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Phyllosphere Microbiome: Its Role in Plant Health and Ecosystems

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Abstract

The phyllosphere, comprising the aerial components of plants, represents a dynamic and heterogeneous habitat for diverse microbial communities. Leaves, flowers, stems, fruits and pollen provide distinct microhabitats that are colonized by epiphytic microorganisms, while endophytes inhabit internal plant tissues. Phyllosphere microbiota originates from diverse sources, including soil, seeds and air, and are subsequently shaped by host characteristics and environmental conditions. Despite exposure to intense solar and ultraviolet radiation, fluctuating temperature and moisture, and limited nutrient availability, microbial communities persist through specialized adaptations. They contribute to plant nutrition through biological nitrogen fixation and mineral solubilization, influence growth and development through plant-growth regulators and protect plants against pathogens through competition, antibiosis and modulation of host defence. Phyllosphere microorganisms also participate in volatile-compound transformation, biogeochemical cycling and phylloremediation, highlighting their broader ecological and biotechnological significance.

Keywords: Phylloremediation, Phyllosphere microbiome, Plant health, Plant-microbe interactions

Introduction

The phyllosphere is a general term used to describe the aerial components of plants, including leaves, flowers, stems, fruits and pollen. Each of these structures possesses distinct morphological and physicochemical characteristics that influence microbial colonization. The phyllosphere consequently represents a mosaic of specialized microbial habitats rather than a uniform plant surface. Microorganisms occurring on the external surfaces of these structures are generally referred to as epiphytes, whereas microorganisms inhabiting internal plant tissues, including plant cells and intercellular spaces or apoplasts, are termed endophytes (Sohrabi *et al.*, 2023).

Phyllosphere microorganisms can originate from several sources, including soil, seeds, rainwater and the atmosphere, and may colonize plants at different stages of development. Their establishment is governed by dispersal, host characteristics, nutrient availability and interactions with other microorganisms. Once established, microbial communities are exposed to environmental conditions that are considerably more variable than those encountered in many other plant-associated habitats.

The leaf surface, in particular, constitutes a challenging environment because of intense solar and ultraviolet (UV) radiation, fluctuations in temperature and humidity, intermittent water availability and relatively limited supplies of readily available nutrients. Nevertheless, phyllosphere microorganisms have evolved diverse mechanisms that enable them to survive and colonize this habitat. Production of UV-protective pigments, extracellular polymeric substances, biofilms and other protective compounds can reduce environmental stress and facilitate microbial persistence on plant surfaces (Bashir *et al.*, 2022).

Thus, the phyllosphere should be viewed not simply as a physical surface inhabited by microorganisms, but as an active ecological interface where plants, microorganisms and the atmosphere interact. Through these interactions, the phyllosphere microbiome can influence plant nutrition,

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growth, defence and environmental adaptation, while also contributing to ecosystem-level processes.

Composition of the Phyllosphere Microbiome

The phyllosphere harbours taxonomically and functionally diverse microbial communities, including bacteria, filamentous fungi, yeasts, cyanobacteria, actinobacteria, archaea, viruses and, in lower abundance, protists and nematodes (Bashir *et al.*, 2022). Among these groups, bacteria are generally the most abundant and may occur at densities of approximately 10^6-10^8 cells cm^{-2} of leaf tissue.

The bacterial community includes several major taxonomic groups, notably Proteobacteria, Bacteroidetes, Firmicutes and Actinobacteria. Methylotrophic bacteria constitute an ecologically important component of the phyllosphere because they can utilize carbon-containing compounds released by plants. Representative genera include *Methylobacterium*, *Hyphomicrobium*, *Methylibium*, *Methylocapsa*, *Methylocella*, *Methylophilus* and *Methylocystis* (Bashir *et al.*, 2022).

The relative abundance and functional contribution of these microbial groups are not constant. Instead, phyllosphere communities are shaped by the characteristics of their host plants, environmental conditions, geographical location and seasonal variation. Consequently, the same plant species may harbour different microbial assemblages under different environmental conditions.

Factors Influencing Phyllosphere Microbial Communities

Phyllosphere microbial communities are highly dynamic and their composition is determined by interactions among host identity, plant traits, geographical location, seasonality and environmental conditions. Pollution and other anthropogenic disturbances may further modify microbial diversity and community structure (Bashir *et al.*, 2022).

Host plants can exert strong selective effects on their associated microbiota through differences in leaf morphology, chemistry, nutrient composition and physiological characteristics. An important demonstration of this relationship was provided by Kembel *et al.* (2014), who examined phyllosphere bacterial communities associated with 57 tree species in a Panamanian neotropical forest. They found significant associations between microbial community composition and several host characteristics, including wood density, leaf mass per area, leaf thickness, leaf nitrogen and phosphorus concentrations, as well as plant growth and mortality rates. These findings indicate that plant functional traits can contribute substantially to the assembly and organization of phyllosphere microbial communities.

Environmental variability further modifies these interactions. Changes in temperature, humidity, solar radiation and rainfall can alter microbial abundance and activity, while air pollutants and other anthropogenic factors may favour or suppress particular microbial groups. The resulting microbiome is therefore a dynamic product of both plant-mediated selection and environmental filtering (Bashir *et al.*, 2022).

Functions and Ecological Roles of the Phyllosphere Microbiome

Phyllosphere microbial colonization can influence plant productivity and health at various scales, ranging from individual plants to terrestrial ecosystems. The major ecological functions of leaf-surface microorganisms are summarized in figure 1. These effects arise through interactions involving nutrient acquisition, plant growth, pathogen suppression, environmental stress tolerance and biogeochemical processes.

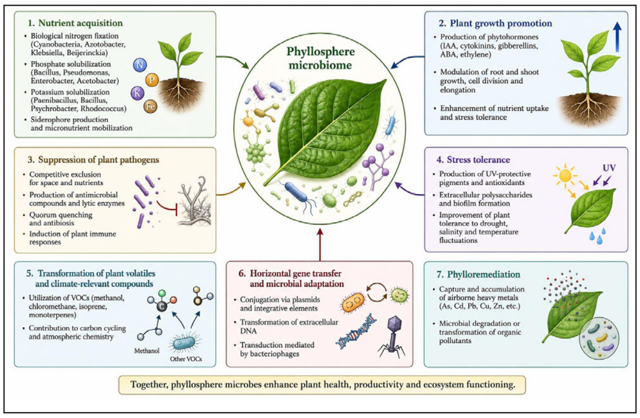

Figure 1: Ecological functions of leaf-surface (phyllosphere) microbes

Role in Plant Health

1. Nutrient Acquisition

One of the most extensively investigated functions of phyllosphere microorganisms is their contribution to nutrient acquisition. Biological nitrogen fixation is particularly important because certain diazotrophic microorganisms can convert atmospheric nitrogen (N_2) into biologically available forms. Nitrogen-fixing microorganisms reported from the phyllosphere include cyanobacteria such as *Nostoc*, *Stigonema* and *Scytonema*, together with bacterial genera such as *Azotobacter*, *Klebsiella* and *Beijerinckia* (Bashir *et al.*, 2022; Sohrabi *et al.*, 2023).

Phyllosphere microorganisms may also enhance the availability of phosphorus and potassium. Several bacterial taxa, including species of *Bacillus*, *Acetobacter*, *Pseudomonas*, *Enterobacter*, *Arthrobacter*, *Klebsiella* and *Paenibacillus*, have been reported to possess phosphate- or potassium-solubilizing abilities (Bashir *et al.*, 2022). Such activities can increase the availability of otherwise poorly accessible mineral nutrients and thereby contribute to plant nutrition and productivity.

Siderophore production provides another mechanism by which phyllosphere microorganisms can influence nutrient availability. By chelating iron and modifying its availability, siderophore-producing bacteria may improve micronutrient acquisition while simultaneously restricting iron availability to competing microorganisms, including some plant pathogens.

2. Suppression of Plant Pathogens

The phyllosphere microbiome can act as an important biological barrier against foliar pathogens. Beneficial microorganisms employ several complementary mechanisms, including competitive exclusion, antibiosis, nutrient sequestration, quorum quenching and stimulation of plant defence responses (Bashir *et al.*, 2022).

Competition for nutrients and physical colonization sites can restrict the establishment of pathogens, while antimicrobial compounds directly inhibit their growth. Certain *Streptomyces* species, for example, produce antifungal and antibacterial metabolites, including streptomycin and 1-H-pyrrole-2-carboxylic acid (PCA), which can suppress a range of plant-associated pathogens.

Microorganisms may also protect plants indirectly by modifying host physiology. The endophytic bacterium *Enterobacter aerogenes* associated with maize (*Zea mays*) has been reported to produce 2,3-butanediol, a microbial volatile compound associated with plant growth and induced resistance against phytopathogens. Such interactions demonstrate that microbial protection may involve both direct antagonism of pathogens and indirect activation of host defence mechanisms.

3. Modulation of Plant Growth and Phytohormones

Phyllosphere microorganisms can influence plant growth and development through the production, degradation or modulation of plant growth regulators, including auxins, cytokinins, gibberellins, ethylene and abscisic acid (ABA). These interactions can influence cell division, cell elongation, stomatal behaviour and plant responses to environmental stress (Bashir *et al.*, 2022).

ABA-mediated regulation of stomatal behaviour is particularly relevant to drought tolerance because stomatal closure can reduce water loss under conditions of water limitation. Microorganisms may influence such hormone-dependent responses and thereby modify plant adaptation to environmental stress.

Methylotrophic bacteria belonging to the genus *Methylobacterium* provide a well-known example of plant-microbe interaction involving phytohormones. These bacteria utilize methanol released from plant tissues, particularly during plant growth and cell-wall expansion, and some strains can produce cytokinins and other growth-promoting compounds. The resulting interaction may benefit both partners by providing the microorganism with carbon while influencing plant growth and development (Sohrabi *et al.*, 2023).

4. Horizontal Transfer and Microbial Adaptation

The phyllosphere may also provide conditions favourable for horizontal gene transfer (HGT) among microorganisms. Leaf-associated microhabitats such as veins, trichomes and stomatal regions can support microbial aggregation and biofilm formation, increasing opportunities for cell-to-cell contact. Such conditions may facilitate conjugation-mediated transfer of plasmids and integrative conjugative elements carrying traits associated with environmental tolerance, antimicrobial resistance or plant colonization.

Environmental stresses can additionally influence other mechanisms of gene exchange. UV radiation and fluctuations in moisture may cause microbial cell damage and lysis, releasing extracellular DNA that can subsequently be taken up by naturally competent bacteria through transformation. Bacteriophages may contribute to gene movement through transduction, while plant-derived compounds can modify microbial growth, competence and prophage activity.

These processes suggest that the phyllosphere can function as an evolutionary arena in which microbial communities exchange genetic information and acquire traits that influence their persistence and ecological performance. However, the ecological consequences of HGT in natural phyllosphere communities require further investigation.

Contribution to Ecosystem Processes

1. Transformation of Plant-Emitted Volatile Compounds

Plants release a diverse range of volatile organic compounds (VOCs), including terpenes, isoprene, monoterpenes and C1 compounds such as methanol and chloromethane. These compounds participate in plant-microbe and plant-environment interactions and can influence atmospheric chemistry.

Phyllosphere microorganisms contribute to the transformation of these compounds by using selected VOCs as sources of carbon and energy. Methylotrophic bacteria, particularly members of the genus *Methylobacterium*, can utilize C1 compounds such as methanol and chloromethane released from plant surfaces. Through these metabolic activities, phyllosphere microorganisms contribute to carbon cycling and influence the environmental fate of plant-derived volatile compounds (Bashir *et al.*, 2022; Sohrabi *et al.*, 2023).

The role of the phyllosphere in atmospheric processes should therefore be understood as part of a broader biological network linking plant emissions, microbial metabolism and biogeochemical cycling, rather than as an independent regulator of global climate.

2. Phylloremediation

Phylloremediation refers broadly to the contribution of plant foliage and its associated microorganisms to the capture, transformation or immobilization of atmospheric contaminants. The large surface area of foliage provides an interface for interaction with airborne particles and gaseous pollutants, while associated microorganisms may transform selected organic compounds.

Evidence also indicates that plant foliage can capture atmospheric heavy metals. Schreck *et al.* (2012) demonstrated the capacity of foliage from species including *Lactuca sativa*, *Petroselinum crispum* and *Lolium perenne* to accumulate metals and metalloids such as arsenic, copper, cadmium, zinc, lead and tin following atmospheric exposure.

The potential of phyllosphere-associated microbial communities for atmospheric depollution is particularly relevant in urban and industrial environments. However, the mechanisms differ among pollutants. Organic compounds may undergo microbial degradation or transformation, whereas heavy metals are primarily captured, accumulated, immobilized or transformed chemically, rather than biologically degraded. This distinction is important when considering the potential of phyllosphere-based approaches for environmental remediation.

Integrating Phyllosphere Functions

The ecological functions described above are interconnected rather than independent. Microorganisms capable of nutrient acquisition may simultaneously promote plant growth; microorganisms that compete with pathogens may also stimulate host immunity; and microbial metabolism of plant-derived compounds may influence both community assembly and ecosystem-level carbon cycling. The principal functional roles of the phyllosphere microbiome and their ecological significance are summarized in table 1.

Table 1: Principal functions and significance of the phyllosphere microbiome

Functional role	Major mechanisms	Ecological significance
Nutrient acquisition	Nitrogen fixation; phosphate and potassium solubilization; siderophore production	Improved nutrient availability
Plant growth promotion	Phytohormone production and modulation	Growth and developmental regulation
Pathogen suppression	Competition; antibiosis; quorum quenching; induced defence	Biological disease suppression
Stress tolerance	Pigments; extracellular polysaccharides; antioxidant and hormonal responses	Microbial and plant adaptation
VOC transformation	Utilization of methanol, chloromethane and other VOCs	Carbon cycling and atmospheric chemistry
Phylloremediation	Pollutant capture, transformation and immobilization	Potential atmospheric pollution mitigation

Source: Bashir *et al*. (2022), Sivakumar *et al*. (2020), Prasad and Varma (2025) and Schreck *et al*. (2012)

Biotechnological Significance and Future Prospects

The functional versatility of phyllosphere microorganisms creates opportunities for developing environmentally compatible approaches to crop production. Nitrogen-fixing and mineral-solubilizing microorganisms may contribute to biofertilization, while antagonistic bacteria and fungi have potential as biological control agents. Microbial production or modulation of phytohormones may further support plant growth and stress tolerance (Bashir *et al.*, 2022; Sivakumar *et al.*, 2020).

The application of phyllosphere microbiomes in environmental management is another promising area. Microorganisms capable of transforming plant-emitted VOCs or selected atmospheric pollutants may contribute to phytoremediation and atmospheric depollution. Nevertheless, the performance of introduced microorganisms under field conditions is influenced by host genotype, environmental fluctuations, resident microbial communities and seasonal changes.

Future research should therefore move beyond the isolation and characterization of individual microbial strains towards understanding microbial consortia, community assembly, host-microbe signalling and microbiome stability. Advances in metagenomics, metatranscriptomics, metabolomics and other high-throughput approaches can help identify functional microbial groups and clarify their contributions to plant health and ecosystem processes.

Conclusion

The phyllosphere represents one of the most extensive and ecologically dynamic microbial habitats associated with terrestrial plants. Its microbial communities are shaped by the interaction of host traits, environmental conditions and microbial relationships and, in turn, influence plant nutrition, growth, defence and environmental resilience.

Phyllosphere microorganisms contribute to biological nitrogen fixation, mineral nutrient mobilization, phytohormone-related processes and pathogen suppression. At broader scales, they participate in the transformation of plant-emitted volatile compounds and contribute to the capture and transformation of atmospheric pollutants. These functions highlight the importance of the phyllosphere microbiome as a component of both plant health and ecosystem functioning.

Harnessing these microbial functions could contribute to sustainable agriculture, biological disease management and environmentally compatible remediation strategies. However, successful application will depend on a better understanding of the complex interactions among plants, resident microbial communities and the surrounding environment. The future of phyllosphere research therefore lies not merely in identifying which microorganisms occur on leaves, but in determining what they do, how they interact and how their collective functions can be sustainably utilized.

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