Phytomicrobiome: An Unexplored Wealth of Plants for The Management of Plant Diseases

Pramesh D[1]*., Usha I[1]., Padma Priya D[1]., Pushpa H[1]., Sharanabasav H[1]., Tulasi M[1]., Prashanth Kumar[1], and Mahanthesh M.T[2].

[1]Rice Pathology Laboratory, AICRP-Rice, Gangavathi, University of Agricultural Sciences, Raichur, Karnataka

[2]College of Agriculture, Gangavathi, University of Agricultural Sciences, Raichur, Karnataka

*Corresponding Author: pramesh84@uasraichur.edu.in

The term "phytobiome" refers to all biotic and abiotic elements that affect the health and production of plants in a given biome, not only the collection of microorganisms associated with a particular plant. Abiotic factors such as soil and climate also impact plants and regulate the presence and function of many organisms interacting with them. Historically, Agriculture and natural systems have been managed by concentrating on specific phytobiome components (e.g., nutrient applications, pesticides, and novel of invasive organisms). To achieve optimum and long-lasting ecosystem production and health, regulating the phytobiome as a whole system of interrelated components is more advantageous. Plant colonization of terrestrial and aquatic habitats ignited the formation of biodiverse systems termed phytobiome. In phytobiome, plants constantly interact with microbial communities adapted to colonize plant tissues, termed microbiomes.

The phytomicrobiome comprises a community of microorganisms that associate and interact with a host plant, including bacteria, archaea, fungi, oomycetes, viruses, protozoa, algae, and nematodes. Collectively, the plant and its phytomicrobiome are a holobiont, a term originally coined by Adolf Meyer-Abich but most frequently associated with and popularized by Lynn Margulis and rigorously explored by Bordenstein and Theis.

The phytomicrobiome includes Parasitic and commensal microbes; it is also comprised of mutualists, or beneficial microbes, such as mycorrhizal fungi (MF) and plant growth-promoting bacteria (PGPB) that enable the plant holobiont to survive within a wide range of environments. Based on habitats, plant-associated microbial communities are referred to as rhizosphere microbiome, rhizoplane microbiome, phyllosphere microbiome, and endosphere microbiome.

The term 'endophytic bacteria' refers to those bacteria that colonize the interior of the plant parts, *viz*., root, stem, or seeds, without causing any harmful effect on the host plant. These bacteria may promote plant growth in terms of increased germination rate, biomass, leaf area, chlorophyll content, nitrogen content, protein content, hydraulic activity, roots, shoot length, yield, and tolerance to abiotic stresses like drought, flood, salinity, etc., Plant associated bacteria can promote plant growth directly through biological nitrogen fixation (BNF), phytohormone production, phosphate solubilization, inhibition of ethylene biosynthesis in response to biotic or abiotic stress (induced systemic tolerance), etc., or indirectly through inducing resistance to the pathogen. Bacteria can be highly competitive for nutrients and produce various antimicrobial metabolites allowing them to colonize and proliferate on plant surfaces in the presence of indigenous microbial communities.

How phytobiome microorganisms involve in plant health and growth:

Different microbiome interacts with host plants and impact plants in various ways. Plant-associated microbial organisms can positively and negatively impact plant growth, development, and health. Beneficial microbes mediate plant holobiont responses to abiotic and biotic stresses and allow the plant holobiont to adapt to environmental variations. The plant host can then modify the abundance and composition of beneficial microbial species within the phytomicrobiome, at least in part, by secreting biochemical compounds. This selection occurs most strongly in the endosphere, followed by the rhizoplane and the rhizosphere. For example, root exudates can select for and promote the growth of certain beneficial microbes by serving as carbon and/or energy sources for microbial metabolism.

Direct impacts on plant growth and development by microorganisms include improved nutrient accessibility such as nitrogen fixation and phosphate solubilization; altered microenvironments such as changed acidity (p^H); and hormonal stimulation (phytohormone production). Microorganisms are also involved in promoting or suppressing plant diseases either directly (such as antibiotics production) or indirectly (*via* disease resistance). In addition to direct antagonism, these organisms also appear to trigger ISR in plants.

Plants depend upon beneficial interactions between roots and microbes for nutrient availability, growth promotion, and disease suppression. The root microbiome is predominantly assembled from the external microbes in the soil. Plants and microbes have adapted to use their close association for mutual benefit. Microbes convert critical nutrients to more usable forms before plants' assimilation. In turn, bacteria in the rhizosphere receive carbon metabolites from the plant through root exudates. Beneficial soil microbes also contribute to pathogen resistance, water retention and synthesis of growth-promoting hormones. Microbial communities associated with plants carry a great diversity of metabolic capabilities and often influence broad aspects of plant biology. In agricultural environments, the composition of these communities affects overall crop performance by contributing to essential plant functions such as nutrient uptake, environmental responses and host development.

Beneficial Microbes Aid Plant Holobionts in Nutrient Acquisition:

As organisms fought for newly discovered resources with the development of oxygenic photosynthesis, species were quickly diversified. However, to help them meet their nutrient needs, plants have historically relied on helpful microbes (specifically bacteria). Beneficial microbes can support plant holobiont nutrition through 1) biological nitrogen fixation (BNF), 2) solubilization of insoluble nutrients, and 3) increased root surface area.

Almost all plants also form interactions with mycorrhizal fungi (MF) to improve nutrient acquisition. MF can increase the effective root surface area and improve nitrogen, phosphorus, iron, and zinc extraction efficiency from the rhizosphere. MF also produces organic acid (e.g., acetic acid, oxalic acid, and succinic acid) exudates that decrease the rhizosphere pH, dissolving insoluble minerals into the soil solution and contributing to greater nutrient acquisition. Simard illustrated that MF facilitates plant "cognition," enabling the plant host to recognize signals from its environment and take action to improve its resistance to stress and general fitness. In addition, MF promotes communication among plants via signaling pathways, contributing to specific changes or overall shifts in plant morphology, physiology, and fitness. It is true that the evolutionary success of a plant and its companion microorganisms are inextricably linked.

Plant holobiont microbiome interactions influence nutrient cycling in the rhizosphere, which in turn influences plant nutritional status and crop productivity in farming environments. For example, arbuscular mycorrhizal fungi create a suitable environment for the colonization of plant growth-promoting bacterial endophytes if inoculated together onto crop plants, and plant root and hyphal exudates provide a carbon source for the bacterial endophytes. Co-inoculation of both fungi and bacteria as a consortium can improve crop yields more than single-strain inoculants.

Microbial Phytohormone Production Promotes Plant Holobiont Growth and Stress Resistance

By producing and delivering plant growth regulators, growth regulatory precursors, or their counterparts, microbial communities found in the rhizosphere can regulate the growth, development, and stress reactions of plant holobionts. These plant-microbe interactions rely on a wide variety of long-distance chemical signaling compounds, including plant hormones (indole-3-acetic acid (IAA), auxins, cytokinins, and gibberellins) and microbial-produced compounds that can mimic or induce plant hormone production. For example, many bacteria produce auxin or manipulate host auxin signaling to, in the case of rhizosphere PGPB, promote plant root growth or interfere with plant development in the case of plant pathogens. A specific example is microbially produced auxins from either pathogenic or mutualistic bacteria, which can influence plant root growth and branching.

Signal compounds, such as thuricin and lipochitooligosacchardies, produced by beneficial microbes can also assist plant adaptation to be biotic and abiotic stresses. For example, When plant cells detect microbial signal molecules, messages are transmitted from stressed tissues to healthy tissues through the plant, enabling the healthy tissues to receive "danger" signals that cause defense-related gene activation. Interestingly, beneficial microbes can also induce resistance in the absence of a phytopathogen, and this may give the plant a stronger defense against upcoming phytopathogenic threats. These shared, interconnected signaling networks are essential for boosting long-term stress adaption at the level of plant holobionts and enable complex and coordinated defense responses to intruders quickly, improving ecological fitness. In a similar way, these signaling substances can support a plant's defensive mechanisms in response to abiotic challenges, including salinity, low temperatures, and drought.

Phytomicrobiome as Biocontrol Agents

Plant holobionts promote the growth of phytomicrobiomes that inhibit pathogens by favoring microbial taxa with biocontrol capabilities. Many examples of *Pseudomonas* spp., *Bacillus* spp., and *Trichoderma* spp. strains, among others, have been described as being capable of plant pathogen biocontrol. The potential to harness and improve this auxiliary plant holobiont immunity underlines the real-world applications of the holobiont concept in our era of agricultural optimization.

Some members of the phytomicrobiome provide either direct or indirect mechanisms of biocontrol. Direct mechanisms involve microbes that discharge different chemicals with antibacterial characteristics. Indirect mechanisms of biocontrol limit the fitness of plant pathogens by reducing their ability to access vital resources. The metal depletion biocontrol mechanism is accomplished through the excretion of siderophores, which chelate soil metals such as iron, copper, and zinc, and funnel them back to the excreting cells using active transport systems. The vulnerable host biocontrol mechanism is subtracted via the production of volatile organic compounds (VOCs) that lead to the establishment of induced systemic resistance (ISR) in infected plants.

There are nevertheless abundant indications of the existence of other holobiont biocontrol systems. All signs point, for example, to phytomicrobiome diversity being key in reducing pathogenic infection efficiency. This phenomenon inherently suggests the existence of yet-to-be-identified pathogen adversaries, a hypothesis supported by analyses of rhizosphere microbiome responses to pathogen-induced root exudation. Genomic and metagenomic analyses have identified many putatively novel pathogen-antagonistic genes in known biocontrol microbes and suppressive soils. Analyses of species-specific and community-wide microbial VOCs have also singled out many compounds that may have the same role. Moreover, VOCs produced by microbes can act as plant growth promoters and signaling molecules between plant holobionts and their rhizosphere communities. Furthermore, as signals, VOCs can be transferred via mycorrhizal networks in the rhizosphere between plants and their neighbors. The production and roles of VOCs are complex and indicate a wide range of roles within the rhizosphere; more information on microbial VOCs can be found in several recent reviews.

Plant microbiota colonizes all plant organs and plays crucial roles, including providing nutrients to plants, stimulating seed germination, promoting plant growth, and defending plants against biotic and abiotic stress.

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