe disease outbreak after it has developed. Environmental conditions must also be considered because they influence microbial survival and activity. Therefore, biological crop protection requires good diagnosis, monitoring, timing, and integration with other agronomic practices.

Integrated Pest Management

The most effective role of biopesticides is often within Integrated Pest Management. IPM is a decision-based approach that combines different pest-management strategies while considering economic, ecological, and biological factors. Crop monitoring is used to determine pest or disease pressure, and management measures are selected according to the specific situation. Preventive practices such as crop rotation, sanitation, resistant cultivars, appropriate irrigation, balanced fertilization, and maintenance of beneficial organisms can reduce the probability of severe pest outbreaks.

Biological agents can then provide additional protection, while chemical pesticides may be used when necessary and appropriate. Combining multiple strategies reduces reliance on a single mode of action and can contribute to resistance management. However, compatibility must be considered because some chemical treatments may inhibit beneficial microorganisms. An effective IPM program therefore requires knowledge of interactions among biological products, conventional pesticides, crop management practices, pests, and environmental conditions.

Resistance Management

Pest and pathogen populations can evolve resistance when they are repeatedly exposed to the same control mechanism. This is a major challenge for conventional pesticides and can also occur in response to biologically derived control factors. Sustainable pest management therefore requires diversity of control methods. Biological products can introduce additional mechanisms such as competition, parasitism, induced resistance, and specific toxins, making them useful components of resistance-management programs.

The objective is not simply to alternate products randomly but to understand their modes of action and integrate them strategically. Crop rotation, genetic resistance, biological control, monitoring, and appropriate pesticide use can together reduce selection pressure. Maintaining agricultural and ecological diversity can also contribute to more resilient crop-protection systems.

Biotechnology and Improvement of Biological Control Agents

Modern biotechnology provides new tools for understanding and improving biological-control microorganisms. Genome sequencing can identify genes associated with antimicrobial compound production, host recognition, stress tolerance, colonization, and other useful characteristics. Transcriptomics can reveal how gene expression changes during interactions among microorganisms, plants, and pathogens. Proteomics and metabolomics can identify proteins and metabolites involved in biological control.

Bioinformatics and artificial intelligence can help analyze large biological datasets and identify promising microbial strains or molecular mechanisms. Molecular technologies can also improve identification and quality control of commercial microbial products. Rather than relying only on visible characteristics, microorganisms can be characterized using DNA-based approaches, allowing more precise identification of strains and monitoring of their persistence in agricultural environments.

Environmental and Biosafety Considerations

Before a biological-control organism is widely applied, its potential effects on the environment should be evaluated. Important questions include its host range, interactions with non-target organisms, environmental persistence, ability to spread, and possible effects on native microbial communities. The fact that a microorganism occurs naturally does not automatically guarantee that large-scale application will be environmentally neutral. Risk assessment must therefore consider the specific strain, formulation, application pattern, crop, target organism, and receiving environment.

Quality assurance and regulatory oversight are also important. A commercial biological product should contain the microorganism or active biological component stated on the label and should meet appropriate standards for identity, purity, biological activity, and safety. Reliable regulation helps ensure that biological crop-protection products provide consistent agricultural benefits while minimizing unacceptable risks.

Future Perspectives

The future of biopesticides and biofungicides is closely connected with microbiome research, genomics, synthetic biology, precision agriculture, and improved formulation technologies. Instead of studying individual microorganisms in isolation, researchers increasingly investigate microbial consortia, in which several compatible beneficial microorganisms may perform complementary functions. Such systems could potentially combine pathogen suppression, nutrient mobilization, plant-growth promotion, and stress tolerance, although their interactions are more complex and require careful evaluation.

Precision agriculture can also improve biological crop protection by using environmental sensors, disease monitoring, imaging, and data analysis to identify where and

when treatments are most needed. Genomic and metabolomic approaches may accelerate discovery of new biological-control agents and active natural compounds. Better formulations could increase shelf life and protect microorganisms against environmental stress after application. These advances may make biological crop protection more predictable and effective across diverse agricultural environments.

Conclusion

Biopesticides and biofungicides are important tools for sustainable crop protection. They include microorganisms and biologically derived substances capable of suppressing insects, plant pathogens, and other harmful organisms through mechanisms such as competition, antibiosis, parasitism, biological infection of pests, and activation of plant defense responses. Important microbial groups include selected strains of *Bacillus*, *Trichoderma*, *Beauveria*, *Metarhizium*, and other beneficial microorganisms. Their major advantages can include target specificity, additional modes of action, compatibility with integrated pest management, and reduced dependence on conventional synthetic pesticides. Their limitations include variable performance under environmental conditions, potentially slower activity, formulation and storage challenges, and the need for accurate identification of the target organism. Biological crop protection is most effective when integrated with resistant crop varieties, appropriate agricultural practices, monitoring, crop rotation, sanitation, and responsible use of other pest-management technologies. Advances in microbiome science, genomics, bioinformatics, biotechnology, and precision agriculture are expected to improve the discovery, characterization, formulation, and application of biological-control agents. Consequently, biopesticides and biofungicides are likely to play an increasingly important role in developing productive agricultural systems that combine effective crop protection with environmental sustainability.