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Plant Beneficial Symbionts: Charming Members in the Phytomicrobiome Community

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Abstract

Plants, seemingly solitary, engage in a fascinating dance of co-existence with a diverse cast of microbial and animal partners, playing a vital role in securing our future food supply While appearing self-sufficient, plants co-exist with diverse microbial and animal partners, ensuring our future food supply. This intricate community, the phytomicrobiome, harbors both microscopic and macroscopic allies, each contributing significantly to plant health and growth. This review delves into these symbiotic relationships, exploring how microbes like nitrogen-fixing bacteria (e.g., *Rhizobium* sp.) and mycorrhizal fungi enhance nutrient acquisition and promote plant growth. Furthermore, it highlights the potential of these symbionts as biofertilizers, through the focus on endophytes and rhizosphere microorganisms offering a sustainable alternative to chemical fertilizers by enriching soil and enhancing plant root systems. Beyond the microscopic world, insects also play a pivotal role in securing future food production, while ensuring successful plant reproduction, acting as natural pest control, and reducing reliance on harmful insecticides. Understanding and harnessing the potential of both microbial and insect symbionts holds immense promise for sustainable agriculture. By fostering these partnerships, we can promote healthy plant growth, minimize reliance on chemical inputs, and ensure a secure food supply for generations to come.

Keywords: Phytomicrobiome, Beneficial symbionts, Rhizosphere, Endophytes, Plant growth promotion (PGP).

1. Introduction

Plant beneficial microorganisms (PBMs) play crucial roles in plant health and growth by promoting nutrient supply, combating diseases, and inducing stress tolerance in plants [1, 2, 5, 7]. Notably, these microbes interact with plants mainly within the rhizosphere or endophytic region, aiding in nutrient mobilization, disease suppression, and hormone secretions [5].

Plant probiotic microorganisms (PPM), also function as biofertilizers. biocontrol agents, and supporting sustainable agriculture by providing eco-friendly alternatives to intensive use of pesticides and fertilizers [2, 4, 6]. For instance, *Trichoderma* and *Bacillus* species have been identified as notable biocontrol agents that can enhance disease resistance in plants [6, 8].

Additionally, beneficial microorganisms positively impact plant metabolome and biochemistry. They can stimulate new biosynthetic pathways in plants, which may help discover novel pathways, genes, and enzymes associated with natural plant product biosynthesis [9]. In specific studies, it has been noted that a suitable combination of beneficial microorganisms, such as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting bacteria (PGPB), can improve plant growth and fruit quality [11].

Despite the importance of PBMs, the adoption ofthese beneficial microbes in the field still has room for progress. Some challenges lie in the understanding of mechanisms of interaction between plants and these microbes, gaps in efficacy, and regulatory processes for bio fungicides [4].

1.1 Historical Journey

The story of plant-beneficial symbionts is far from complete. As research delves deeper, we are constantly uncovering new aspects of this ancient alliance. Future explorations may reveal previously unknown symbionts, uncover the specific mechanisms underlying their beneficial effects, and shed light on their role in shaping plant evolution and ecosystem functioning.

The intricate partnership between plants and beneficial microorganisms stretches back millennia, shaping the course of plant evolution and influencing the very foundation of terrestrial ecosystems.

Early hints of this ancient alliance come from fossilized evidence. Studies suggest the presence of arbuscular mycorrhizal fungi (AMF), a vital group of rhizosphere symbionts, in association with plant fossils dating back 450-530 million years [11]. This suggests that these beneficial partnerships were

established early on, playing a crucial role in plant colonization of land.
Over time, this collaboration diversified, with various groups of microorganisms evolving intricate mechanisms to interact with their plant hosts. Nitrogen-fixing bacteria, like *Rhizobium* sp. emerged approximately 60 million years ago [12], enabling legumes and other plants to thrive in nitrogen-deficient environments. This symbiosis revolutionized terrestrial ecosystems, contributing significantly to soil fertility and plant diversity.
The 20th century witnessed a significant advancement in our understanding of plant-microbe interactions. Pioneering work by Frank (1885) and Beijerinck (1888) laid the foundation for research on nitrogen fixation, while Nobbe and Hiltner (1896**)** established the symbiotic nature of this process in legumes [13]. Franciszek Kamienski made significant contributions to the field during the same era. Around the same time, Kamienski undertook another crucial step in our understanding of plant-microbe interactions by differentiating mycorrhizae based on their morphology and interaction with host plant roots [14]. His meticulous observations and classifications laid the foundation for future research on these essential rhizosphere symbionts, paving the way for a deeper understanding of their diverse functionalities and importance in plant health.
The 20th century also saw the discovery of numerous other beneficial symbionts, including plant growth-promoting bacteria (PGPB) and endophytes.

Recent research continues to fuel our understanding of the complex and dynamic nature of these partnerships. Advances in genomics and metagenomics, as exemplified by the work of Zhang et al. (2023), have enabled scientists to unravel the intricate genetic basis of these symbioses, revealing the molecular dialogue between plants and their microbial partners [15, 16, 17, 18]. Additionally, ecological studies, such as those conducted by van der Putten et al. (2023), have highlighted the diverse roles of beneficial symbionts beyond nutrient acquisition, including stress tolerance, pathogen protection, and plant community interactions [19, 20, 21, 22].

1.2 Unveiling the Wonders of Phytomicrobiome: A Universe Within Plants

Imagine a hidden world teeming with life, intimately intertwined with the very fabric of our planet's green tapestry. This is the phytomicrobiome, a diverse and dynamic community of microorganisms residing within and around plants. Just as the human body harbors a unique microbiome, each plant plays host to a staggering array of bacteria, fungi, archaea, and viruses, collectively shaping its health, resilience, and even its very existence.
The sheer diversity of the phytomicrobiome is mind-boggling. Estimates suggest that a single plant might harbor millions, even billions, of microbial cells, representing thousands of distinct species. This diversity varies greatly depending on plant species, geographical location, soil conditions, and even the specific plant organ (e.g., leavesand roots). Some microbes reside internally, colonizing plant tissues as endophytes, while others populate the rhizosphere, the soil zone directly influenced by plant roots.
Plant beneficial symbionts, including insect-associated symbionts, root microbes, and fungi, play substantial roles in plant responses to herbivory, interactions up to the third trophic level, and plant defense mechanisms against pests and diseases [23, 24, 25].

For example, insects' symbiotic associations with microbes can result in trade-offs between their growth, fecundity, and resistance to natural enemies, which inevitably influence their interactions with plants [26, 27]. Similarly, *Rhizobiales* symbionts in the hindgut of *Acromyrmex* leaf-cutting ants are significant to the ants due to their production of vitamins, antioxidants, and enzymes that support the ant-fungus farming symbiosis [28].

1.3 What is the Impact of Climate Change on these Symbiotic Relationships and their Functions?

Given the increasing concerns about climate change, understanding how various environmental factors impact these beneficial symbiotic relationships is another crucial area of research. Questions could investigate the resilience of various symbionts under different climate change scenarios, whether symbionts can adapt to changing conditions, and how any alterations in symbiont functionality could affect plant productivity, pest resistance, and disease control. It's important to note that research should aim to ensure that any interventions proposed to mitigate adverse effects are sustainable and have a minimal negative impact on the environment [29, 30].

1.4 Endophytes: Nature's Internal Guardians

Imagine a plant harboring millions of microscopic friends within its tissues. These are endophytes, diverse microorganisms that establish long-term, often mutualistic, relationships with their plant hosts. Some endophytes act as chemical bodyguards, producing antimicrobial compounds that deter pathogens and herbivores [31, 32]. Others enhance nutrient acquisition by fixing nitrogen or solubilizing phosphorus, vital elements for plant growth [33, 34]. Endophytes in grasses, for instance, contribute to drought tolerance by producing specialized molecules that help retain water [35]. These hidden allies illustrate the intricate dance of symbiosis, where both plant and microbe benefit.
Rhizosphere Microbes: The Power of the Root Zone: Beyond the plant's interior lies the rhizosphere, a dynamic zone teeming with microbial life. Here, the roots release a cocktail of nutrients and signals, attracting a diverse cast of microbial partners. Some, like rhizobia, form symbiotic relationships with

legume roots, fixing atmospheric nitrogen into a form usable by the plant [36]. Others, like mycorrhizal fungi, extend the plant's root system, dramatically increasing its reach for water and nutrients [37]. This intricate network of interactions in the rhizosphere underscores the importance of soil health for plant well-being **(Fig. 1)**.

These microscopic inhabitants are not merely passive passengers. They forge intricate symbiotic relationships with their plant hosts, engaging in a constant exchange of nutrients, signals, and metabolites. This dynamic interplay shapes the plant's ability to thrive in the face of environmental challenges, defend itself against pathogens, and even acquire essential nutrients.

Understanding the intricate workings of the phytomicrobiome is not just an academic exercise. It holds immense potential for transforming agriculture, offering sustainable solutions to improve plant health, boost yields, and mitigate the negative impacts of conventional farming practices. By harnessing the power of beneficial microbes, we can cultivate a more resilient and productive future for our planet's flora.

Plant beneficial symbionts play a crucial role in enhancing plant growth, health, and defensive capabilities. Mutualistic relationships between plants and symbionts have gained significant recognition, with the potential to influence plant responses to herbivory and interactions within a food-web system [38].

Elm fungal endophytes, for example, are known to activate the plant's immune and antioxidant systems, providing defense against diseases like Dutch Elm Disease [39]. Similarly, arbuscular mycorrhizal fungi (AMF) improve plant nutrition and health, and they are seen as a valuable resource for sustainable agriculture and creating functional food with enhanced nutritional value [40]

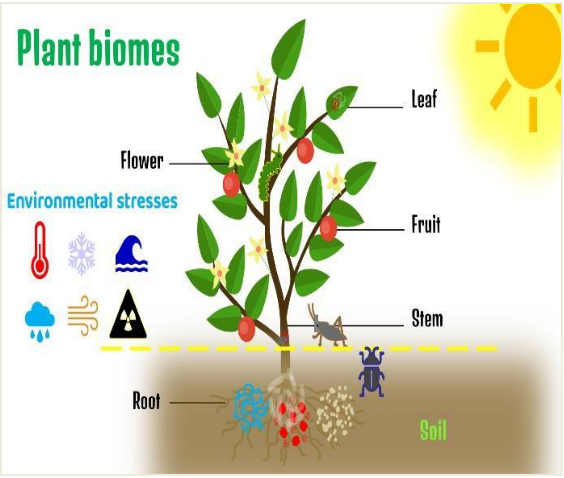

Figure 1. In plant-biomes, tiny helpers like bacteria and fungi can live on or inside plants, forming mutually beneficial partnerships. These helpers provide plants with nutrients, protection from disease, and even help them cope with stress. While some insects have similar partnerships with microbes, the details are still fuzzy. These plant-microbe friendships can boost plant growth and even reduce the need for fertilizers, making them valuable allies for sustainable agriculture and healthier plants.

Research has also focused on understanding the common symbiotic pathway (CSP), a group of plant proteins believed to transduce signals from beneficial microbes, and how this pathway differentiates between various symbionts [42].

The plant innate immune system also plays an important role in balancing beneficial and harmful microbes. It recognizes microbe-associated molecular patterns (MAMPs) through pattern recognition receptors (PRRs), leading to immune responses that control microbial load [43].

Beneficial root microbes may also indirectly solidify plant defenses against herbivores by attracting predators [44]. On the other hand, bacterial endophytes in agricultural crops, initially seen as weak pathogens, are now recognized for promoting plant growth and enhancing resistance against pathogens and parasites [45].

Furthermore, the importance of beneficial symbionts extends to pest control in agriculture with examples like *Photorhabdus* bacteria, insecticidal symbionts of nematodes, being employed for managing plant pests and pathogens [46].

The link between environmental conditions and the behavior of endophytes remains a complex, interactive relationship. While there is recognitionthat the environment can determine whether an endophyte behaves as a harmful pathogen or advantageous symbiont, a thorough understanding of this relationship remains elusive [47]. Researchersneed to delineate the specific environmental factors, both biotic and abiotic, that influence an endophyte's behavior. Multi-dimensional experiments aimed at isolating different environmental variables could shed a great deal of light on these interactions. Additionally, the role of climate change and how alterations in environmental stability might disrupt the plant-symbiont relationship is worth exploration.

Recent research notes the existence of the common symbiotic pathway (CSP), a set of plant proteins presumed to transduce signals from beneficial microbes [48]. However, how this pathway distinguishes between beneficial and harmful symbionts is still unclear. Studies could explore the function and mechanism of this CSP and how it interfaces with the plant's immune recognition systems including microbe-associated molecular patterns (MAMPs) and pattern recognition receptors (PRRs) [49]. Researchers should consider not only genetic and molecular investigations but also cross-disciplinary approaches, such as computational biology (e.g., Docking and Bioinformatics), which could simulate these complex interactions.

1.5 Types of Plant Symbiosis

Several types of plant symbiosis are shared across multiple studies, including mycorrhizal symbiosis, endosymbiotic relationships with nitrogen-fixing bacteria, symbiosis with ant, and ericoid mycorrhizal symbiosis.

Mycorrhizal symbiosis involves a relationship between fungi and plant roots, and it significantly influences plant performance. One study specified four distinct types of mycorrhizal symbiosis: ectomycorrhizae, ericoid mycorrhizae, arbutoid mycorrhizae, and arbuscular mycorrhizae, found in alpine plant species of the Rocky Mountains [50]. These mycorrhizal associations are also seen to be affected by human impacts, such as increasing urbanity and alterations in plant species distribution ranges [51].

Arbuscular mycorrhizal (AM) symbioses are distinguished into two types: Arum-type and Paris-type. The latter is seen in *Eustoma grandiflorum* where gibberellin (GA) is found to promote fungal colonization, contrasting its inhibitory role in Arum-type [52, 53]. Specific genes such as the receptor-like kinase gene SymRK have also been reported to play a crucial role in arbuscular mycorrhiza fungi interactions [54].

Nitrogen-fixing endosymbiosis involves cyanobacteria from the order *Nostocales* and various plant species - these cyanobacteria provide fixed nitrogen and other beneficial compounds to the host plant [55].

Besides, another diversity of symbiosis in plants involves ants. Although no specific details were provided in the extracts, one of the studies mentions its role in plant performance growth responses [56].

Lastly, ericoid mycorrhizal (ErM) symbiosis involves fungus and ericaceous plants like blueberry and cranberry. These fungi enhance plant tolerance to various stresses and positively influence plant establishment and growth [57] (**Fig. 2**).

Some species of symbiotic microbes reportedly undergo changes that increase the efficiency of the symbiosis from the plant's perspective, a phenomenon termed as 'altruistic symbiosis.' This aspect of microbial behavior merits a more detailed exploration. The molecular mechanisms responsible for this change, how it's triggered, and the cascade of events leading to increased efficiency in symbiosis can be investigated [58].

A comparative study of such organisms with conventional strains could reveal fascinating insights into the factors promoting this 'selfless' behavior, and it may even offer genetic manipulation possibilities to induce such behaviors in other symbiotic relations. It's crucial not only for better understanding the depths of microbial behavior complexity but also to potentially improve the efficiency of natural resource use in plants and to explore other potential applications in environmental sustainability [59].

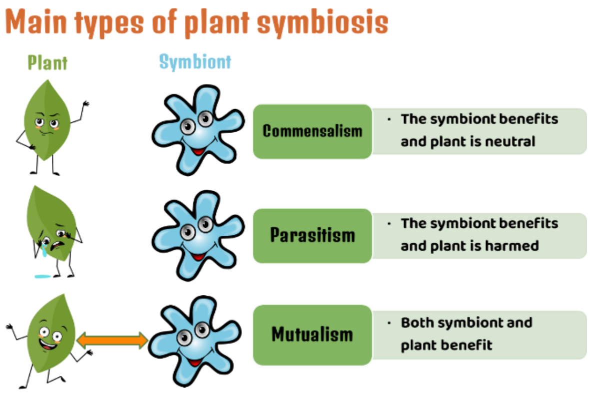

Figure 2. Plants can have different types of partnerships with other creatures; These types of partnerships show the diverse and complex interactions plants have with their environment!

- **Commensalism:** Like **epiphytes** (air plants) growing on trees. The epiphyte benefits from the support and access to sunlight, while the tree isn'tharmed.
- **Parasitism:** Like **mistletoe** stealing water and nutrients from the tree it grows on.
- **Mutualism:** Like ***Rhizobium* bacteria** living in legume roots. The bacteria fix nitrogen for the plant, and the plant provides sugars for the bacteria.

With the rising threat of pests and diseases to plants, understanding their defensive mechanisms is crucial. Certain protective responses are triggered in plants on encountering a symbiotic organism or pathogen, such as the production of plant volatiles and phenolic compounds. Understanding the mechanisms that trigger these responses could aid in developing methods to stimulate these protective measures, making the plants more resilient [60].

Furthermore, the correlation between the presence and absence of specific volatile-phenolic compound combinations with specific strains of beneficial or pathogenic microbes could be explored. This information could aid in precise and quicker identification of plant health and disease, leading to the formulation of more effective and quicker disease mitigation strategies. Potential applications of these naturally produced compounds could be explored in other areas, such as pesticide development and the food industry [61].

2. Microbial biofertilizer application in agriculture

The application of microbial biofertilizers in agriculture is seen as a promising method for enhancing productivity sustainably, potentially reducing the reliance on agrochemicals. The global market for these microbial products is expanding rapidly, including various biofertilizers and biopesticides that leverage microbial tools [62].

There is particular interest in combining nanotechnology and biotechnology to produce nano-biofertilizers that may increase plant nutrient uptake and improve soil health. Synthesis methods, applications modes, and the interactions between nanoparticle and bacterial species in these specialized fertilizers are among the focal points of recent research [63]. Meanwhile, plant growth-promoting microorganisms (PGPMs) are being used either alone or in combination with plant biostimulants (PBs) to enhance fruit quality and prevent soil degradation. This approach supports the creation of sustainable and productive agricultural systems that maintain soil fertility and biodiversity [64].

Plant rhizosphere microbes can promote plant growth and offer other benefits, such as suppressing diseases and increasing nutrient uptake [65], making them effective alternative tools for sustainable agriculture practices. Furthermore, the growing understanding of plant-microbe interactions and the exploration of synthetic microbial communities could guide the creation of advanced microbial inoculants for agriculture [66].

Microbes are also explored in biobed systems to degrade pesticide residue [67] and are used to address nutrient leaching, a problem exacerbated by increased fertilizer use, especially in developing countries like India. Two studies demonstrated that enriched microbial consortia could sequester excess nutrients within a biomass applied as a biofertilizer, thus preventing nutrient leaching and enhancing crop yields [68].

2.1 Biofertilizer Application Methods: Delivering Microbial Allies to Plants

Biofertilizers, composed of beneficial microorganisms, offer a sustainable and eco-friendly approach to enhancing plant growth and health. But how do we effectively deliver these microbial allies to their plant partners? Here are some key methods of biofertilizer application (**Fig. 3**).

2.2 Seed Inoculation

- This is the most common and an efficient method for applying biofertilizers, particularly for seed-borne microorganisms like *Rhizobium* sp. and PGPB.
- The process involves mixing the biofertilizer with a sticker solution like jaggery or gum Arabic and coating seeds before sowing.
- This ensures close contact between the microbes and the seeds, facilitating colonization and establishment of the symbiotic relationship upon germination [69].

2.1.1 Seedling Root Dip

- This method is suitable for transplanting seedlings, especially vegetables and fruit trees.
- The roots of healthy seedlings are dipped into a solution containing the biofertilizer for a predetermined period, typically 30 minutes to an hour.
- This allows the microbes to adhere to the root surface, increasing the likelihood of colonization and establishing beneficial interactions with the plant [70].

2.1.2 Soil Application

- This method involves directly incorporating the biofertilizer into the soil, either before planting or during crop growth stages.
- While less targeted than seed or seedling application, it can be beneficial for establishing soil microbial communities and promoting overall plant health.
- However, higher application rates are often required compared to other methods due to potential losses through soil interactions and competition with native microbial populations [71].

2.1.3 Foliar Application

- This method involves spraying the biofertilizer solution directly onto the leaves of growing plants [72].
- While less common, it can be beneficial for specific applications, such as delivering biocontrol agents to combat aerial plant diseases.

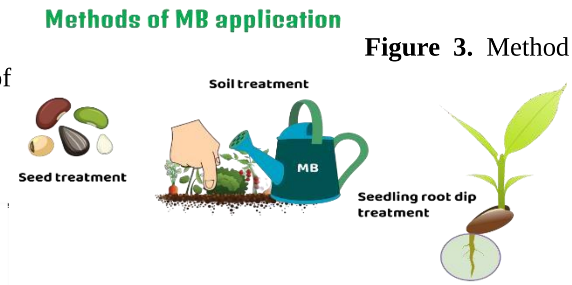

Figure 3. Method of microbial biofertilizer (MB) application.

3. Additional Considerations

- **Compatibility with other Agricultural Practices:** It's crucial to ensure compatibility between the chosen biofertilizer application method and other agricultural practices like pesticide or herbicide use.
- **Dosage and Timing:** Following the recommended dosage and application timings provided by the biofertilizer manufacturer is essential for optimal results.
- **Environmental Conditions:** Factors like temperature, moisture, and soil type can influence the efficacy of biofertilizer application. Considering these factors can help optimize the delivery and establishment of beneficial microbes.

By understanding these application methods and considering the specific needs of the plant-microbe system, farmers and growers can effectively utilize biofertilizers to promote sustainable and productive agricultural practices [73].

To conclude, microbial biofertilizers have emerged as a critical tool for sustainable agriculture. They provide not only an eco-friendly alternative to traditional agrochemicals but also offer practical potential benefits, such as enhancing plant growth, preventing soil degradation, and mitigating pesticide pollution. Further research is needed to fully exploit their potential and address challenges such as inconsistent performance in field conditions and the risk of introducing antibiotic-resistant microbial flora through the application of biofertilizers [74]. The collaborative studies of synthetic microbial communities and nano-biotechnology may lead to future advancements in the deployment of microbial biofertilizers in agriculture [75].

Given the increasing interest in blending nanotechnology with biotechnology, understanding and harnessing the interactions between nanoparticles and bacterial species is crucial for the optimal functioning of microbial nano-biofertilizers. One could focus on synthesizing nanoparticles that offer the most advantageous effects on bacterial growth,colonization, and nutrient acquisition [76]. The key forthe researcher would be to determine the optimal size, shape, composition, and coating of nanoparticles and to thoroughly explore their mechanisms of action on microbes [77].

As the understanding of plant-microbe interactions grow, it is important to delve deeper into designing synthetic microbial communities that provide the most benefits to plant health and growth. Questions can be focused on identifying the appropriate mix of microbes that synergistically facilitate plant productivity, and how to engineer these communities to ensure stability and consistency in field conditions [78].

There are challenges associated with nutrient leaching in areas of high fertilizer use, particularly in developing countries. Research into enriched microbial consortia that can sequester excess nutrients within a biomass offers a potential solution, as they can prevent nutrient leakage and enhance crop yields. Research focus can be on constructing efficient consortia, the practical application of such solutions in developing countries, their socioeconomic implications and possible side effects [78].

4. Future Perspectives

Current research trends and advancements in the study of plant beneficial symbionts involve various techniques and approaches. These include analyzing plant microbiomes, studying the genes encoded by plant growth-promoting bacteria (PGPB) through DNA genome sequencing, and investigating gene expression using transcriptomics, proteomics, and metabolomics [78, 79]. Additionally, researchers are exploring the use of genome editing to modify PGPB, encapsulating PGPB inoculants for plant treatment, and imaging techniques to visualize plant-bacteria interactions [79]. The study of symbiotic partners through transcriptome analysis has revealed the modulation of gene expression and unique functional metabolic pathways in symbionts [80]. Challenges remain in understanding the complex relationships between plant beneficial symbionts and plants [81]. These include deciphering the mechanisms of codependency, physiological adaptation to different environments, and the influence of hosts on symbiont evolution [82, 83, 84]. Further research is needed to develop clear expectations for how hosts influence microbial niches and genomes in different symbiotic lifestyles.

4.1 Unlocking the Future of Agriculture

The reliance on chemical fertilizers and pesticides in modern agriculture has disrupted the delicate balance of the phytomicrobiome, leading to environmental concerns and declining soil health. Harnessing the power of beneficial symbionts offers a sustainable alternative to conventional practices. By encouraging and manipulating these natural partnerships, we can improve crop yields, reduce reliance on chemicals, and promote soil health. Research is exploring techniques like microbial inoculants and targeted microbiome manipulation to cultivate beneficial microbes and unlock their full potential for sustainable agriculture [85, 86].

With growing concerns about food security and the environmental impact of traditional agriculture, plant beneficial symbionts could serve as organic alternatives to chemical fertilizers and pesticides. However, best practices for their integration into farming systems are still in the infant stages. How can we harness the power of these symbionts most effectively while ensuring the balance of the ecological system? What kind of crops benefit most from specific symbionts? How can we tailor symbiont use for different geographic and climatic conditions? All are areas of potential investigation that could lead to practical solutions for sustainable and resilient agriculture systems [87].

4.2 Contemporary Significance

In today’s world, the significance of plant beneficial symbionts has magnified amidst pressing global challenges such as food security, climate change, and the need for sustainable agricultural practices. The contemporary understanding goes far beyond the early fascination with nitrogen fixation and nutrient uptake [87].

Now, we recognize phytomicrobiome members—including mycorrhizal fungi, rhizobia, and others—as key players in:

1. Carbon Sequestration: Plant beneficial symbionts play roles in carbon capture and soil carbon storage, critical processes in mitigating the effects of climate change [88].
2. Sustainable Agriculture: The application of these symbionts in agroecosystems promotes plant growth, improves soil health, and reduces dependency on chemical fertilizers and pesticides [89].
3. Soil Health and Biodiversity: Symbionts help create a more robust and resilient soil ecosystem, which is essential for both crop production and the preservation of natural plant communities [90].
4. Bioremediation: Certain symbiotic fungi and

bacteria have been used to degrade or sequester pollutants in the soil, contributing to environmental cleanup efforts [91].

5. Plant Stress Tolerance: Enhancing a plant's resilience to stresses such as drought, salinity, and pathogens through symbiotic relationships could be vital in adapting to changing climatic conditions [91].

6. Discovery of Novel Compounds: Symbiotic organisms can synthesize bioactive compounds that may have pharmaceutical applications or could serve as biostimulants and biopesticides in agriculture [92].

In recent decades, symbiont research has also become a hotspot for cutting-edge technologies like genomics, proteomics, and metabolomics, providing deeper insights into the molecular dialogues between plants and their symbiotic partners. Additionally, the sustainability aspect of using plant symbionts aligns with the global goals for environmental conservation and responsible agricultural practices [93].

The historical study of plant beneficial symbionts has transitioned from observed phenomena to a detailed understanding of complex interactions that underpin ecosystem functionality and support human agricultural activities. These organisms, once merely curiosities or tools for improving crop yields, are now recognized as essential contributors to the health of the planet and its inhabitants. Their continued study is paramount as we work towards a more sustainable and resilient future [94].

5. Conclusion

The charming members of the phytomicrobiome are not just passive passengers; they are active participants in the drama of plant life. By understanding their history, diverse roles, and potential for defense and growth enhancement, we can unlock a new era of sustainable agriculture. As we move forward, let us remember the hidden universe within each plant, teeming with life and holding the key to a healthier, more resilient future for our planet.

Despite the known benefits of PBMs, the specific mechanisms by which these organisms contribute to plant health and growth are yet to be fully understood. Research should aim to delve deeper into the symbiotic relationship between PBMs and plants. This may include investigations into the molecular, biochemical, and physiological interactions. Gaining more detailed insights will help not just in devising better usage strategies of these organisms but also unravel potentially

The efficacy of PBMs is a significant factor influencing their adoption in the field. Some strains may produce remarkable results in a laboratory setting but may not maintain the same efficacy in open fields. Therefore, studies could be conducted to understand this discrepancy. Future research could investigate the adoption process and obstacles, identify potential strategies for enhancing consistency (such as co-culturing with other complementary organisms), and explore methods of improving field application.

Regulatory hurdles are one of the challenges in the widespread use of beneficial microbes. As each country has its own set of regulations regarding biocontrol agents, navigating this landscape could be tricky. Future research should explore how these regulations can be streamlined or refined to support better adoption of PBMs. Investigations could also assess the safety and potential impacts of these organisms on non-target organisms, human health, and the environment. This will aid in establishing better frameworks for the evaluation and approval of these potential biofungicides and biofertilizers.

In summary, beneficial microorganisms offer significant advantages to plant health and productivity. Their diverse roles range from promoting soil health, aiding in nutrient mobilization, providing disease resistance, to possibly altering plant metabolome. Research continues to optimize the use of these organisms in the field, paving their way to support sustainable agriculture and forestry.

Conflict of Interest Disclosure: Author/s disclose that there is no financial or non-financial conflicts of interest that could potentially affect the research or its interpretation.

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