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Harnessing the Plant Microbiome: A New Frontier in Disease Resistance

Madhaiyan Sakthivel[1*], Marimuthu Elangovan[1] and Senthilkumar S[2]

[1]Ph.D. Scholar, Division of Plant Pathology, ICAR-Indian Agricultural Research Institute, New Delhi, India- 110012

[2]Ph.D. Scholar, Department of Plant Pathology, College of Agriculture, G. B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India- 263145

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Abstract

Harnessing the plant microbiome offers a transformative approach to sustainable agriculture by enhancing disease resistance, reducing chemical dependencies, and improving crop resilience. This article explores the intricate interactions between plants and their microbiomes, highlighting mechanisms such as induced systemic resistance, microbial competition, and pathogen suppression. The "cry for help" hypothesis and microbiome engineering are novel strategies that enable plants to recruit beneficial microbes for improved immunity. Advances in synthetic biology, artificial intelligence, and CRISPR-based microbiome editing pave the way for precision agriculture. This study underscores the potential of microbiome-driven innovations to revolutionize food security and climate-resilient farming.

Keywords: Plant microbiome, immunity, hormones, disease resistance

Introduction

Plant diseases caused by microbial pathogens pose a significant threat to global food security, agricultural productivity, and economic stability. Climate change and global trade are expected to intensify the spread and severity of emerging plant diseases, further threatening agricultural systems. While traditional approaches like genetic modification and chemical pesticides have been partially effective, they face limitations due to pathogen resistance and environmental concerns. Overuse of pesticides also harms beneficial microbiota that naturally protect plants. As agricultural challenges grow due to climate change, soil degradation, and increasing pathogen resistance, harnessing the potential of plant beneficial microbiomes and their products is a viable strategy for the mitigation of plant diseases in sustainable agriculture, owing to their multifaceted functions such as promoting growth, providing nutrient availability, increasing soil fertility, being ecofriendly and boosting multiple stress resilience.

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Plant microbiome

The plant microbiome consists of three main parts: the phyllosphere (above-ground plant surfaces), the endosphere (internal plant tissues), and the rhizosphere (soil around roots). Within the plant rhizosphere reside not only prokaryotic organisms (e.g. bacteria and archaea), but also unicellular (e.g. protozoa) and multicellular (e.g. nematodes, fungi) eukaryotes and viruses, which all play important roles towards plant growth and development. These microorganisms often outnumber the plant's own cells and significantly enhance its protein-coding and metabolic capabilities. Both abiotic factors (drought, salinity, flooding, heavy metals and pH) and biotic factors (invading pathogens and plant growth-promoting organisms) can affect the composition of organisms within the plant's microbiome. Similarly, agricultural practices such as fertilizer and pesticide use, can also alter microbial communities and in some cases, can select for antimicrobial resistant bacteria.

Role of plant microbiome in Disease resistance

The microbiome protects plants against pathogens directly or indirectly through various mechanisms such as activating immune responses, induced systemic resistance (ISR), compete for resources and space and callose deposition. Direct pathogen suppression is attributed to antimicrobial molecules and resource competition, while indirect suppression involves activation of the plant immune system (Du *et al.,* 2024).

1. Induced Systemic Resistance (ISR): ISR is a phenomenon where beneficial microbes prime the plant's immune system, enabling it to better defend against a wide range of pathogens. This process is regulated by plant hormones such as jasmonic acid (JA) and ethylene (ET). For example, certain strains of Pseudomonas and Trichoderma have been shown to activate ISR in plants, providing protection against diseases like Fusarium wilt and powdery mildew

2. Production of Antimicrobial Compounds: Many beneficial microbes produce antimicrobial compounds that directly inhibit the growth of pathogens. For example, *Pseudomonas fluorescens* produces 2,4-diacetylphloroglucinol, a compound that suppresses soil-borne pathogens like *Fusarium* and *Pythium*.

3. Competition for Resources: Beneficial microbes can outcompete pathogens for nutrients and space, reducing the likelihood of infection. For instance, mycorhizal fungi form symbiotic relationships with plant roots, improving nutrient uptake and creating a physical barrier against pathogens.

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"Cry for Help" Hypothesis: Plants Recruit Beneficial Microbes

A new hypothesis has emerged in plants in the context of stress and plant beneficial microbiome recruitment, known as the 'cry for help'. According to this hypothesis, when plants are under pathogen attacks or disease development it actively recruit or enrich specific microorganisms that can provide an array of growth-promoting benefits (Rolfe *et al.,* 2019). For example, studies have shown that when Arabidopsis plants are infected with the pathogen *Pseudomonas syringae*, they release root exudates that attract beneficial *Bacillus* sps. These bacteria then colonize the plant's roots and activate ISR, providing systemic protection against the pathogen.

Guardians at the Gate: How the Plant Immune System Detects Friends and Foes

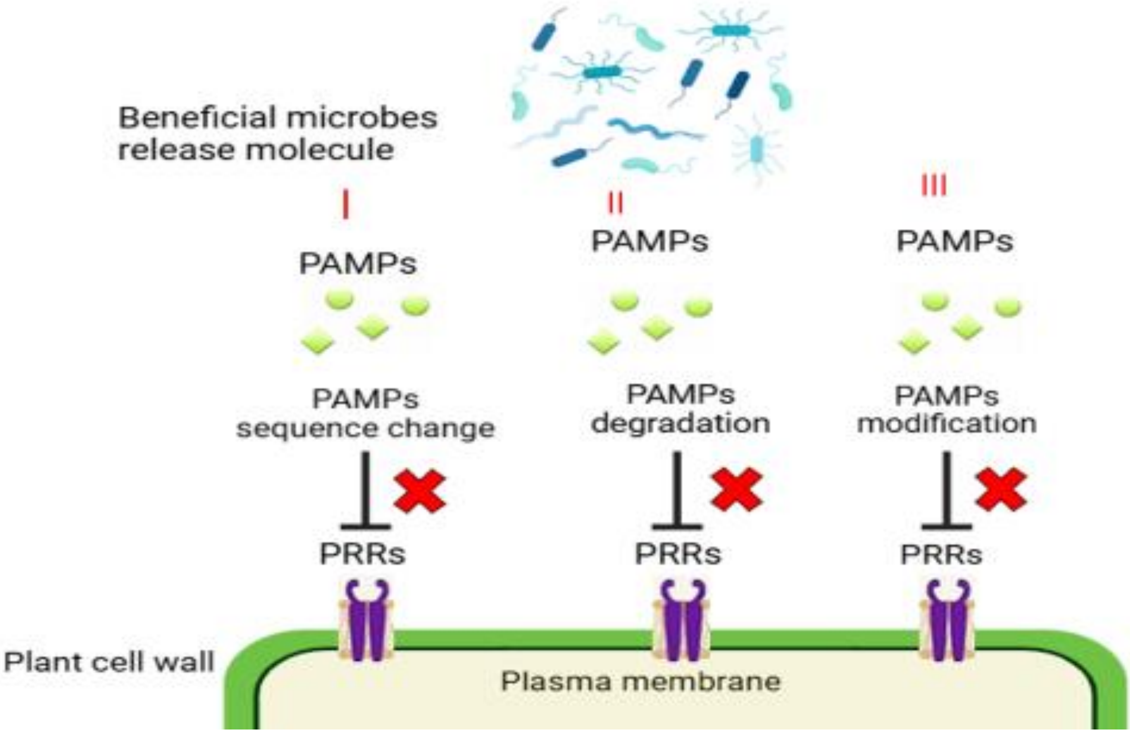
Plants are constantly exposed to a wide range of microbes (beneficial and pathogenic), which either supports or limits their growth and development. However, plants have sophisticated immune systems that allow them to distinguish friends from foes. to detect and react to pathogen infections, plants primarily depend on two tier levels of their innate immune system, namely pattern recognition receptors (PRRs) on the cell surface to recognize microbe associated molecular patterns (MAMPs) or host-derived damage-associated molecular patterns (DAMPs) is called PAMP-triggered immunity (PTI) and disease resistance (R) proteins that respond to effector molecules, also called effector triggered immunity (ETI) (Ali *et al.,* 2023). Furthermore, while models like PTI and ETI provide a strong overview of the fundamental principles of plant immunity and they primarily focus on plant interactions with pathogenic microbes.

The plant immune system not only defends against harmful microbes but also helps shape a healthy community of beneficial microbes. However, some microbes have developed ways to bypass plant immunity, specifically PTI (Pattern-Triggered Immunity). They use different strategies:

1. **PAMPs Divergence** – Microbes change the structure or sequence of their PAMPs (Microbe-Associated Molecular Patterns) so they are no longer recognized by plant receptors.
2. **PAMPs Degradation or Sequestration** – Microbes release enzymes that break down or hide their PAMPs, making them invisible to the plant's immune system.
3. **PAMPs Modification** – Some microbes modify their PAMPs, like flagellin and chitin, so the plant's immune receptors can't detect them.

Interestingly, beneficial microbes might use similar tricks to avoid triggering plant immunity, allowing them to coexist with plants. Since common MAMPs like flg22 and chitin are found in both harmful and helpful microbes, beneficial bacteria may have developed ways to modify them too. Furthermore, how the beneficial microbiome evades plant immunity has shown in Figure 1.

Figure 1. How beneficial microbes evade the plant immune system



The Role of Plant Hormones in Shaping the Microbiome

Plant hormones play a crucial role in shaping the composition of the plant microbiome. Hormones like salicylic acid (SA), jasmonic acid (JA), and ethylene (ET) are not only involved in defense responses but also influence the colonization of beneficial microbes. Recently, researchers have been identified as important drivers of plant beneficial microbiome assembly. Lebeis et al. (2015) reported that SA has been shown to modulate the root microbiome in Arabidopsis, with SA-deficient mutants exhibiting different microbial communities compared to wild-type plants. Similarly, JA and ET have been found to influence the assembly of beneficial microbial communities in the rhizosphere, the region of soil surrounding plant roots. However, the effect of plant defense signatures on plant beneficial microbiome assembly varies among plant species and compartments. For example, it has been shown that JA plays a different role in epiphytic Arabidopsis leaf communities and wheat (T. aestivum) root endosphere community composition.

Engineering Disease-Resilient Microbial Communities

Advances in microbiome research and synthetic biology now allow scientists to design tailored microbial consortia that enhance disease resistance. Strategies for developing disease-resilient plants include:

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1. **Microbiome engineering:** Introducing specific beneficial microbes into soil or plant tissues to enhance plant immunity.
2. **High-throughput screening:** Identifying microbes with the strongest disease-suppressing traits.
3. **Synthetic microbial communities (SynComs):** Combining multiple beneficial microbes to create optimized microbial formulations for agricultural use.
4. **Artificial intelligence and deep learning:** Predicting how different microbial communities interact with plant immune systems.

The Future of Plant Microbiome Research

The plant microbiome is a vast community of bacteria, fungi, and other microorganisms living in and around plants, which plays a crucial role in plant health, disease resistance, and environmental adaptation. As research advances, harnessing these microbial interactions could revolutionize agriculture, reduce chemical dependencies, and improve food security. Here's what the future of plant microbiome research might look like,

1. Precision Microbiome Engineering

Genetic engineering and synthetic biology may allow for the development of customized microbial communities tailored to specific crops.

New Biostimulant Formulations: Researchers are working on combining beneficial microbes with plant hormones or other bioactive compounds for enhanced effectiveness.

Microbiome Editing with CRISPR: Advanced gene-editing tools like CRISPR may help modify microbial genomes to improve their plant-supporting functions.

2. Microbial-Based Disease Control

Beneficial microbes can act as natural biocontrol agents, suppressing plant pathogens and reducing reliance on chemical pesticides.

Inducing Plant Immunity Through Microbes: Some microbes can "train" plants to activate their immune responses before pathogen attacks.

Microbial-Based Vaccines for Plants: Scientists are exploring the potential of using non-pathogenic microbes to stimulate plant defenses in a manner similar to vaccines in humans.

3. Climate-Resilient Agriculture

Microbiomes may help crops withstand extreme weather conditions, such as drought, heat, and soil degradation.

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Microbial Adaptation to Changing Climates: Understanding how microbes evolve under stress conditions can help in designing climate-adaptive microbiomes.

4. Next-Generation Technology for Microbiome Analysis

Advances in metagenomics, artificial intelligence, and big data analytics are helping researchers decode complex plant-microbe interactions. Also, High-throughput sequencing and bioinformatics are enabling deeper insights into microbial diversity and functions.

Real-Time Microbiome Monitoring: Wearable sensors and advanced imaging techniques could allow farmers to track microbial activity in soil and plants.

AI-Powered Predictive Modeling: Machine learning is being used to predict how microbiomes respond to environmental changes and agricultural practices.

5. Microbiome-Driven Crop Breeding

Instead of focusing solely on plant genetics, future breeding programs may incorporate microbiome traits to develop crops that interact better with beneficial microbes.

Identifying Microbiome-Responsive Crop Varieties: Some plant varieties are naturally better at recruiting beneficial microbes, offering a new target for breeding.

Integrating Microbiome Traits into Genomic Selection: Advanced breeding strategies may incorporate microbiome-associated genes for enhanced crop performance.

Conclusion

The plant microbiome represents a new frontier in sustainable agriculture, offering a natural and eco-friendly solution to the growing threat of plant diseases. By harnessing the power of beneficial microbes, we can enhance plant immunity, improve crop yields, and reduce our reliance on chemical pesticides. As research in this field continues to advance, the potential for microbiome-based solutions to transform agriculture and ensure global food security is immense. The future of farming may well lie beneath our feet, in the hidden world of the plant microbiome.

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