*Uttar Pradesh Journal of Zoology*

***Volume 45, Issue 16, Page 502-526, 2024; Article no.UPJOZ.3853***
***ISSN: 0256-971X (P)***

# Role of Microorganisms in Shaping Insect-plant Interactions

**Milind D. Joshi [a], Pooja Gupta [b], Gaurav [c], Asutosh Kumar Srivastava [d], Shikha Jaggi [e], Wajid Hasan [f*] and Sheetanshu Gupta [g]**

*[a] Plant Protection, Agricultural Development Trust's Krishi Vigyan Kendra, Baramati, Tal. Baramati, Dist. Pune – 413 115, Maharashtra, India.*
*[b] Department of Molecular Microbiology and Immunology, CSIR-Central Drug Research Institute, India.*
*[c] Department of Agronomy, Faculty of Agriculture Science, Udai Pratap College, Varanasi, India.*
*[d] Department of Zoology, Kashi Naresh Government Post Graduate College, Gyanpur, Bhadohi (UP), India.*
*[e] Department of Zoology, Gandhi Memorial National College, Ambala Cantt., Haryana, India.*
*[f] Entomology, KVK Jehanabad, Bihar Agricultural University Sabour, Bihar, India.*
*[g] Department of Biochemistry, G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India.*

***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

***Article Information***

DOI: https://doi.org/10.56557/upjoz/2024/v45i164332

**Open Peer Review History:**
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://prh.mbimph.com/review-history/3853

***Review Article***

***Received: 29/05/2024***
***Accepted: 02/08/2024***
***Published: 06/08/2024***

---

**Corresponding author: Email: entowajid@gmail.com;*

***Cite as:*** *Joshi, Milind D., Pooja Gupta, Gaurav, Asutosh Kumar Srivastava, Shikha Jaggi, Wajid Hasan, and Sheetanshu Gupta. 2024. "Role of Microorganisms in Shaping Insect-Plant Interactions". UTTAR PRADESH JOURNAL OF ZOOLOGY 45 (16):502-26. https://doi.org/10.56557/upjoz/2024/v45i164332.*

## ABSTRACT

Plants and insects have a strong interaction in the natural world, and it turns out that the little organisms known as microbes have a significant influence on how they interact. Extremely tiny living creatures called microorganisms are crucial to these interactions. Some of them work in tandem with plants to produce compounds that function as natural insect repellents. These microbes receive food from the plants in return, which allows them to survive. Furthermore, certain microbes that reside inside insects alter their behaviour and even what they eat. They may increase the likelihood that bugs will consume a certain plant or possibly lessen their resistance to the plant's defenses. Furthermore, microbes have the power to alter their environment, including the soil, by converting detritus into plant food, which influences the plants' resistance to disease and other external stresses. All of this is being studied by scientists to develop safer alternatives to conventional pesticides for protecting plants and insects. Gaining knowledge about how these microscopic organisms affect the relationships between insects and plants may help us maintain a balanced environment and healthy plants. This manuscript investigates how microorganisms influence the interactions between plants and insects. It explores how microbes aid plants in producing natural insect repellents and how they affect insect behavior and diet. The study also looks into how microorganisms impact soil health and plant resistance. Understanding these roles can lead to sustainable alternatives to conventional pesticides.

*Keywords: Microorganisms; bacteria; fungi; viruses; plant tissues.*

## 1. INTRODUCTION

Microorganisms, including bacteria, fungi, viruses, and protozoa, play crucial roles in the interactions between plants and insects. These microorganisms can influence plant health, pest resistance, and ecological dynamics, making their study essential for understanding and managing agricultural and natural ecosystems.

Microorganisms, encompassing a vast array of bacteria, fungi, viruses, and protozoa, are fundamental to the intricate web of interactions between plants and insects. These microscopic entities do not merely exist passively within ecosystems; rather, they actively participate in shaping the health and resilience of plants, the behavior and survival of insects, and the overall dynamics of ecological communities.

The role of microorganisms in plant health is multifaceted. Beneficial bacteria and fungi, for instance, can enhance nutrient uptake, improve soil structure, and produce bioactive compounds that boost plant immunity. Such microorganisms can be found in various parts of the plant, including the roots (rhizosphere), leaves (phyllosphere), and even within plant tissues (endophytes). By fostering robust plant health, these microorganisms indirectly influence insect-plant interactions by making plants more resilient to pest attacks and environmental stressors. On the other hand, microorganisms associated with insects, particularly those residing in the insect gut, play crucial roles in the digestion of plant material, detoxification of plant defenses, and modulation of insect behavior. Gut microbiota can enhance the nutritional quality of plant-derived diets, enabling insects to exploit a wider range of host plants. Additionally, some microbes can influence insect physiology and immune responses, affecting their fitness and survival.

The study of these microbial interactions is essential for several reasons. Understanding how microorganisms contribute to plant pest resistance can inform the development of sustainable agricultural practices, such as the use of microbial inoculants as biocontrol agents. Moreover, insights into the microbial modulation of insect behavior can lead to novel pest management strategies that exploit microbial symbionts to disrupt pest populations. Microorganisms play a pivotal role in the broader ecological dynamics of natural ecosystems. They contribute to nutrient cycling, organic matter decomposition, and the maintenance of soil health, all of which are critical for the sustainability of plant and insect communities. By mediating interactions between plants and insects, microorganisms help to maintain the balance and functionality of ecosystems, underscoring their importance in both natural and managed environments.

## 2. DEFINITION AND SCOPE OF MICROORGANISMS

Microorganisms are microscopic organisms that exist in virtually every environment on Earth, including soil, water, air, and within other organisms. In the context of insect-plant interactions, microorganisms can be categorized into various functional groups:

1. **Endophytes:** These are microorganisms, primarily bacteria and fungi, that live within plant tissues without causing harm. They can enhance plant growth, improve stress tolerance, and confer resistance to pests and diseases [1].
2. **Rhizosphere Microbes:** These microorganisms reside in the soil surrounding plant roots. They play significant roles in nutrient cycling, soil structure, and plant health. Rhizosphere microbes can also influence plant resistance to insect herbivory by modulating plant defense mechanisms [2].
3. **Phyllosphere Microbes:** These microorganisms inhabit the aerial parts of plants, such as leaves and stems. They can affect plant physiology and resistance to insect pests through direct and indirect interactions [3].
4. **Gut Microbiota:** Insects harbor diverse microbial communities within their digestive systems. These gut microbes can aid in digestion, detoxification, and nutrient absorption. They can also influence insect behavior and fitness, which in turn affects plant-insect interactions [4].

Microorganisms are microscopic organisms that exist in virtually every environment on Earth, including soil, water, air, and within other organisms. In the context of insect-plant interactions, microorganisms can be categorized into various functional groups, each playing a unique role in these interactions:

1. **Endophytes**: These are microorganisms, primarily bacteria and fungi, that live within plant tissues without causing harm. They can enhance plant growth, improve stress tolerance, and confer resistance to pests and diseases [1]. Recent studies have shown that endophytes can produce bioactive compounds that deter insect herbivores and boost plant immune responses [5,6]. These beneficial interactions are crucial for developing sustainable agricultural practices and understanding plant resilience.
2. **Rhizosphere Microbes**: These microorganisms reside in the soil surrounding plant roots. They play significant roles in nutrient cycling, soil structure, and plant health. Rhizosphere microbes can also influence plant resistance to insect herbivory by modulating plant defense mechanisms [2]. Recent research has highlighted the role of mycorrhizal fungi in enhancing plant resistance to soil-borne pathogens and insects by altering root exudates and inducing systemic resistance [7], Huang, Xiao, & Zhu, 2020). These interactions are pivotal for improving crop productivity and soil health.
3. **Phyllosphere Microbes**: These microorganisms inhabit the aerial parts of plants, such as leaves and stems. They can affect plant physiology and resistance to insect pests through direct and indirect interactions [3]. New findings suggest that phyllosphere microbes can produce volatile organic compounds (VOCs) that repel insect pests and attract beneficial predators or parasitoids [8,9]. Understanding these interactions can lead to innovative strategies for pest management in agriculture.
4. **Gut Microbiota**: Insects harbor diverse microbial communities within their digestive systems. These gut microbes can aid in digestion, detoxification, and nutrient absorption. They can also influence insect behavior and fitness, which in turn affects plant-insect interactions [4]. Recent studies have revealed that gut microbiota can mediate the detoxification of plant secondary metabolites, allowing insects to exploit a wider range of host plants [10,11]. These insights are essential for developing biocontrol methods and understanding insect adaptation to plant defenses.

Microorganisms play a pivotal critical role in ecosystem functioning, particularly in the context of insect-plant interactions (Fig. 1). The vast diversity of microorganisms, including bacteria, fungi, viruses, and protozoa, ensures their presence in every conceivable environment on Earth, from the depths of the soil to the aerial surfaces of plants. These microorganisms are not merely passive inhabitants but active participants in ecological processes, influencing and affecting the health, growth, and resilience of plants and the behavior, fitness, and survival of insects.

Insect-plant interactions are complex and multifaceted, involving a delicate balance of mutualistic, antagonistic, and commensal relationships. Microorganisms add another layer of complexity to these interactions, mediating and modulating the responses of both plants and insects. For example, endophytes, which are microorganisms that reside within plant tissues without causing harm, can enhance plant growth, improve stress tolerance, and confer resistance to pests and diseases. These benefits are not just incidental but are often the result of intricate biochemical and genetic interactions between the microorganisms and their plant hosts.

Rhizosphere microbes, which inhabit the soil surrounding plant roots, play a crucial role in nutrient cycling and soil structure. These microbes can significantly influence plant health and resistance to insect herbivory by modulating plant defense mechanisms. For instance, certain rhizobacteria can induce systemic resistance in plants, making them less susceptible to insect attacks. This interaction is a classic example of how microorganisms can shape the outcome of insect-plant interactions in favor of the plant (Fig. 2).

Phyllosphere microbes, which live on the aerial parts of plants, such as leaves and stems, can also impact plant physiology and resistance to insect pests. These microorganisms can produce volatile organic compounds (VOCs) that repel insect herbivores or attract natural enemies of the pests. Thus, the presence of beneficial phyllosphere microbes can enhance a plant's ability to withstand insect attacks.

Insect gut microbiota, the diverse microbial communities within the digestive systems of insects, can aid in digestion, detoxification, and nutrient absorption. These gut microbes can also influence insect behavior and fitness, thereby affecting plant-insect interactions. For example, certain gut bacteria can degrade plant secondary metabolites that are toxic to insects, allowing the insects to feed on otherwise resistant plants. Conversely, disruptions in the gut microbiota can reduce the fitness of insect pests, making them more susceptible to plant defenses and biocontrol measures.

## 3. HISTORICAL PERSPECTIVES ON MICROBIAL ROLES

The recognition of the importance of microorganisms in insect-plant interactions has evolved. Early studies primarily focused on the detrimental effects of plant pathogens and insect pests. However, advances in microbiology and molecular biology have revealed the beneficial roles of microorganisms in these interactions.

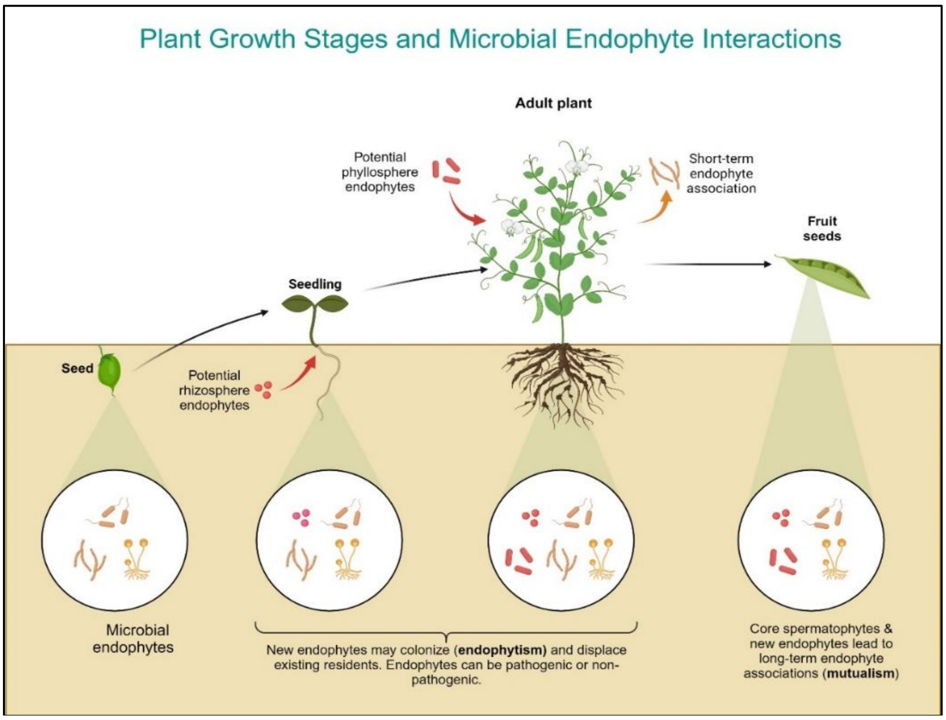


**Fig. 1. Image showing the growth of the leguminous pea plant and interaction with the microbial endophytes (created in Biorender.com)**

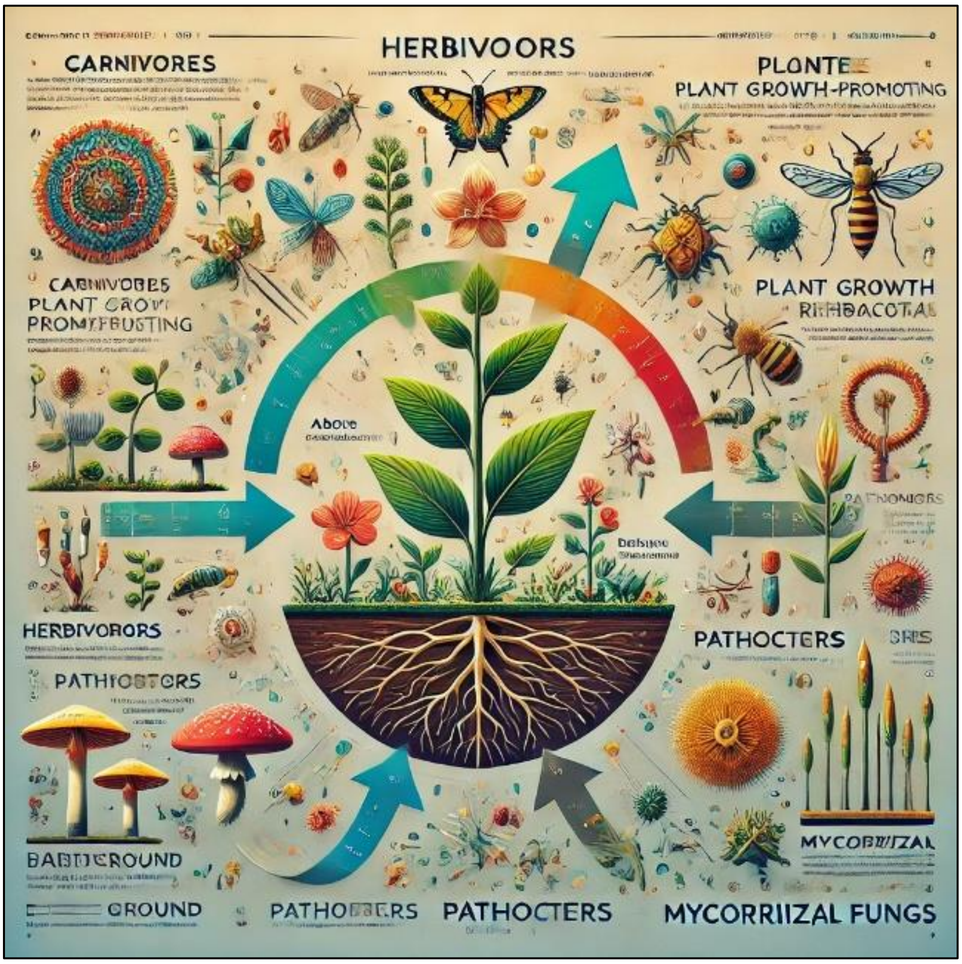


**Fig. 2. Interactions between plants and various organisms**

### 3.1 Early Discoveries

In the early 20th century, researchers began to uncover the symbiotic relationships between plants and microorganisms. For instance, the discovery of nitrogen-fixing bacteria in legume root nodules highlighted the mutualistic interactions that benefit plant growth and soil fertility [12]. Similarly, the identification of mycorrhizal fungi and their role in enhancing nutrient uptake emphasized the importance of microbial symbiosis in plant health [13].

The early recognition of the roles of microorganisms in insect-plant interactions was driven by observations of the beneficial effects of certain microbes on plant health and productivity. Nitrogen-fixing bacteria, such as those in the genus Rhizobium, were among the first to be studied in this context. These bacteria form symbiotic relationships with leguminous plants, fixing atmospheric nitrogen into a form that plants can utilize for growth. This discovery not only highlighted the importance of microorganisms in nutrient cycling but also demonstrated the potential for harnessing microbial processes to enhance agricultural productivity.

Mycorrhizal fungi, which form symbiotic associations with plant roots, were also recognized for their role in improving nutrient uptake. These fungi extend the root system of plants through their hyphal networks, increasing the surface area for nutrient absorption. This mutualistic relationship enhances plant growth and resilience, particularly in nutrient-poor soils. The identification of mycorrhizal fungi underscored the critical role of microorganisms in supporting plant health and ecosystem functioning.

### 3.2 Mid-20th Century to Present

The mid-20th century saw a shift in focus towards understanding the ecological and evolutionary dynamics of in microbial interactions with plants and insects. Studies on endophytic fungi and their ability to produce secondary metabolites that deter herbivores marked significant progress in recognizing the protective roles of microorganisms [14]. The development of molecular techniques in the late 20th and early 21st centuries further broadened our understanding expanded our knowledge, allowing researchers to explore the diversity and functions of microbial communities associated with plants and insects [15].

During the mid-20th century, the scope of research on microorganisms in insect-plant interactions expanded significantly. The discovery of endophytic fungi and their protective roles against herbivores was a key milestone. These fungi reside within plant tissues and produce secondary metabolites that can deter or inhibit herbivorous insects. For example, alkaloids produced by endophytic fungi in grasses have been shown to reduce herbivory by insect pests, providing a natural form of pest resistance.

The advent of molecular techniques revolutionized the study of microbial interactions, allowing researchers to identify and characterize the diverse microbial communities associated with plants and insects. Techniques such as DNA sequencing and metagenomics have enabled the exploration of microbial diversity at an unprecedented scale. This has led to the discovery of numerous beneficial microorganisms and their roles in enhancing plant health, pest resistance, and ecosystem resilience.

### 3.3 Recent Advances

Recent research has delved into the complex tripartite interactions among plants, insects, and microorganisms. For example, studies have shown how rhizosphere microbes can induce systemic resistance in plants, making them less susceptible to insect herbivores [16]. Additionally, the role of gut microbiota in shaping insect herbivory and plant responses has gained significant attention, highlighting the intricate connections between microbial communities and ecosystem dynamics [17].

Recent advances in research have shed light on the intricate and multifaceted interactions among plants, insects, and microorganisms. One area of focus has been the role of rhizosphere microbes in inducing systemic resistance in plants. Certain rhizobacteria can trigger defense mechanisms in plants, making them less attractive or more resistant to insect herbivores. This phenomenon, known as induced systemic resistance (ISR), involves complex signaling pathways and the production of defensive compounds that deter insect feeding.

The gut microbiota of insects has also emerged as a critical factor in shaping insect-plant interactions. The microbial communities within insect guts can influence the insects' ability to digest plant material, detoxify plant secondary metabolites, and resist pathogens. For example, certain gut bacteria can degrade toxic compounds produced by plants, allowing insects to feed on otherwise resistant plants. Conversely, disruptions in the gut microbiota, such as those caused by environmental changes or antibiotics, can reduce the fitness of insect pests and make them more susceptible to plant defenses and biocontrol measures.

The exploration of these tripartite interactions has provided valuable insights into the co-evolution of plants, insects, and microorganisms. It has also highlighted the potential for manipulating microbial communities to enhance pest resistance, improve crop productivity, and promote sustainable agricultural practices.

## 4. IMPORTANCE OF STUDYING MICROORGANISMS IN ECOSYSTEMS

### 4.1 Enhancing Crop Protection

Microorganisms offer potential solutions for sustainable pest management. By harnessing beneficial microbes, such as endophytes and rhizosphere bacteria, we can develop biological control strategies that reduce the reliance on chemical pesticides. For instance, certain endophytic fungi can produce alkaloids that deter herbivores, providing natural pest resistance [18].

The study of microorganisms in insect-plant interactions holds great promise for enhancing crop protection. Beneficial microorganisms, such as endophytes and rhizobacteria, can be harnessed to develop biological control strategies that reduce the need for chemical pesticides. For example, endophytic fungi that produce alkaloids can deter herbivorous insects, providing a natural form of pest resistance. This approach not only reduces the environmental impact of pesticide use but also promotes the sustainability of agricultural systems.

The mechanisms through which microorganisms confer pest resistance, researchers can develop microbial inoculants and biopesticides that can be applied to crops. These microbial products can enhance plant defenses, improve stress tolerance, and increase yield, offering a sustainable and eco-friendly alternative to chemical pesticides.

### 4.2 Promoting Plant Health

Microorganisms play a vital role in maintaining plant health and resilience. Rhizosphere microbes, for example, can enhance nutrient uptake, improve soil structure, and protect plants from pathogens. By fostering healthy microbial communities, we can promote plant growth and productivity, leading to more sustainable agricultural practices [19].

The promotion of plant health is another critical aspect of studying microorganisms in insect-plant interactions. Rhizosphere microbes, including beneficial bacteria and fungi, play a vital role in maintaining plant health and resilience. These microorganisms enhance nutrient uptake by solubilizing essential nutrients such as phosphorus and nitrogen, making them more available to plants. They also improve soil structure by producing extracellular polysaccharides that bind soil particles together, enhancing water retention and aeration.

Moreover, rhizosphere microbes can protect plants from pathogens through various mechanisms. Some produce antimicrobial compounds that inhibit the growth of harmful pathogens, while others compete with pathogens for resources and niches. Additionally, certain rhizobacteria can induce systemic resistance in plants, activating defense pathways that enhance the plants' ability to fend off pathogens and insect herbivores.

### 4.3 Ecosystem Dynamics

Microorganisms are integral components of ecosystems, influencing nutrient cycling, soil fertility, and plant community composition. Studying their interactions with plants and insects provides insights into ecosystem functioning and stability. For example, the presence of mycorrhizal fungi can affect plant competition and succession, shaping the structure and diversity of plant communities [20].

The study of microorganisms in insect-plant interactions is essential for understanding ecosystem dynamics and stability. Microorganisms play critical roles in nutrient cycling, soil fertility, and plant community composition. For example, mycorrhizal fungi form symbiotic associations with plant roots, facilitating nutrient uptake and enhancing plant growth. These fungi can also influence plant competition and succession, shaping the structure and diversity of plant communities.

By studying the interactions between microorganisms, plants, and insects, researchers can gain insights into the factors that drive ecosystem stability and resilience. This knowledge can inform the development of sustainable land management practices that promote biodiversity, enhance soil health, and support ecosystem services such as pollination and pest regulation.

### 4.4 Mitigating Climate Change

Microorganisms contribute to carbon and nitrogen cycling, impacting greenhouse gas emissions and climate change. Understanding their roles in these processes can inform strategies for mitigating climate change through soil management and sustainable agriculture. For instance, promoting soil microbial diversity can enhance carbon sequestration and reduce methane emissions [21].

Microorganisms play a crucial role in mitigating climate change by influencing carbon and nitrogen cycling. Soil microorganisms, including bacteria, fungi, and archaea, are key players in the decomposition of organic matter and the release and sequestration of greenhouse gases. For example, certain soil microbes can convert organic carbon into stable forms that are sequestered in the soil, reducing atmospheric carbon dioxide levels.

Promoting soil microbial diversity through sustainable agricultural practices, such as cover cropping, reduced tillage, and organic amendments, can enhance carbon sequestration and reduce greenhouse gas emissions. Additionally, certain soil microbes can reduce methane emissions by oxidizing methane in the soil. Understanding the roles of microorganisms in these processes can inform strategies for mitigating climate change and promoting sustainable land management.

### 4.5 Advancing Scientific Knowledge

The study of microorganisms in insect-plant interactions expands our understanding of biological diversity and evolutionary processes. It reveals the intricate web of relationships that sustain life on Earth and underscores the importance of microbial ecology in shaping ecosystems. By exploring these interactions, we gain valuable insights into the co-evolution of plants, insects, and microorganisms [22].

The study of microorganisms in insect-plant interactions is essential for advancing scientific knowledge in fields such as ecology, microbiology, and evolutionary biology. Microorganisms play a critical role in shaping the diversity and function of ecosystems. By exploring the interactions between microorganisms, plants, and insects, researchers can gain insights into the co-evolution of these organisms and the factors that drive ecological and evolutionary processes.

Microbial ecology, which examines the distribution, abundance, and interactions of microorganisms in different environments, provides a foundation for understanding the roles of microorganisms in ecosystems. This knowledge can inform the development of sustainable agricultural practices, conservation strategies, and biotechnological applications. By studying microorganisms in insect-plant interactions, researchers can uncover new insights into the complex web of relationships that sustain life on Earth and contribute to the advancement of scientific knowledge.

## 5. TYPES OF MICROORGANISMS INVOLVED IN INSECT-PLANT INTERACTIONS (TABLE 1)

### 5.1 Beneficial Microorganisms

Beneficial microorganisms play a crucial role in enhancing plant health, growth, and resilience. These microorganisms often form mutualistic relationships with their host plants, providing essential nutrients, enhancing stress tolerance, and protecting against pests and diseases. The main types of beneficial microorganisms involved in insect-plant interactions include symbiotic bacteria, endophytic fungi, and mycorrhizal fungi.

### 5.2 Symbiotic Bacteria

Symbiotic bacteria engage in mutualistic relationships with plants, offering numerous benefits such as nutrient acquisition, growth promotion, and protection against pests and diseases. These bacteria can be found in various parts of the plant, including roots, leaves, and stems.

### 5.3 Nitrogen-Fixing Bacteria

Nitrogen-fixing bacteria, such as those in the genera *Rhizobium* and *Frankia*, form symbiotic relationships with legumes and actinorhizal plants. These bacteria convert atmospheric nitrogen into ammonia, which plants can readily use for growth (Fig 3). This process not only enhances plant nutrition but also reduces the need for synthetic nitrogen fertilizers. For example, *Rhizobium* species form nodules on the roots of leguminous plants where they fix nitrogen, significantly improving soil fertility and plant growth [23].

The symbiotic relationship between nitrogen-fixing bacteria and plants is highly specialized. Bacteria infect the plant roots, leading to the formation of nodules where nitrogen fixation occurs. This symbiosis benefits both partners: the plant provides carbohydrates to the bacteria, while the bacteria supply the plant with fixed nitrogen. This mutualistic interaction is crucial for sustainable agriculture, as it reduces the dependency on chemical fertilizers, which can have adverse environmental impacts.

### 5.4 Plant Growth-Promoting Rhizobacteria (PGPR)

PGPR, including species of *Pseudomonas*, *Bacillus*, and *Azospirillum*, colonize the rhizosphere and promote plant growth by producing phytohormones, solubilizing phosphorus, and suppressing plant pathogens. These bacteria can also induce systemic resistance in plants, making them less susceptible to insect herbivores. For instance, *Pseudomonas fluorescens* produces antibiotics that suppress soil-borne pathogens and promote root growth, enhancing overall plant health and resistance to pests [24].

PGPR are known for their ability to produce plant hormones such as auxins, gibberellins, and cytokinins, which promote root and shoot development. They also produce siderophores that sequester iron, making it less available to pathogenic microorganisms. Furthermore, PGPR can trigger induced systemic resistance (ISR) in plants, which primes the plant's immune system to respond more robustly to subsequent pathogen attacks and insect herbivory.

### 5.5 Endophytic Fungi

Endophytic fungi live within plant tissues without causing apparent harm. These fungi can enhance plant growth, improve stress tolerance, and protect plants from herbivores and pathogens through various mechanisms.

### 5.6 Production of Secondary Metabolites

Many endophytic fungi produce secondary metabolites, such as alkaloids, terpenoids, and phenolics, which deter herbivorous insects. For example, *Neotyphodium* species in grasses produce alkaloids that reduce insect herbivory and increase plant fitness. These metabolites can interfere with the feeding behavior and development of insect pests, providing a natural defense mechanism for the host plant [18].

Endophytic fungi are known for their ability to produce a diverse array of bioactive compounds. These secondary metabolites can act as deterrents or toxins to herbivorous insects, reducing the damage caused by these pests. Additionally, some endophytes enhance the production of plant defense chemicals, further boosting the plant's ability to resist insect attacks. The mutualistic relationship between endophytic fungi and their host plants is a key factor in the natural defense strategies of many plant species.

### 5.7 Enhanced Stress Tolerance

Endophytic fungi can enhance plant tolerance to abiotic stresses, such as drought and salinity, by modulating plant physiology and hormone levels. This increased resilience can indirectly reduce plant vulnerability to insect attacks. For instance, the endophyte *Piriformospora indica* has been shown to improve drought tolerance in barley by enhancing root growth and water uptake [25].

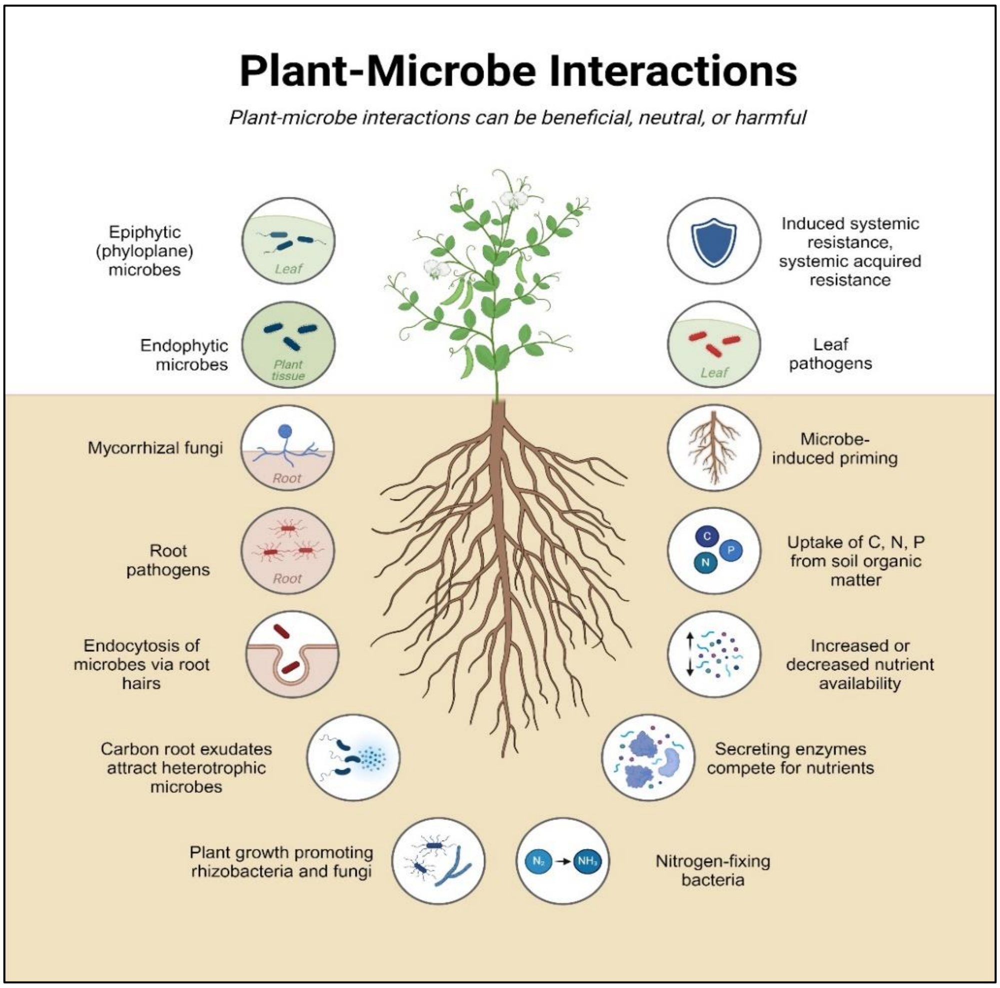


**Fig. 3. Plant microbe interactions (created in Biorender.com)**

**Table 1. Types of microorganisms involved in insect-plant interactions**

| S.No | Type of Microorganism | Subtype | Description | Examples |
|---|---|---|---|---|
| **1** | Beneficial Microorganisms | Symbiotic Bacteria | Engage in mutualistic relationships with plants, providing nutrients, promoting growth, and protecting against pests and diseases. | *Rhizobium* (nitrogen-fixing bacteria forming nodules on leguminous plants), *Pseudomonas fluorescens* (induces systemic resistance and produces antibiotics), *Azospirillum* (promotes root growth and nutrient uptake) |
| | | Endophytic Fungi | Live within plant tissues without causing harm, enhancing growth, stress tolerance, and protection against herbivores and pathogens. | *Neotyphodium* (produces alkaloids deterring herbivores), *Piriformospora indica* (improves drought tolerance in barley), *Trichoderma* spp. (enhances plant resistance and growth) |
| | | Mycorrhizal Fungi | Form symbiotic associations with plant roots, enhancing nutrient uptake and providing ecological benefits. | *Glomus* (arbuscular mycorrhizal fungi enhancing phosphorus uptake), *Rhizophagus* (arbuscular mycorrhizal fungi improving plant health), *Laccaria bicolor* (ectomycorrhizal fungi associated with trees) |
| | | Nematode-Endosymbionts | Symbiotic bacteria that live within nematodes and assist in parasitizing insect pests. | *Photorhabdus luminescens* (endosymbiont of entomopathogenic nematodes), *Xenorhabdus nematophila* (used in biological control) |
| | | Plant Growth-Promoting Fungi (PGPF) | Enhance plant growth and resilience through various mechanisms, including nutrient solubilization and phytohormone production. | *Piriformospora indica* (improves drought tolerance and nutrient uptake), *Penicillium* spp. (enhances plant growth) |
| **2** | Pathogenic Microorganisms | Bacterial Pathogens | Cause diseases in plants, weakening them and making them more susceptible to insect herbivory. | *Xanthomonas campestris* pv. *vesicatoria* (causes bacterial spot in tomatoes), *Pseudomonas syringae* pv. *tomato* (causes bacterial speck in tomatoes), *Erwinia amylovora* (causes fire blight in apples and pears) |
| | | Fungal Pathogens | Responsible for many plant diseases, significantly impacting plant health and yield. | *Botrytis cinerea* (gray mold affecting a wide range of plants), *Fusarium oxysporum* f. sp. *lycopersici* (causes wilt in tomatoes), *Verticillium dahliae* (causes verticillium wilt in various crops) |

| S.No | Type of Microorganism | Subtype | Description | Examples |
|---|---|---|---|---|
| | | Viral Pathogens | Infect plants and are transmitted by insect vectors, leading to complex plant-virus-insect interactions. | Tomato Yellow Leaf Curl Virus (TYLCV) (transmitted by whiteflies), Potato Virus Y (PVY) (transmitted by aphids, affects potatoes and other solanaceous crops), *Cucumber mosaic virus* (CMV) (transmitted by aphids, affects cucumbers and other crops) |
| | | Nematode Pathogens | Parasitize plant roots, causing damage and facilitating secondary infections by other pathogens and pests. | *Meloidogyne incognita* (root-knot nematode affecting a wide range of crops), *Heterodera glycines* (soybean cyst nematode) |
| **3** | Neutral and Opportunistic Microorganisms | Commensal Bacteria | Live on plant surfaces or within plant tissues without causing harm, can become opportunistic pathogens under stress conditions. | *Pseudomonas fluorescens* (typically beneficial but can cause root rot under stress), *Bacillus cereus* (harmless under normal conditions but can cause disease in stressed plants) |
| | | Latent Pathogens | Exist within plant tissues without causing symptoms until the plant is stressed, then become active and cause disease. | *Colletotrichum* spp. (can remain dormant in plant tissues, causing anthracnose disease under favorable conditions), *Phytophthora infestans* (causes late blight in potatoes and tomatoes under favorable conditions) |
| | | Epiphytes | Microorganisms that live on the surface of plants, often without causing harm, but can sometimes facilitate infections by pathogens. | *Erwinia herbicola* (can act as a precursor to fire blight in apple and pear orchards), *Pseudomonas syringae* (can survive epiphytically and then infect plants under certain conditions) |

By colonizing plant tissues, endophytic fungi can influence the expression of stress-related genes and the production of stress hormones such as abscisic acid. This can lead to improved water use efficiency, better nutrient uptake, and enhanced overall plant health. In stressful environments, plants with endophytic fungi are more likely to survive and thrive, which can also reduce the attractiveness of these plants to insect pests that prefer weakened hosts.

## 5.8 Mycorrhizal Fungi

Mycorrhizal fungi form symbiotic associations with plant roots, improving nutrient uptake and providing various ecological benefits.

## 5.9 Arbuscular Mycorrhizal Fungi (AMF)

AMF, such as species of *Glomus* and *Rhizophagus*, enhance the uptake of phosphorus and other nutrients from the soil. This improved nutrition boosts plant growth and vigor, thereby making plants more resistant to insect herbivores. AMF also induces changes in plant root architecture, increasing the surface area for nutrient absorption and improving overall plant health [26].

The symbiotic relationship between AMF and plants is one of the most ancient and widespread mutualisms in the plant kingdom. AMF hyphae extend far into the soil, accessing nutrient pools that plant roots alone cannot reach. This symbiosis enhances the plant's nutrient status, particularly phosphorus, which is often limiting in soils. In return, the fungi receive carbohydrates produced by the plant through photosynthesis. This mutualistic relationship is fundamental to plant health and productivity, especially in nutrient-poor environments.

### 5.10 Ectomycorrhizal Fungi

Ectomycorrhizal fungi, primarily associated with trees and shrubs, form a sheath around plant roots and extend into the soil. These fungi improve water and nutrient absorption and can enhance plant resistance to pathogens and herbivores. For example, ectomycorrhizal associations with pine trees have been shown to reduce the incidence of root-feeding insect pests, improving tree health and growth [27].

Ectomycorrhizal fungi form extensive networks in the soil, known as the mycelial network, which connects multiple plants and facilitates nutrient and water transfer between them. This network can improve plant resilience to environmental stresses and reduce susceptibility to pests. The presence of ectomycorrhizal fungi can also enhance the plant's ability to compete with other plants, thus influencing plant community dynamics and ecosystem functioning.

## 6. PATHOGENIC MICROORGANISMS

Pathogenic microorganisms cause diseases in plants, often weakening them and making them more susceptible to insect herbivory. These pathogens include bacteria, fungi, and viruses.

### 6.1 Bacterial Pathogens

Bacterial pathogens can infect various plant parts, leading to diseases that reduce plant health and productivity.

### 6.2 Xanthomonas spp.

Species of *Xanthomonas* cause bacterial leaf spot, canker, and blight in a wide range of crops. These infections can weaken plants, making them more vulnerable to insect pests. For example, *Xanthomonas campestris* pv. *vesicatoria* causes bacterial spots in tomatoes and peppers, leading to lesions on leaves and fruits that facilitate secondary infections by insect pests [28].

*Xanthomonas* spp. are notorious for their ability to cause severe plant diseases that can lead to significant yield losses. These bacteria infect plant tissues through natural openings or wounds and multiply rapidly, causing extensive damage. The lesions created by *Xanthomonas* infections can serve as entry points for other pathogens and insect pests, exacerbating the damage to the plant. Managing *Xanthomonas* infections requires integrated disease management strategies, including the use of resistant varieties, cultural practices, and chemical treatments.

### 6.3 Pseudomonas Syringae

*Pseudomonas syringae* is responsible for bacterial speck, blight, and cankers in numerous plant species. The damage caused by these infections can create entry points for insect herbivores and reduce plant vigor. For instance, *P. syringae* pv. *tomato* causes bacterial speck in tomatoes, which weakens the plants and increases their susceptibility to aphid infestations [29].

*P. syringae* is a highly adaptable pathogen that can capable of infecting a wide range broad spectrum of host plants. It produces a variety of virulence factors that allow it to evade plant defenses and establish infections. The infections caused by *P. syringae* can lead to chlorosis, necrosis, and reduced plant growth, making plants more attractive to insect herbivores. Effective management of *P. syringae* infections involves the use of resistant cultivars, proper irrigation practices, and the application of bactericides.

### 6.4 Fungal Pathogens

Fungal pathogens are responsible for many plant diseases, which can severely impact plant health and yield.

### 6.5 Botrytis Cinerea

*Botrytis cinerea*, commonly known as gray mold, affects a wide range of plants, causing necrotic lesions and rot. Infected plants often become more susceptible to insect feeding due to weakened tissues. For example, gray mold in grapevines can lead to increased feeding by grapevine moth larvae, exacerbating crop damage [30].

*B. cinerea* is a highly aggressive pathogen that thrives in cool, humid conditions. It produces a wide range of enzymes and toxins that break down plant cell walls, leading to extensive tissue necrosis. The damage caused by *B. cinerea* infections can make plants more susceptible to secondary infections and insect herbivory. Managing gray mold requires a combination of cultural practices, such as improving air circulation and removing infected plant debris, as well as the use of fungicides.

### 6.6 Fusarium spp.

Species of *Fusarium* cause wilt, root rot, and ear rot in various crops. These infections can lead to significant yield losses and create opportunities for secondary insect infestations. For instance, *Fusarium oxysporum* f. sp. *lycopersici* causes wilt in tomatoes, weakening the plants and making them more vulnerable to whitefly infestations [31].

*Fusarium* spp. are soil-borne pathogens that can persist in the soil for long periods, making them difficult to control. They infect plants through the roots and disrupt the vascular system, leading to wilting, chlorosis, and plant death. The weakened state of infected plants makes them more susceptible to insect pests, which can further reduce crop yields. Effective management of *Fusarium* infections involves crop rotation, resistant varieties, and the use of soil amendments and fungicides.

### 6.7 Viral Pathogens

Viral pathogens infect plants and can be transmitted by insect vectors, leading to complex interactions between plants, viruses, and insects.

### 6.8 Tomato Yellow Leaf Curl Virus (TYLCV)

TYLCV is transmitted by whiteflies and causes stunted growth and yellowing of leaves in tomato plants. Infected plants are less vigorous and more prone to insect attacks. The virus can alter plant physiology and defense responses, making them more attractive to herbivorous insects [32].

TYLCV is a highly damaging virus that can cause significant yield losses in tomato crops. The virus alters the plant's metabolic pathways and defense mechanisms, making infected plants more susceptible to secondary infections and insect herbivory. Managing TYLCV involves controlling the whitefly vector through the use of insecticides, reflective mulches, and resistant varieties.

### 6.9 Potato Virus Y (PVY)

PVY is transmitted by aphids and affects potatoes and other solanaceous crops. The virus causes mosaic patterns on leaves and reduces plant productivity, making plants more susceptible to insect damage. Infected plants can exhibit altered volatile emissions that attract aphid vectors, facilitating virus spread [33].

PVY is one of the most economically important viruses affecting potato crops worldwide. The virus can cause severe yield losses and reduce the quality of tubers. Managing PVY involves controlling the aphid vectors through the use of insecticides and cultural practices, such as removing infected plants and using virus-free seed tubers.

## 7. NEUTRAL AND OPPORTUNISTIC MICROORGANISMS

Neutral and opportunistic microorganisms may not directly impact plant health under normal conditions but can become pathogenic or beneficial under certain circumstances.

### 7.1 Commensal Bacteria

Commensal bacteria live on plant surfaces or within plant tissues without causing harm. These bacteria can become opportunistic pathogens if the plant's defenses are compromised.

### 7.2 Pseudomonas Fluorescens

While typically beneficial, *Pseudomonas fluorescens* can become pathogenic under stress conditions, such as drought or nutrient deficiency, leading to root rot and other issues. For example, in nutrient-poor soils, *P. fluorescens* can switch from a commensal to a pathogenic lifestyle, causing root diseases in various crops [34].

*P. fluorescens* is widely known for its role in promoting plant growth and suppressing soil-borne pathogens. However, under certain conditions, such as nutrient deficiency or environmental stress, *P. fluorescens* can become pathogenic and cause root rot and other diseases. This opportunistic behavior highlights the importance of maintaining optimal soil health and plant nutrition to prevent the transition of beneficial microbes to pathogenic states.

### 7.3 Latent Pathogens

Latent pathogens exist within plant tissues without causing disease symptoms until the plant is stressed or weakened.

### 7.4 Colletotrichum spp.

*Colletotrichum* species can remain dormant in plant tissues and become active under favorable conditions, causing anthracnose disease. This opportunistic behavior can lead to sudden outbreaks following environmental stress. For instance, *Colletotrichum* spp. can lie dormant in strawberry plants and become pathogenic under high humidity and temperature, causing significant crop losses [35].

*Colletotrichum* spp. are known for their ability to remain latent in plant tissues for extended periods. These fungi can survive as quiescent infections until environmental conditions become favorable for disease development. Factors such as high humidity, temperature, and plant stress can trigger the activation of latent pathogens, leading to sudden and severe disease outbreaks. Managing latent pathogens requires vigilant monitoring, proper environmental management, and the use of resistant varieties.

The diverse roles of microorganisms in insect-plant interactions is crucial for developing sustainable agricultural practices and managing plant health. By leveraging beneficial microorganisms and mitigating the impacts of pathogenic and opportunistic microbes, we can enhance crop resilience and productivity.

## 8. MECHANISMS OF MICROBIAL INFLUENCE ON INSECT-PLANT DYNAMICS

Microorganisms play intricate and multifaceted roles in shaping the interactions between plants and insects. They can modulate plant defenses, influence insect physiology, and facilitate complex tripartite interactions involving plant, microbe, and insect signaling pathways. These mechanisms is crucial for developing sustainable agricultural practices and enhancing crop resilience against pests.

### 8.1 Microbial Mediation of Plant Defenses

Microorganisms can mediate plant defenses through various mechanisms, including the induction of plant resistance and the suppression of plant defenses. These interactions can significantly impact the plant's ability to deter insect herbivores and withstand environmental stresses.

### 8.2 Induction of Plant Resistance

Microorganisms can induce systemic resistance in plants, enhancing their ability to defend against insect herbivores and pathogens. This induced resistance is often mediated through the production of signaling molecules and the activation of plant defense pathways.

### 8.3 Systemic Acquired Resistance (SAR)

Systemic acquired resistance (SAR) is a form of induced resistance that is activated in response to localized infection by a pathogen. SAR involves the accumulation of salicylic acid and the activation of defense-related genes throughout the plant. Beneficial microorganisms, such as plant growth-promoting rhizobacteria (PGPR) and endophytic fungi, can trigger SAR, enhancing the plant's resistance to insect herbivores [36].

For example, PGPR such as *Pseudomonas fluorescens* can induce SAR in plants, leading to increased resistance against a range of pests and diseases. The bacteria produce signaling molecules that trigger the plant's immune system, resulting in the production of pathogenesis-related proteins and other defensive compounds. This systemic response not only protects the plant from the initial pathogen but also enhances its resistance to subsequent insect attacks [37].

### 8.4 Induced Systemic Resistance (ISR)

Induced systemic resistance (ISR) is another form of plant defense that is triggered by beneficial microorganisms, particularly those in the rhizosphere. ISR involves the activation of jasmonic acid and ethylene signaling pathways, leading to the production of defensive compounds that deter insect herbivores.

For instance, the rhizobacterium *Bacillus subtilis* can induce ISR in plants, enhancing their resistance to insect pests. The bacterium colonizes the plant roots and produces signaling molecules that travel to the aerial parts of the plant, activating defense pathways. This results in the accumulation of secondary metabolites, such as phenolics and terpenoids, which are toxic or repellent to herbivorous insects [38].

## 9. SUPPRESSION OF PLANT DEFENSES

While many microorganisms enhance plant defenses, some can suppress these defenses to facilitate their own colonization or to benefit associated insect herbivores. This suppression can make plants more vulnerable to insect attacks and other stresses.

### 9.1 Pathogen-Mediated Suppression

Certain plant pathogens can suppress host defenses to establish infections and promote disease. These pathogens produce effector proteins that interfere with the plant's immune system, weakening its ability to resist insect herbivores.

For example, the bacterial pathogen *Pseudomonas syringae* produces effector proteins that inhibit the production of salicylic acid and suppress SAR. This suppression of plant defenses can make the plant more susceptible to insect herbivores that exploit the weakened state of the host. Infected plants often exhibit increased levels of nutrients and reduced levels of defensive compounds, making them more attractive to herbivores [39].

### 9.2 Symbiont-Mediated Suppression

Some insect symbionts can suppress plant defenses to benefit their insect hosts. These symbionts produce molecules that modulate plant signaling pathways, reducing the plant's defensive responses and facilitating insect feeding.

For instance, the symbiotic bacteria associated with aphids can suppress plant defenses by interfering with jasmonic acid signaling. This suppression reduces the production of defensive compounds, such as proteinase inhibitors and secondary metabolites, allowing aphids to feed more efficiently. The symbionts produce enzymes that degrade plant signaling molecules or inhibit their synthesis, effectively disarming the plant's defense system [40].

## 10. MICROBIAL INFLUENCE ON INSECT PHYSIOLOGY

Microorganisms associated with insects, particularly gut microbiota, can have profound effects on insect physiology, influencing digestion, detoxification, and overall fitness. These microbial interactions can enhance the insect's ability to exploit plant resources and resist plant defenses.

### 10.1 Gut Microbiota and Digestion

The gut microbiota of insects plays a critical role in the digestion of plant material. These microorganisms produce enzymes that break down complex polysaccharides, proteins, and other macromolecules, allowing insects to extract nutrients from their food.

### 10.2 Cellulose Degradation

Many herbivorous insects rely on their gut microbiota to degrade cellulose, a major component of plant cell walls. Cellulolytic bacteria and fungi in the insect gut produce cellulases that hydrolyze cellulose into glucose, which the insect can then absorb and utilize for energy.

For example, termites harbor a diverse community of cellulolytic microorganisms in their hindgut, including bacteria from the phyla Firmicutes and Bacteroidetes, and protists. These microorganisms produce a suite of cellulases and hemicellulases that break down plant cell walls, enabling termites to thrive on a diet of wood and other plant materials [41].

### 10.3 Nitrogen Fixation

Some insect gut microbiota can fix atmospheric nitrogen, providing an additional source of nitrogen to their hosts. This is particularly important for insects feeding on nitrogen-poor diets, such as wood or other plant materials with low protein content.

For instance, the gut microbiota of certain wood-feeding beetles includes nitrogen-fixing bacteria that convert atmospheric nitrogen into ammonia, which the insect can use for protein synthesis. This symbiotic relationship enhances the insect's nutritional status and supports its growth and development [42].

### 10.4 Detoxification of Plant Allelochemicals

Insects often encounter toxic secondary metabolites (allelochemicals) produced by plants as defenses against herbivory. The gut microbiota can aid in the detoxification of these compounds, enabling insects to feed on otherwise toxic plants.

### 10.5 Enzymatic Detoxification

Gut microorganisms produce enzymes that can degrade or modify plant allelochemicals, reducing their toxicity. These enzymes include esterases, oxidases, and reductases, which can neutralize a wide range of toxic compounds.

For example, the gut microbiota of the tobacco hornworm (*Manduca sexta*) includes bacteria that produce enzymes capable of detoxifying nicotine, a potent neurotoxin produced by tobacco plants. These bacteria convert nicotine into less toxic metabolites, allowing the hornworm to feed on tobacco leaves without suffering from nicotine poisoning [43].

### 10.6 Biotransformation

In addition to enzymatic detoxification, gut microorganisms can also biotransform plant allelochemicals into compounds that are less harmful or even beneficial to the insect. This process can involve the conjugation of toxins with sugars, amino acids, or other molecules, making them more water-soluble and easier to excrete.

For instance, the gut microbiota of the gypsy moth (*Lymantria dispar*) can biotransform tannins, which are toxic polyphenolic compounds found in many plants. The microorganisms convert tannins into less toxic forms, reducing their impact on the insect's digestive system and overall health [44].

## 11. TRIPARTITE INTERACTIONS

Tripartite interactions involve complex signaling and communication between plants, microorganisms, and insects. These interactions can influence plant health, insect behavior, and the overall dynamics of plant-insect ecosystems.

### 11.1 Plant-Microbe-Insect Signaling Pathways

Plants, microorganisms, and insects engage in sophisticated signaling interactions that can mediate their responses to each other. These signaling pathways involve the production and perception of various chemical signals.

### 11.2 Plant Signaling

Plants produce a range of signaling molecules, such as jasmonic acid, salicylic acid, and ethylene, in response to microbial colonization and insect herbivory. These signals activate plant defense pathways and modulate interactions with beneficial and pathogenic microorganisms.

For example, plants infected with beneficial rhizobacteria may produce volatile organic compounds (VOCs) that attract natural enemies of insect pests, enhancing biocontrol. Conversely, pathogen-infected plants may alter their VOC profiles to deter herbivores or attract parasitoids [45].

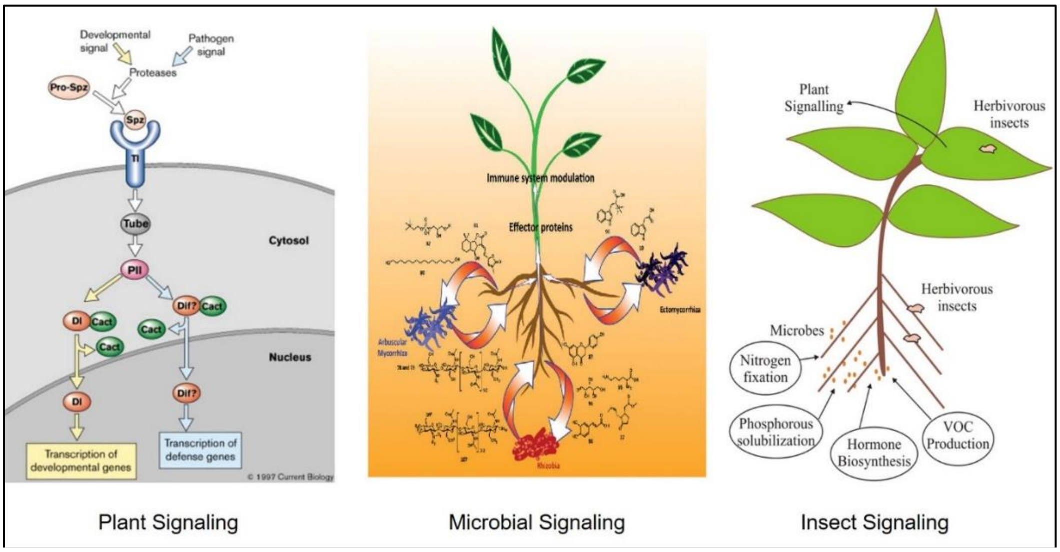


**Fig. 4. Image showing the comparison between plant, microbial and insect signalling**

### 11.3 Microbial Signaling

Microorganisms produce signaling molecules that can influence plant and insect physiology. These signals can modulate plant defenses, enhance microbial colonization, or affect insect behavior.

For instance, rhizosphere bacteria produce quorum-sensing molecules that regulate their population density and biofilm formation. These signals can also influence plant root development and immune responses, creating a favorable environment for microbial colonization and plant growth [46].

### 11.4 Insect Signaling

Insects produce and perceive a variety of chemical signals, including pheromones and kairomones, which mediate their interactions with plants and microorganisms. These signals can influence feeding behavior, mate attraction, and predator avoidance.

For example, herbivorous insects can detect plant VOCs released in response to microbial colonization or pathogen infection. These VOCs can serve as cues for insects to locate suitable host plants or avoid plants that are heavily defended or infected [47].

### 11.5 Microbial Volatile Organic Compounds (VOCs)

Microorganisms produce VOCs that can affect plant-insect interactions by influencing plant physiology, signaling pathways, and insect behavior (Fig. 5).

### 11.6 Plant Growth Promotion

Certain microbial VOCs can promote plant growth and enhance resistance to pests and diseases. These VOCs can stimulate root and shoot development, increase nutrient uptake, and induce systemic resistance (Fig. 5).

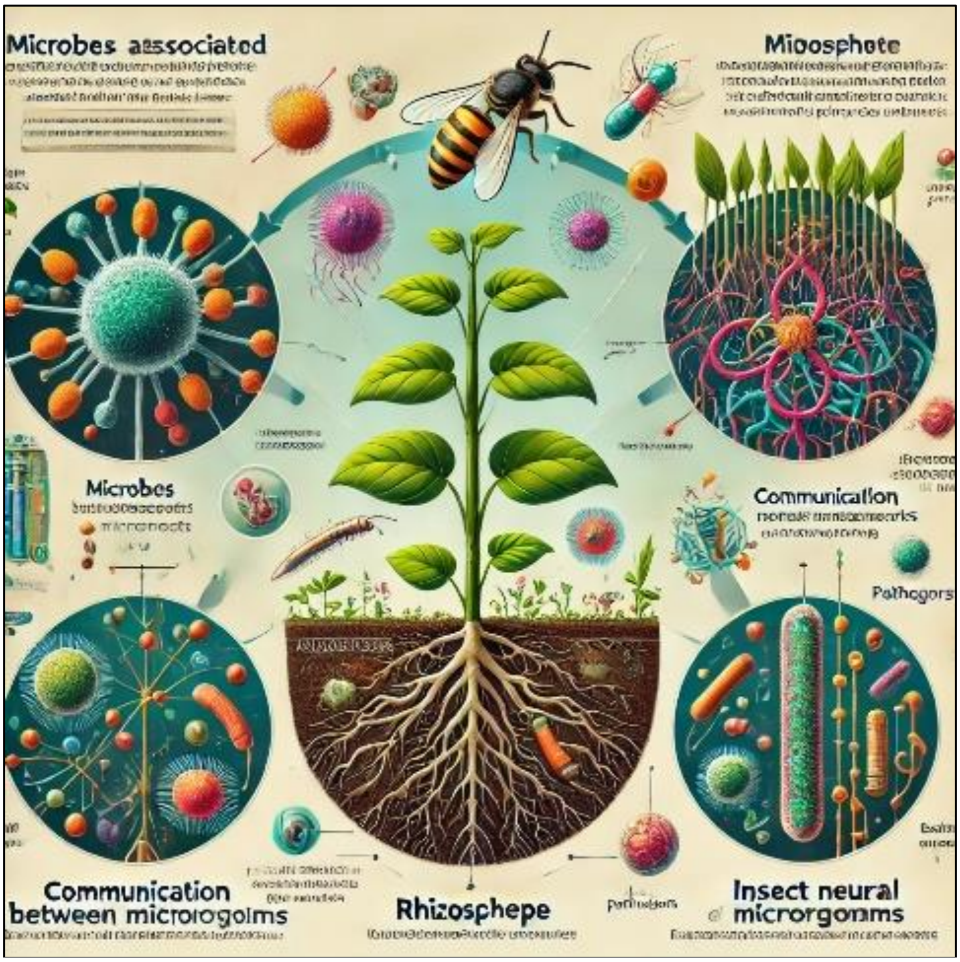


**Fig. 5. Plant growth Promotion through microorganism**

For example, VOCs produced by the rhizobacterium *Bacillus subtilis* have been shown to promote plant growth and induce resistance against fungal pathogens and insect pests. These VOCs include compounds such as 2,3-butanediol and acetoin, which can enhance plant vigor and defense responses [48].

### 11.7 Insect Attraction or Repellence

Microbial VOCs can also influence insect behavior by acting as attractants or repellents. These VOCs can affect insect feeding, oviposition, and mate-finding behaviors.

For instance, VOCs produced by endophytic fungi in maize can attract parasitoid wasps that prey on herbivorous insects. This indirect defense mechanism enhances the plant's ability to control pest populations. Conversely, certain microbial VOCs can repel herbivorous insects, reducing their feeding and damage to the plant [49].

### 11.8 Complex Tripartite Interactions

The interactions between plants, microorganisms, and insects are often complex and context-dependent. Microbial VOCs can modulate these interactions in various ways, depending on the specific microbial species, plant genotype, and environmental conditions.

For example, the interaction between the bacterium *Serratia plymuthica*, the nematode *Heterorhabditis bacteriophora*, and their plant host can be influenced by microbial VOCs. *S. plymuthica* produces VOCs that attract nematodes, enhancing their ability to control soil-dwelling insect pests. This tripartite interaction highlights the potential for microbial VOCs to modulate multi-trophic interactions and improve biocontrol strategies [50].

## 12. APPLICATIONS OF MICROBIAL KNOWLEDGE IN AGRICULTURE

The utilization of microbial knowledge in agriculture has revolutionized modern farming practices, offering sustainable solutions for pest management, plant health, and crop productivity. Microorganisms play a pivotal role in biological control, enhancing plant resistance, and promoting sustainable pest management.

### 12.1 Biological Control Strategies

Biological control strategies leverage beneficial microbes to manage pests and diseases, reducing reliance on chemical pesticides and promoting sustainable agriculture. The use of beneficial microbes and microbial inoculants has become a cornerstone of integrated pest management (IPM) programs.

### 12.2 Use of Beneficial Microbes

Beneficial microbes, including bacteria, fungi, and viruses, are employed as biological control agents to suppress pest populations and enhance plant health. These microbes can act directly by parasitizing pests or indirectly by inducing plant defenses.

### 12.3 Bacterial Biocontrol Agents

Bacterial biocontrol agents, such as *Bacillus thuringiensis* (Bt) and *Pseudomonas fluorescens*, are widely used in agriculture. Bt produces insecticidal toxins that target specific pests, making it an effective biopesticide. The toxins disrupt the gut lining of insect larvae, leading to their death. Bt-based products are used extensively in organic farming and IPM programs to control pests like caterpillars, beetles, and mosquitoes [51].

*Pseudomonas fluorescens* is another beneficial bacterium known for its ability to suppress soil-borne pathogens and promote plant growth. It produces antibiotics and siderophores that inhibit pathogenic fungi and bacteria, enhancing plant health and resilience. Additionally, *P. fluorescens* can induce systemic resistance in plants, providing broad-spectrum protection against various pests and diseases [24].

### 12.4 Fungal Biocontrol Agents

Fungal biocontrol agents, such as *Trichoderma* spp. and *Beauveria bassiana*, are also employed to manage plant diseases and insect pests. *Trichoderma* species are effective against soil-borne pathogens like *Rhizoctonia*, *Fusarium*, and *Pythium*. They colonize the root zone, outcompeting harmful pathogens and promoting plant growth through the production of growth-promoting compounds and enzymes [52].

*Beauveria bassiana* is an entomopathogenic fungus used to control a wide range of insect pests. It infects insects through the cuticle, proliferates inside the host, and eventually kills it. *B. bassiana* is effective against pests like aphids, whiteflies, and thrips, making it a valuable tool in IPM programs [53].

### 12.5 Viral Biocontrol Agents

Baculoviruses are viruses that specifically infect insects and are used as making them effective agents in biocontrol agents. These viruses target pest species such as caterpillars, leading to their death. Baculoviruses are highly specific and environmentally safe, posing no risk to non-target organisms, including humans and beneficial insects. They are used in various crops, including cotton, soybean, and vegetables, to control pests like the cotton bollworm and the cabbage looper [54].

Baculoviruses are viruses that specifically infect insects, making them effective agents in biological control. These viruses target pest species, such as caterpillars, causing their death. Baculoviruses are highly specific and environmentally safe pesticides, posing no risk to non-target organisms, including humans and beneficial insects. They are used in various crops, including cotton, soybeans, and vegetables, to control pests such as the cotton bollworm and cabbage worm [54].

## 13. MICROBIAL INOCULANTS FOR PLANT HEALTH

Microbial inoculants are formulations containing beneficial microorganisms that enhance plant growth, health, and resilience. These inoculants can be applied to seeds, soil, or plant surfaces to establish beneficial microbial communities.

### 13.1 Rhizobium Inoculants

*Rhizobium* inoculants are used to promote nitrogen fixation in leguminous crops. These bacteria form nodules on the roots of legumes, converting atmospheric nitrogen into a form that plants can use. Inoculating legume seeds with *Rhizobium* can significantly enhance nitrogen availability, reducing the need for synthetic fertilizers and improving soil fertility [55].

### 13.2 Mycorrhizal Inoculants

Mycorrhizal inoculants contain arbuscular mycorrhizal fungi (AMF) that form symbiotic associations with plant roots. These fungi enhance nutrient uptake, particularly phosphorus, and improve plant tolerance to drought and other stresses. Applying mycorrhizal inoculants can boost crop yields, enhance soil health, and reduce the need for chemical fertilizers [26].

### 13.3 Biostimulants

Biostimulants are microbial inoculants that promote plant growth by enhancing nutrient uptake, improving soil structure, and stimulating plant hormone production. They include products containing beneficial bacteria, fungi, and other microorganisms. Biostimulants can improve crop productivity, resilience to stress, and overall plant health [56].

## 14. ENHANCING PLANT RESISTANCE

Microorganisms can enhance plant resistance to pests and diseases through various mechanisms, including microbial priming of plant defenses and engineering symbiotic relationships.

### 14.1 Microbial Priming of Plant Defenses

Microbial priming involves exposing plants to beneficial microbes that enhance their ability to respond to subsequent pest and pathogen attacks. This priming effect leads to faster and stronger activation of plant defenses.

### 14.2 Induced Systemic Resistance (ISR)

ISR is a form of microbial priming where beneficial microbes, such as PGPR and mycorrhizal fungi, trigger plant defense pathways. These microbes produce signaling molecules that prime the plant's immune system, resulting in enhanced resistance to a broad spectrum of pests and pathogens. For example, PGPR like *Bacillus subtilis* can induce ISR, leading to the accumulation of defensive compounds and increased resistance to insects and diseases [57].

### 14.3 Systemic Acquired Resistance (SAR)

SAR is another form of induced resistance that is activated in response to localized pathogen infection. Beneficial microbes can trigger SAR, leading to the production of pathogenesis-related proteins and other defensive compounds. This systemic response enhances the plant's overall resistance to pests and diseases. For instance, rhizobacteria like *Pseudomonas fluorescens* can induce SAR, providing broad-spectrum protection against various pathogens and herbivores [36].

### 14.4 Engineering Symbiotic Relationships

Advances in genetic engineering have enabled the modification of microbial symbionts to enhance their beneficial effects on plants. These engineered symbiotic relationships can improve nutrient uptake, stress tolerance, and resistance to pests and diseases.

### 14.5 Nitrogen-Fixing Endophytes

Genetic engineering has been used to enhance the nitrogen-fixing capabilities of endophytic bacteria. These engineered endophytes can colonize non-leguminous crops, providing them with an additional source of nitrogen. This approach can reduce the need for synthetic fertilizers and enhance crop yields. For example, engineering the endophyte *Gluconacetobacter diazotrophicus* to fix nitrogen more efficiently can benefit crops like rice and wheat [58].

### 14.6 Enhanced Mycorrhizal Fungi

Mycorrhizal fungi can be genetically modified to enhance their symbiotic efficiency and stress tolerance. These engineered fungi can improve nutrient uptake and resilience to environmental stresses, benefiting a wide range of crops. For instance, enhancing the phosphorus uptake efficiency of AMF can improve crop productivity in phosphorus-deficient soils [26].

### 14.7 Biocontrol Symbionts

Genetic engineering can also be used to enhance the biocontrol properties of symbiotic microbes. By introducing genes that produce insecticidal proteins or antimicrobial compounds, these engineered symbionts can provide enhanced protection against pests and pathogens. For example, engineering *Bacillus thuringiensis* to produce multiple insecticidal toxins can increase its efficacy as a biopesticide [59].

## 15. SUSTAINABLE PEST MANAGEMENT

Sustainable pest management involves the integration of microbial agents into IPM programs and reducing dependence on chemical pesticides. These strategies promote environmental health, biodiversity, and long-term agricultural productivity.

### 15.1 Integration of Microbial Agents in IPM

Integrating microbial agents into IPM programs enhances pest control while minimizing the environmental impact of chemical pesticides. This holistic approach combines biological control, cultural practices, mechanical methods, and chemical interventions to manage pest populations sustainably (Fig. 6).

### 15.2 Biocontrol Integration

Biocontrol agents, such as beneficial bacteria, fungi, and viruses, are used alongside other IPM components to manage pests effectively. For instance, combining *Bacillus thuringiensis* with cultural practices like crop rotation and resistant varieties can enhance pest control and reduce the need for chemical insecticides. This integrated approach leverages the strengths of multiple strategies, providing robust and sustainable pest management [60].

**Fig. 6. Biological pest control**

### 15.3 Monitoring and Thresholds

Regular monitoring of pest populations and the use of economic thresholds are essential components of IPM. Microbial agents can be applied based on pest population levels and environmental conditions, ensuring their effective use. For example, monitoring for specific pest species can determine the optimal timing for applying microbial biopesticides, maximizing their impact and reducing unnecessary applications [61].

### 15.4 Conservation of Natural Enemies

IPM programs aim to conserve and enhance the populations of natural enemies of pests, such as predators, parasitoids, and pathogens. Using microbial agents that are compatible with natural enemies can support their conservation. For instance, biopesticides like *Bacillus thuringiensis* are specific to target pests and have minimal impact on beneficial insects, promoting a balanced ecosystem [62].

## 16. REDUCING CHEMICAL PESTICIDE DEPENDENCE

Reducing dependence on chemical pesticides is a key goal of sustainable pest management. Microbial agents offer an effective alternative, minimizing the environmental and health risks associated with chemical pesticides.

### 16.1 Environmental Benefits

Microbial biopesticides are biodegradable and have minimal impact on non-target organisms, making them environmentally friendly. They reduce the risk of pesticide runoff and contamination of water bodies, preserving biodiversity and ecosystem health. For example, using *Beauveria bassiana* for pest control in vegetable crops can reduce the need for synthetic insecticides, protecting pollinators and other beneficial insects [53].

### 16.2 Resistance Management

The overuse of chemical pesticides can lead to the development of pest resistance, reducing their effectiveness over time. Microbial biopesticides have diverse modes of action and lower potential for resistance development. Integrating microbial agents into pest management programs can delay the onset of resistance and prolong the efficacy of chemical pesticides. For instance, rotating microbial biopesticides with chemical insecticides can manage resistance in pest populations, ensuring long-term pest control [63].

### 16.3 Health and Safety

Reducing chemical pesticide use has significant health benefits for farmers, consumers, and communities. Microbial agents pose minimal health risks and are safer to handle and apply. This promotes a healthier working environment for farmers and reduces pesticide residues in food, enhancing food safety. For example, using *Trichoderma* spp. [64,65] as a biocontrol agent in horticulture reduces the need for chemical fungicides, protecting farmworkers and consumers from exposure to harmful chemicals [52].

## 17. CONCLUSION

The study of microorganisms in insect-plant interactions provides a profound offers a deep understanding of the complex relationships that sustain ecosystem health and maintain ecosystem health and boost agricultural productivity. Microorganisms, which include including bacteria, fungi, viruses, and protozoa, play pivotal roles in shaping these interactions through various mechanisms. From the early recognition of beneficial microbial roles to recent advancements in molecular biology, the historical perspectives on microbial interactions have highlighted their essential functions in plant health, pest resistance, and ecosystem dynamics. This understanding has shifted from viewing microbes merely as pathogens to recognizing their multifaceted contributions to plant and insect ecology.

Beneficial microorganisms, such as symbiotic bacteria, endophytic fungi, and mycorrhizal fungi, enhance plant growth and resilience. Symbiotic bacteria like *Rhizobium* fix atmospheric nitrogen, providing essential nutrients to leguminous plants and improving soil fertility. Plant growth-promoting rhizobacteria (PGPR) such as *Pseudomonas fluorescens* induce systemic resistance in plants, enhancing their defenses against pests and pathogens. Endophytic fungi produce secondary metabolites that deter herbivorous insects and improve plant stress tolerance. Mycorrhizal fungi, both arbuscular and ectomycorrhizal, enhance nutrient uptake and plant resistance to environmental stresses.

Conversely, pathogenic microorganisms, including bacterial, fungal, and viral pathogens, can weaken plants, making them more susceptible to insect herbivory. Pathogens such as *Xanthomonas* and *Pseudomonas syringae* cause diseases that reduce plant vigor and facilitate secondary infections by insects. Fungal pathogens like *Botrytis cinerea* and *Fusarium* species cause significant yield losses and create opportunities for insect infestations. Viral pathogens transmitted by insect vectors, such as the Tomato Yellow Leaf Curl Virus (TYLCV) and Potato Virus Y (PVY), alter plant physiology and defense mechanisms, making them more attractive to herbivores.

Neutral and opportunistic microorganisms, including commensal bacteria and latent pathogens, can become pathogenic or beneficial under certain conditions. For instance, *Pseudomonas fluorescens* can switch from a commensal to a pathogenic lifestyle under stress conditions, causing root diseases. Latent pathogens like *Colletotrichum* species remain dormant in plant tissues and become active under favorable conditions, leading to disease outbreaks.

Microorganisms influence insect-plant dynamics through various mechanisms, including the mediation of plant defenses and the modulation of insect physiology. Microbial mediation of plant defenses involves both the induction of plant resistance and the suppression of plant defenses. Beneficial microbes can trigger systemic acquired resistance (SAR) and induced systemic resistance (ISR), enhancing the plant's ability to defend against pests and diseases. However, some pathogens and insect symbionts can suppress plant defenses, facilitating their own colonization or benefiting associated insects. Microbial influence on insect physiology includes the role of gut microbiota in the digestion and detoxification of plant allelochemicals, enabling insects to exploit plant resources more efficiently. Tripartite interactions among plants, microbes, and insects involve complex signaling pathways and the production of microbial volatile organic compounds (VOCs), which can modulate plant-insect interactions and influence ecological dynamics.

The applications of microbial knowledge in agriculture are vast extensive and transformative. Biological control strategies utilizing beneficial microbes and microbial inoculants enhance plant health and pest resistance. The use of bacterial biocontrol agents like *Bacillus thuringiensis* and fungal agents like *Trichoderma* species reduces reliance on chemical pesticides. Enhancing plant resistance through microbial priming and engineering symbiotic relationships improves crop resilience to pests and environmental stresses. Sustainable pest management integrates microbial agents into integrated pest management (IPM) programs, reducing chemical pesticide dependence and promoting environmental health. Microbial biopesticides offer environmentally friendly alternatives with minimal impact on non-target organisms and reduced risk of resistance development.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

## REFERENCES

1. Stone JK. Bacon CW, White JF. An overview of endophytic microbes: endophytism defined. Microbial Endophytes. 2000;3-29.
2. Compant S, Duffy B, Nowak J, Clément C, Barka EA. Use of plant growth-promoting bacteria for biocontrol of plant diseases: Principles, mechanisms of action, and future prospects. Applied and Environmental Microbiology. 2005;71(9): 4951-4959.
3. Lindow SE, Brandl MT. Microbiology of the phyllosphere. Applied and Environmental Microbiology. 2003;69(4):1875-1883.
4. Engel P, Moran NA. The gut microbiota of insects – diversity in structure and function. FEMS Microbiology Reviews. 2013;37(5): 699-735.
5. Verma VC, Kharwar RN, Strobel GA. Chemical and functional diversity of natural bioactive compounds from plant-associated endophytic fungi. Natural Product Communications. 2009;4(11): 1511-1532.
6. Chitnis VR, Suryanarayanan TS, Nataraja KN, Prasad SR. Endophyte-induced enhancement of defense against

herbivores in plants. Journal of Pest Science. 2020;93(1):17-28.
7. Cameron DD, Neal AL, van Wees SC, Ton J. Mycorrhiza-induced resistance: more than the sum of its parts? Trends in Plant Science. 2013;18(10):539-545.
8. Vorholt JA. Microbial life in the phyllosphere. Nature Reviews Microbiology. 2012;10(12):828-840.
9. Rastogi G, Coaker GL, Leveau JH. New insights into the structure and function of phyllosphere microbiota through high-throughput molecular approaches. FEMS Microbiology Letters. 2019;366(1):fnz034.
10. Douglas AE. Multiorganismal insects: diversity and function of resident microorganisms. Annual Review of Entomology. 2015;60:17-34.
11. Hammer TJ, Janzen DH, Fierer N. Caterpillars lack a resident gut microbiome. Proceedings of the National Academy of Sciences. 2017;114(36):9641-9646.
12. Buchanan BB. Symbiotic nitrogen fixation in plants. Plant Physiology. 1901;26(1):85-106.
13. Harley JL, Smith SE. Mycorrhizal Symbiosis. Academic Press; 1983.
14. Clay K. Fungal endophytes of grasses: A defensive mutualism between plants and fungi. Ecology. 1988;69(1):10-16.
15. Handelsman J. Metagenomics: Application of genomics to uncultured microorganisms. Microbiology and Molecular Biology Reviews. 2004;68(4):669-685.
16. Pineda A, Dicke M, Pieterse CMJ, Pozo MJ. Beneficial microbes in a changing environment: Mechanisms and consequences. Frontiers in Plant Science. 2013;4:356.
17. Hammer TJ, Dickerson JC, Fierer N. Evidence-based recommendations on storing and handling specimens for microbial analysis. Frontiers in Microbiology. 2015;6:658.
18. Saikkonen K, Faeth SH, Helander M, Sullivan TJ. Fungal endophytes: A continuum of interactions with host plants. Annual Review of Ecology and Systematics. 1998;29:319-343.
19. Berendsen RL, Pieterse CMJ, Bakker PAHM. The rhizosphere microbiome and plant health. Trends in Plant Science. 2012;17(8):478-486.
20. van der Heijden MGA, Bardgett RD, van Straalen NM. The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecology Letters. 2008;11(3):296-310.
21. Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P. Climate-smart soils. Nature. 2016;532(7597):49-57.
22. Bever JD, Broadhurst LM, Thrall PH. Microbial phylotype composition and diversity predicts plant productivity and plant-soil feedbacks. Ecology Letters. 2013;16(2):167-174.
23. Oldroyd GE. Speak, friend, and enter: Signalling systems that promote beneficial symbiotic associations in plants. Nature Reviews Microbiology. 2013;11(4):252-263.
24. Lugtenberg B, Kamilova F. Plant-growth-promoting rhizobacteria. Annual Review of Microbiology. 2009;63:541-556.
25. Rodriguez RJ, White Jr JF, Arnold AE, Redman RS. Fungal endophytes: Diversity and functional roles. New Phytologist. 2009;182(2):314-330.
26. Smith SE, Read DJ. Mycorrhizal Symbiosis. Academic Press; 2008.
27. Courty PE, Buée M, Diedhiou AG, Frey-Klett P, Le Tacon F, Rineau F, Garbaye J. The role of ectomycorrhizal communities in forest ecosystem processes: New perspectives and emerging concepts. Soil Biology and Biochemistry. 2010;42(5):679-698.
28. Ryan RP, Vorhölter FJ, Potnis N, Jones JB, Van Sluys MA, Bogdanove AJ, Dow JM. Pathogenomics of Xanthomonas: Understanding bacterium–plant interactions. Nature Reviews Microbiology. 2011;9(5):344-355.
29. Xin XF, Kvitko B, He SY. Pseudomonas syringae: What it takes to be a pathogen. Nature Reviews Microbiology. 2018; 16(5): 316-328.
30. Dean R, Van Kan JA, Pretorius ZA, Hammond-Kosack KE, Di Pietro A, Spanu PD, Foster GD. The Top 10 fungal pathogens in molecular plant pathology. Molecular Plant Pathology. 2012;13(4): 414-430.
31. Michielse CB, Rep M. Pathogen profile update: Fusarium oxysporum. Molecular Plant Pathology. 2009;10(3):311-324.
32. Hanssen IM, Lapidot M, Thomma BP. Emerging viral diseases of tomato crops. Molecular Plant-Microbe Interactions. 2010;23(5):539-548.
33. Karasev AV, Gray SM. Continuous and emerging challenges of Potato virus Y in potato. Annual Review of Phytopathology. 2013;51:571-586.

34. Weller DM. Pseudomonas biocontrol agents of soilborne pathogens: Looking back over 30 years. Phytopathology. 2007; 97(2):250-256.
35. Cannon PF, Damm U, Johnston PR, Weir BS. Colletotrichum – current status and future directions. Studies in Mycology. 2012;73(1):181-213.
36. Durrant WE, Dong X. Systemic acquired resistance. Annual Review of Phytopathology. 2004;42:185-209.
37. Pieterse CMJ, Zamioudis C, Berendsen RL, Weller DM, Van Wees SCM, Bakker PAHM. Induced systemic resistance by beneficial microbes. Annual Review of Phytopathology. 2014;52:347-375.
38. Van Loon LC, Bakker PA, Pieterse CM. Systemic resistance induced by rhizosphere bacteria. Annual Review of Phytopathology. 1998;36(1):453-483.
39. Cui H, Tsuda K, Parker JE. Effector-triggered immunity: From pathogen perception to robust defense. Annual Review of Plant Biology. 2015;66:487-511.
40. Oliver KM, Degnan PH, Burke GR, Moran NA. Facultative symbionts in aphids and the horizontal transfer of ecologically important traits. Annual Review of Entomology. 2010;55:247-266.
41. Brune A, Dietrich C. The gut microbiota of termites: Digesting the diversity in the light of ecology and evolution. Annual Review of Microbiology. 2015;69:145-166.
42. Ohkuma M. Termite symbiotic systems: Efficient bio-recycling of lignocellulose. Applied Microbiology and Biotechnology. 2003;61(1):1-9.
43. Kumar P, Pandit SS, Steppuhn A, Baldwin IT. Natural history-driven, plant-mediated RNAi-based study reveals CYP6B46's role in a nicotine-mediated antipredator herbivore defense. Proceedings of the National Academy of Sciences. 2014; 111(4):1245-1252.
44. Morrison WR, Gibson DM, Nault BA. Interactions between the polyphagous herbivore Trichoplusia ni (Noctuidae: Lepidoptera) and cultivated grapevines. Environmental Entomology. 2009; 38(4): 1341-1349.
45. Kanchiswamy CN, Malnoy M, Maffei ME, Arimura G, Bossi S. Biological control of plant pathogens: A global perspective. Frontiers in Plant Science. 2015;6:114.
46. Venturi V, Keel C. Signaling in the rhizosphere. Trends in Plant Science. 2016;21(3):187-198.
47. Bruce TJ, Wadhams LJ, Woodcock CM. Insect host location: A volatile situation. Trends in Plant Science. 2005;10(6):269-274.
48. Ryu CM, Farag MA, Hu CH, Reddy MS, Kloepper JW, Paré PW. Bacterial volatiles promote growth in Arabidopsis. Proceedings of the National Academy of Sciences. 2003;100(8):4927-4932.
49. D'Alessandro M, Erb M, Ton J, Brandenburg A, Karlen D, Zopfi J, Turlings TC. Volatiles produced by soil-borne endophytic bacteria increase plant pathogen resistance and affect tritrophic interactions. Plant, Cell & Environment. 2014;37(3):813-826.
50. Ali S, Zhang Q, Li S, Shen Y, Lou C, Wu H. Volatile organic compounds from Serratia plymuthica inhibit Rhizoctonia solani and promote the growth of Tomato (Solanum lycopersicum). Journal of Applied Microbiology. 2012;113(3):694-703.
51. Sanahuja G, Banakar R, Twyman RM, Capell T, Christou P. Bacillus thuringiensis: A century of research, development and commercial applications. Plant Biotechnology Journal. 2011;9(3): 283-300.
52. Harman GE, Howell CR, Viterbo A, Chet I, Lorito M. Trichoderma species—opportunistic, avirulent plant symbionts. Nature Reviews Microbiology. 2004;2(1): 43-56.
53. Zimmermann G. Review on safety of the entomopathogenic fungus Beauveria bassiana. Biocontrol Science and Technology. 2007;17(6):553-596.
54. Szewczyk B, Hoyos-Carvajal L, Paluszek M, Skrzecz I, Lobo de Souza M. Baculoviruses—re-emerging biopesticides. Biotechnologia. 2006;3(74):6-19.
55. Peoples MB, Brockwell J, Herridge DF, Rochester IJ, Alves BJR, Urquiaga S, Baldock JA. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis. 2009;48 (1-3):1-17.
56. Calvo P, Nelson L, Kloepper JW. Agricultural uses of plant biostimulants. Plant and Soil. 2014;383(1-2):3-41.
57. Van Wees SCM, Van der Ent S, Pieterse CMJ. Plant immune responses triggered by beneficial microbes. Current Opinion in Plant Biology. 2008;11(4):443-448.
58. Benedito VA, Torres-Jerez I, Murray JD, Andriankaja A, Allen S, Kakar K, Udvardi MK. A gene expression atlas of the model

legume Medicago truncatula. The Plant Journal. 2010;63(2):233-254.
59. Bravo A, Gill SS, Soberón M. Mode of action of Bacillus thuringiensis Cry and Cyt toxins and their potential for insect control. Toxicon. 2011;49(4):423-435.
60. Eilenberg J, Hajek AE, Lomer C. Suggestions for unifying the terminology in biological control. BioControl. 2001;46(4): 387-400.
61. Flint ML, Dreistadt SH. Natural Enemies Handbook: The Illustrated Guide to Biological Pest Control. University of California Press; 1998.
62. Gurr GM, Wratten SD, Luna JM. Multi-function agricultural biodiversity: Pest management and other benefits. Basic and Applied Ecology. 2004;4(2):107-116.
63. Lacey LA, Grzywacz D, Shapiro-Ilan DI, Frutos R, Brownbridge M, Goettel MS. Insect pathogens as biological control agents: Back to the future. Journal of Invertebrate Pathology. 2015;132:1-41.
64. Hammer TJ, Dickerson JC, Fierer N. Evidence-based recommendations on storing and handling specimens for microbial analysis. Frontiers in Microbiology. 2015;6:658.
65. Stone JK, Bacon CW, White JF. Microbial Endophytes. Marcel Dekker; 2000.



*Peer-review history:*
*The peer review history for this paper can be accessed here:*
*https://prh.mbimph.com/review-history/3853*