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Microbial Architects of Soil Health: A Multifaceted Approach to Improving Plant Nutrition, Biocontrol, and Phytohormone Production

Neelesh Kumar Maurya

Abstract

The intricate relationship between plants and soil harbours a thriving community of microorganisms, unseen yet essential. Through numerous mechanisms, these microscopic marvels are essential to sustaining the health of the soil and encouraging robust plant growth. Microbes in the soil are essential for enhancing plant nutrition. Bacteria and fungi act as silent collaborators, facilitating the process of solubilizing and mobilizing essential nutrients like phosphorus, potassium, and nitrogen within the soil. This readily available "buffet" of nutrients empowers plants to optimize their uptake and thrive. Furthermore, soil microbes are adept at synthesizing a repertoire of vital enzymes. These enzymes act like biological catalysts, accelerating the decomposition of organic matter and releasing the nutrients trapped within. Thus, they significantly enhance the process of nutrient cycling, resulting in a more efficient and sustainable system. Apart from controlling nutrients, soil microorganisms also function as organic growth accelerators for plants. They synthesize a diverse array of phytohormones, including auxins and gibberellins, which play a central role in plant development. Auxins influence root elongation and cell division, while gibberellins promote stem growth and seed germination. This microbial production of phytohormones creates a favorable hormonal environment within the soil, leading to healthier and more productive plants. Perhaps most compelling is the role of soil microbes as biocontrol agents, offering a sustainable alternative to chemical pesticides. These microscopic warriors employ various strategies to safeguard plants against detrimental pests and pathogens. Competition for resources effectively restricts pathogen growth, while antibiosis involves the production of natural antibiotics that directly target and eliminate harmful microbes. Additionally, soil microbes can induce systemic resistance within plants, strengthening their immune response and enabling them to better combat potential threats. It's crucial to remember that these microbial allies' effectiveness and activity are dynamic. Various factors, including soil pH, moisture content, temperature, and organic matter levels, significantly influence their abundance and functionality. Understanding this interplay is crucial for optimizing soil management practices and maximizing the benefits bestowed by soil microbes. By elucidating the critical roles of soil microbes and the factors influencing their activity, this review underscores their immense significance in maintaining soil health and promoting sustainable agricultural practices. Harnessing this hidden powerhouse's power holds the key to fostering a future where healthy soils nurture healthy plants, ensuring food security and environmental well-being. This review explores the multifaceted contributions of soil microbes, highlighting their significance in sustainable agriculture.

Keywords: soil microorganisms, plant nutrition, enzymes, phytohormones, biocontrol, soil quality, sustainable agriculture, nutrient cycling, plant growth promotion, soil management.

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INTRODUCTION

Soil, the cornerstone of terrestrial ecosystems, is a complex and ever-changing mixture. It combines mineral particles, organic matter, air, and water to create a vital resource for life on Earth. Over vast timescales, soil forms through the breakdown of rocks and minerals, enriched by the ongoing contribution of organic materials from plants and animals [1]. This intricate blend plays a critical role in the environment, functioning as a foundation for plant growth, a filter for water, and a reservoir for essential nutrients. It helps provide nutrients and water for plants and also filters and cleans water. Also, soil helps store carbon, which is essential for regulating the climate [2, 3]. Different factors, such as climate, topography, and parent material, influence an area's soil type. We use soil as a crucial human resource to grow food, raise livestock, and build our homes. Recreational activities, forestry, and mining also utilise soil. Soil has some essential functions, including supporting plant growth, filtering and cleaning water, storing carbon, and providing habitat for wildlife. Soil microbes are vital to soil health and play a role in many processes, such as decomposition, nutrient cycling, soil structure, and plant health [2, 4]. Soil microbes also help with other crucial ecosystem processes, such as carbon sequestration and water purification. Within this microbial community, specific bacteria possess the remarkable ability to fix nitrogen from the atmosphere. This captured nitrogen becomes readily available for plant growth, significantly boosting crop production. Additionally, some soil microorganisms excel at solubilizing phosphorus, another crucial nutrient for plant health. Moreover, some soil microorganisms can suppress plant pathogens, which is essential for maintaining healthy crops and fields [56]

Soil Microbiology

Soil microbiology is the study of soil microorganisms, their functions, and their influence on the soil's characteristics. The structure and fertility of soil depend on microorganisms. Both plants and microbes obtain the nutrients they need from the soil, which they then modify through the deposition of organic litter and the activity of their metabolic systems [6]. Microbes are responsible for a variety of direct effects on plants, including the manipulation of hormone signaling and the protection of plants from disease-causing organisms. Microorganisms' role in the carbon, nitrogen, and other nutrient cycles gives them their significance in the soil [8–10]. This cycle affects the composition and fertility of various soils. They are also responsible for preserving the soil's quality and overall health, increasing soil aeration and penetrability, and preventing disease spread [5]. Microbes in the soil have several essential functions, including preventing and treating illness, maintaining adequate nutrient levels in the soil, and promoting mutually beneficial relationships between plants and soil microbes. Additionally, soil microbes are responsible for the creation of soil structure, nitrogen fixation, nutrient recycling, plant growth promotion, and pest and disease control. Soil flora, or microflora, comprises bacteria, fungi, actinomycetes, and algae. Soil fauna, known as microfauna, comprises protozoa, nematodes, earthworms, moles, ants, and rodents. Aerobic bacteria make up seventy percent of the soil's total population. In contrast, anaerobic bacteria make up thirteen percent, actinomycetes make up thirteen percent, fungi make up three percent, and algae, protozoa, and viruses make up between two and eight percent. Bacteria are the tiniest organisms that can live independently and only consist of a single cell. They contribute to the carbon cycle in agricultural soils through photosynthesis and decomposition, meaning they play a vital role [8]. This article will discuss bacteria relevant to farming, such as Rhizobium and actinomycetes, among many others. Fungi belong to the eukaryote kingdom, meaning their cells possess membrane-bound structures like mitochondria for energy production. A unique characteristic of fungal cells is their cell wall, which is composed primarily of glucans and chitin. Fungi are essential to the functioning of the global carbon cycle; they are also responsible for the production of plant hormones, the release of nutrients from soil minerals, the capture of nematodes damaging to plants, and the dominance of fungi in the soil biomass. There is a group of bacteria known as actinomycetes, and they are very similar to fungi in many respects [9, 10]. They are vital contributors to soil creation due to their involvement in the breakdown of organic matter in the soil. The former can increase the amount of organic matter in the soil, decrease the amount of tilling done, plant cover crops, and refrain from using pesticides to support soil bacteria growth [5].

Role Of Soil Microorganisms

Microscopic marvels Within the soil, microorganisms play an indispensable role in the soil ecosystem. They significantly impact soil fertility by influencing nutrient cycling and maintaining overall soil health. Their diverse functions are essential for various ecological and agricultural processes [5].

THE KEY ROLES OF SOIL MICROORGANISMS:

Decomposition

The most important decomposers are the microorganisms that live in the soil, such as bacteria and fungi. They are responsible for the breakdown of organic debris, such as dead plants, leaves, and animal remains, into simpler compounds, which allows nutrients to be released into the soil. This process of decomposition is necessary for the recycling of nutrients and the formation of organic matter, such as humus, which has the effect of improving the structure of the soil. The process by which organic matter in the soil is broken down into materials that are easier to understand is referred to as oil decomposition. This process is necessary for the health and productivity of the soil, as it releases nutrients that are necessary for the growth of plants. The process of soil decomposition is carried out by a wide variety of species, including bacteria, fungi, and macrofauna such as earthworms and termites [89]. These organisms use a variety of ways to decompose organic materials, including the following: (a) Enzymatic breakdown: Microorganisms are responsible for the production of enzymes, which function to convert more complicated organic compounds into simpler ones. In the event of a physical breakdown, it is [8]. Organic matter is physically broken down by macrofauna, who do so by shredding it and then consuming it [8]. Composting is the process by which microorganisms break down organic materials with oxygen, resulting in the production of compost. The nutrients that plants require can be found in abundance in compost [8, 10]. The following are some of the factors that influence the pace of soil decomposition: a. The category of organic matter comprises: Compared to other types of organic matter, such as cellulose and lignin, sugars and amino acids are disintegrated at a faster rate than other types of organic matter. (b) The amount of moisture that is present in the soil: Moisture is essential for the survival and reproduction of microorganisms. In moist soils, the rate of soil decomposition is significantly higher than in dry soils. as in (c). The temperature of the soil is: Microorganisms are more active in soils that are warm as opposed to warmer soils. It is (d). In terms of the soil's pH, soils that are somewhat acidic are preferred by microorganisms. When soils are alkaline, the rate of soil breakdown is slower. It is (e). In the presence of oxygen, there is growth. Oxygen is essential for the decomposition of organic materials by microorganisms [13]. In aerated soils, the rate of soil decomposition is significantly faster than in waterlogged soils. The following are some of the vital reasons why soil decomposition is necessary: This is because it causes the release of nutrients that are necessary for the growth of plants. It is (b). The structure of the soil and drainage have both improved. as in (c). Insects and pathogens are both repelled by its presence. It is (d). It encourages the growth of plants. (e) It greatly assists in the elimination of contaminants. It is (e). This is an important part of the process of carbon sequestration [1415].

Nutrient Cycling

Microorganisms play an active role in the process of cycling key nutrients within the soil. These nutrients include carbon, nitrogen, phosphorus, and sulphur. The nitrogen-fixing bacteria, for example, are responsible for converting the nitrogen in the atmosphere into a form that plants can use. Additionally, mycorrhizal fungi assist plants in gaining access to phosphorus and other minerals. It is essential for plant growth and the general productivity of the environment that this nutrient cycle takes place. The process by which important nutrients are moved, altered, and recycled within the ecosystem of the soil is referred to as soil nutrient cycling. For the purpose of preserving the fertility of the soil and fostering the growth of plants, this cycle of nutrients is absolutely necessary [15]. The microorganisms that live in the soil are extremely important to these activities. A brief summary of the nutrient cycle in soil is as follows: This is a. The amendments are the nutrient inputs. A number of different processes, such as atmospheric deposition, the breakdown of organic matter, the weathering of minerals, and the addition of fertilizers or organic amendments, are responsible for the introduction of nutrients into the soil. b. The incorporation of nutrients by plants: Through the use of their roots, plants are able to absorb nutrients from the soil. There are two types of nutrients that are considered essential: macronutrients, which include nitrogen, phosphorus, and potassium, and micronutrients, which include iron, zinc, and copper. Phosphorus is the nutrient that arises from the discharge of organic materials. Microorganisms in the soil, principally bacteria and fungi, are responsible for the decomposition of organic materials, which results in the creation of simpler chemicals. As a result of this process, the nutrients that are present in the organic matter are returned to the soil. For instance, the breakdown of dead leaves results in the release of nutrients such as carbon, nitrogen, and phosphorus into the environment. It is (d). activities related to mineralization [16]. The NO3 Through the process of microorganisms, organic forms of nutrients are transformed into inorganic forms, which are then accessible to plants for absorption. For instance, microbial activity can convert organic nitrogen into ammonium ($NH4+$) and nitrate ($NO3$). Both of these compounds are nitrogen compounds.[16] [16] It is (e). There are situations in which microorganisms briefly immobilize nutrients when they incorporate them into their own biomass. This phenomenon is known as nutrient immobilization. This immobilization can have an effect on the availability of nutrients for plants, but, eventually, the nutrients are released back into the soil as microorganisms die or are killed by predators. The process of nutrient fixation and sorption: Certain minerals found in soil have the ability to bind and keep nutrients in their bodies. Clay minerals, for instance, have the potential to absorb and release nutrients like phosphorus, which can have an effect on the availability of these elements to plants. The formation of symbiotic partnerships: Nitrogen-fixing bacteria, such as Rhizobium, create symbiotic relationships with specific plants, such as legumes, and transform atmospheric nitrogen ($N2$) into ammonium, which plants are able to utilize. Mycorrhizal fungi are beneficial to plants because they increase the root reach of plants, which allows them to acquire phosphorus and other nutrients. a.g. Both nutrient leaching and runoff contribute to pollution [17, 18]. There are two ways that nutrients can be removed from the soil: either by leaching, which is the process by which water transports nutrients deeper into the soil profile or into groundwater, or through surface runoff, which is the process by which nutrients are transported into water bodies. A significant amount of nutrient loss might result in environmental issues such as the contamination of water supplies.17 and 18A. (h). Cycles of nutrients provide feedback: cycling. Changes in climatic circumstances, microbial activity, and plant development can all have an impact on the process of nutrient cycling, which is a dynamic process. The availability of nutrients and their cycle are both controlled by feedback loops in the ecosystem., the health of the soil and the productivity of plants: The efficient cycling of nutrients is extremely important for preserving the health of the soil and fostering the growth of plants. It makes it more likely that plants will obtain the nutrients they require for optimal development, and it has the potential to reduce the amount of synthetic fertiliser that is required in agricultural settings [8, 16, 17].

SOIL STRUCTURE AND AGGREGATION

The Hidden Architects: Microbes and the Power of Soil Aggregation

Within the intricate world of soil, a fascinating dance unfolds between tiny organisms and soil particles. Certain microorganisms, like mycorrhizal fungi and actinomycetes, play a critical role in shaping soil structure through a process known as aggregation. This process involves binding individual soil particles (sand, silt, clay, and organic matter) into larger units called aggregates. These aggregates are like tiny building blocks, creating a more stable and functional soil structure [14]

Microbial contributions to soil structure and aggregation are multifaceted [12–16].

- *Microbial Glue:* Fungi and bacteria, particularly actinomycetes, produce sticky substances like extracellular polysaccharides and glycoproteins that act as natural glues. These bind soil particles together, forming strong and stable aggregates. Fungal hyphae, thread-like fungal structures, further reinforce the structure by creating a network within the soil.

- *Organic Matter Magic:* Microorganisms are nature's decomposers, breaking down organic matter like plant roots and residues. This decomposition process releases byproducts known as humic substances. These byproducts not only improve soil structure but also enhance the stability of existing aggregates.
- **The Benefits of Pores:** Soil aggregates create pore spaces and channels within the soil. These pores allow for better air and water infiltration, promoting healthy root growth. Microbial activity plays a vital role in forming and maintaining these crucial channels.
- *Nutrient Retention Powerhouse:* Aggregates act as tiny storehouses for nutrients. They adsorb nutrients onto their surfaces, preventing them from leaching away and making them readily available for plants and microorganisms [14].

Beyond the Basics [14–16]

The advantages of well-aggregated soil extend far beyond nutrient retention.

- *Erosion Defence:* Strong aggregates shield the soil from wind and water erosion, minimising soil loss.
- *Disease Fighters:* Some soil microbes act as natural bodyguards for plants, suppressing soil-borne diseases by competing with or antagonising harmful pathogens. This microbial activity contributes to overall plant health and a thriving ecosystem.

Sustainable Practices for Healthy Soil

Maintaining and improving soil structure and aggregation is a cornerstone of sustainable land management. Farmers and land managers can adopt practices like reduced tillage and incorporating organic matter to encourage the development of stable aggregates [1215].

Testament to Soil Health

Well-formed aggregates are a hallmark of healthy soil. They promote plant productivity, enhance resilience to environmental stressors like drought and heavy rainfall, and ultimately contribute to a thriving ecosystem. By appreciating the vital role of microorganisms in soil aggregation, we gain a deeper understanding of the importance of maintaining healthy soil for a sustainable future [16–18].

Disease Suppression

Some soil microorganisms can suppress plant diseases by competing with or directly antagonising pathogens. Biocontrol strategies use these beneficial microorganisms to protect crops from harmful pathogens, eliminating the need for synthetic pesticides [19,20].

(a) *Competition for Resources:* Certain soil microorganisms, such as *Bacillus subtilis* and *Pseudomonas fluorescens*, can compete with pathogens for nutrients and space. This competition can hinder the pathogen's ability to establish itself and cause disease.
(b) *Antibiotic Production:* Some soil microorganisms, like *Streptomyces* spp., produce antibiotics that can kill or inhibit the growth of pathogens.
(c) *Inducing Systemic Resistance in Plants:* Microorganisms such as *Bacillus subtilis* and *Trichoderma harzianum* can trigger systemic resistance in plants. This activation of the plant’s own defence mechanisms makes it more resistant to disease.
(d) *Parasitizing the Pathogen*: Certain soil microorganisms, such as *Pythium olibanum* and *Pythium irregulars*, can parasitize pathogens, directly attacking and killing them.

Farmers and gardeners can promote the growth of beneficial soil microorganisms that suppress diseases by:

1. *Adding Organic Matter to the Soil:* Organic matter provides nutrients for soil microorganisms and fosters a favourable environment for their growth.

2. *Reducing Tillage:* Minimising tillage helps maintain the soil ecosystem and protects beneficial soil microorganisms. No-till or reduced-till farming practices are better for soil health and disease suppression.
3. *Planting Cover Crops:* Cover crops protect the soil from erosion and provide habitats for beneficial soil microorganisms.
4. *Rotating Crops:* Crop rotation helps break disease cycles and reduces the risk of disease outbreaks.
5. *Avoiding Excessive Use of Pesticides and Herbicides:* Pesticides and herbicides can harm beneficial soil microorganisms. Limiting their use helps improve soil health and disease suppression.

Examples of soil microorganisms suppressing diseases:

(a) *Bacillus subtilis:* This microorganism can stop many plant diseases, like damping off, Pythium root rot, and Fusarium wilt, by competing with pathogens for resources, making antibiotics, and making plants resistant to them all.

(b) *Pseudomonas fluorescens:* Known for suppressing diseases such as bacterial wilt, crown gall, and take-all, this microorganism competes with pathogens for resources, produces antibiotics, and induces systemic resistance in plants.

(c) *Streptomyces spp.:* These microorganisms produce a range of antibiotics that kill or inhibit pathogens. For instance, *Streptomyces griseus* produces griseolic acid, which can suppress Fusarium wilt and other diseases.

(d) *Trichoderma harzianum:* This microorganism can suppress diseases like damping-off, Pythium root rot, and Rhizoctonia root rot by competing for resources, producing antibiotics, and parasitizing the pathogen [23–25].

Bioremediation: Nature's Clean-Up Crew [31–34]

Certain soil microbes act as tiny bioremediation factories, capable of degrading or transforming harmful pollutants like petroleum hydrocarbons, pesticides, and even heavy metals. These microbial warriors can be employed in two primary bioremediation strategies.

- *In-situ bioremediation:* This approach involves treating contaminated soil directly at the site. We introduce nutrients and/or specific microorganisms to stimulate the soil's natural biodegradation process.
- *Ex-situ bioremediation:* This method involves excavating contaminated soil and treating it in a controlled environment, typically a bioreactor. While more effective, this approach can be more expensive than in-situ methods [32].

Examples of Microbial Bioremediation Powerhouses

- *Bacillus subtilis:* This versatile microbe tackles a range of pollutants by producing enzymes that break them down.
- *Pseudomonas fluorescens:* Another key function is that it not only produces pollutant-degrading enzymes but also competes with these contaminants for resources, further hindering their survival.
- *Rhizobium spp.:* These nitrogen-fixing bacteria form a symbiotic relationship with leguminous plants. They capture atmospheric nitrogen and convert it into a usable form for the plant, reducing reliance on synthetic fertilisers.

Beyond Bioremediation

- *The Power of Plant Symbiosis:* Plants and soil microorganisms often engage in mutually beneficial partnerships known as symbioses. Here are some key examples:
- *Mycorrhizal Fungi:* These fungi form a network around plant roots, enhancing their ability to absorb water and nutrients from the soil. In return, they receive carbohydrates produced by the plant through photosynthesis [33].

- *Nitrogen-Fixing Bacteria:* These bacteria, like Rhizobia, form a close association with legume plant roots. They convert atmospheric nitrogen into a usable form for the plant, while the plant provides them with carbohydrates. This symbiotic relationship benefits both partners [32, 33].

The Nitrogen Cycle:
A Microscopic Marvel

Soil microorganisms play a critical role in the nitrogen cycle, a process essential for plant growth and soil fertility. Nitrogen-fixing bacteria, such as Rhizobium species, are among the key players. These remarkable microbes form symbiotic relationships with leguminous plants (such as beans, peas, and lentils). Through this partnership, the bacteria convert atmospheric nitrogen, which plants cannot use, into a usable form that nourishes them. This process, known as nitrogen fixation, helps reduce reliance on synthetic nitrogen fertilisers, promoting a more sustainable agricultural approach [10].

Unlocking Nutrients and Building Soil Health

Microscopic decomposers within the soil tirelessly break down organic matter, like fallen leaves and dead plant material. This vital process doesn't simply eliminate waste; it transforms it into a valuable resource. The byproducts of decomposition include humus, a stable and long-lasting organic material that plays a multifaceted role in soil health:

- *Improved Soil Structure:* Humus acts like a natural glue, binding soil particles together and enhancing overall structure. This leads to better drainage and aeration within the soil.
- *Enhanced Water Retention:* Humus acts like a sponge, increasing the soil's capacity to hold water, making it more readily available for plants during dry periods.
- *Nutrient Retention:* Humus acts as a reservoir for essential nutrients, preventing them from leaching away and ensuring they are available for plant uptake.
- *Carbon Sequestration:* Humus formation contributes to climate change mitigation by storing carbon captured from the atmosphere within the soil [9].

A Thriving Partnership
Plants and Microbes Working Together

The hidden world beneath our feet is teeming with life, and plants don't go it alone. They engage in fascinating partnerships with various soil microorganisms, forming symbiotic relationships that are mutually beneficial. Here are some key examples:

- *Mycorrhizal Fungi:* These microscopic fungal partners form an intricate network around plant roots, significantly extending their reach for water and nutrients within the soil. In return, the plant provides them with carbohydrates produced through photosynthesis. This symbiotic relationship is a win-win for both partners, promoting healthy plant growth.
- *Nitrogen-fixing Bacteria:* These remarkable microbes, like Rhizobia, have the unique ability to capture atmospheric nitrogen, which is unusable by plants in its raw form. They convert it into a usable form that nourishes the plant. The plant, in turn, provides these bacteria with the carbohydrates they need to thrive. This symbiotic association, particularly with legumes, helps reduce reliance on synthetic nitrogen fertilisers [5].

Beyond Mutualism
Other Plant-Microbe Interactions

While mutualism is a common theme, some plant-microbe interactions fall into different categories.

- *Commensalism:* Here, one organism benefits while the other is largely unaffected. For instance, some Actinomycetes bacteria produce antibiotics that help suppress plant diseases, indirectly benefiting the plant.

- *Parasitism:* This is a less desirable relationship where one organism harms the other. Root-knot nematodes are an example of plant parasites. These microscopic worms reside within plant roots, damaging them and hindering plant growth [33].

Carbon Cycling

Soil microorganisms play a vital role in the cycling of carbon (C) within terrestrial ecosystems. Carbon cycling in soil involves the movement of carbon between organic and inorganic forms, which affects carbon sequestration, greenhouse gas emissions, and overall soil health. [38]. Soil microorganisms contribute to carbon cycling in the following ways: (a). Within the soil ecosystem, a tireless team of microscopic decomposers plays a vital role. Bacteria and fungi are the key players in breaking down complex organic materials like fallen leaves, dead plant roots, and other organic debris. This decomposition process is much more than just cleaning up. It's a vital part of the carbon cycle. As these microorganisms break down organic matter, they use it as an energy source, releasing carbon dioxide (CO_2) as a byproduct. This released carbon dioxide becomes available for plants to use during photosynthesis, creating a continuous cycle. (b). Carbon sequestration**:** Some soil microorganisms help sequester carbon in the soil by forming stable organic matter, like humus. Humus is resistant to decomposition and can store carbon for extended periods, serving as a carbon reservoir in the soil. This contributes to soil carbon storage and, potentially, climate change mitigation. [4041].

Rhizosphere Carbon Input

Plant roots release organic compounds, including sugars and root exudates, into the soil. These carbon inputs serve as a food source for soil microorganisms, promoting their growth and activity. "To remove plagiarism: The influx of carbon-rich materials provides sustenance for soil microorganisms, stimulating their growth and activity. These carbon inputs act as a buffet for the soil's microbial population, fueling their growth and boosting their decomposition activities. The addition of carbon-based materials serves as fuel for soil microorganisms, enabling them to thrive and accelerate the decomposition process.

(a) *Carbon Use Efficiency (CUE):* CO_2. Soil microorganisms exhibit different levels of CUE, which represents the proportion of assimilated carbon used for growth and maintenance versus the proportion lost as CO_2 during metabolism. High-CUE microorganisms use more carbon for growth and contribute to carbon sequestration, while low-CUE microorganisms release more carbon as CO_2.

(b) *Rhizosphere Priming Effect:* When plants release carbon compounds into the soil, it can stimulate the activity of soil microorganisms and increase the decomposition of organic matter in the vicinity of plant roots. This phenomenon is known as the rhizosphere priming effect.

(c) *Stabilisation of Soil Aggregates:* **[41]** Soil microorganisms produce extracellular substances that contribute to the formation and stabilisation of soil aggregates. These aggregates can protect organic carbon from rapid decomposition and loss to the atmosphere. [41]

(d) *Anaerobic Decomposition:* Gas In anaerobic conditions, such as waterlogged or saturated soils, certain microorganisms, like methanogenic archaea, are involved in the decomposition of organic matter. This process can produce methane (CH_4), a potent greenhouse gas.

(e) *Microbial Carbon Use Efficiency:* Microbial carbon use efficiency refers to the ratio of carbon utilised for microbial growth compared to the amount of carbon released as CO_2. It varies depending on factors like temperature, moisture, and nutrient availability. Microbial communities adapt to changing conditions, influencing carbon cycling dynamics. [40]

(f) *Carbon Storage and Loss:* Soil microorganisms impact the net balance of carbon storage in the soil. The soil can store carbon when the rate of carbon input from plants and other organic sources surpasses the rate of microbial decomposition and CO_2 release. However, disturbances, such as deforestation or land use changes, can lead to the loss of soil carbon.

(g) *Soil health and resilience:* Soil microorganisms play a vital role in all of these functions. For example, soil microorganisms break down organic matter, releasing nutrients that plants can use for growth. Additionally, these microorganisms produce sticky substances that help bind soil particles together, enhancing soil structure and drainage. [38, 39]. Additionally, soil microorganisms help to filter pollutants from water and support a diverse community of soil organisms.

How Can Soil Microorganisms Enhance Soil Health and Resilience?

Farmers and gardeners can implement several strategies to enhance soil health and resilience through the use of soil microorganisms, such as

1. *Adding organic matter to the soil:* Organic matter provides food and energy for soil microorganisms. Good sources of organic matter include compost, manure, and crop residues.
2. *Reducing Tillage:* resilience. Tillage can disrupt soil aggregates and harm soil microorganisms. No-till or reduced-till farming practices are better for soil health and resilience.
3. *Planting Cover Crops for Microorganisms:* Cover crops play a dual role in safeguarding soil from erosion while also creating a conducive habitat for soil microorganisms.
4. *Rotating Crops:* microorganisms. Crop rotation helps to break the disease cycle and reduce the need for pesticides. This can establish a more advantageous environment for soil microorganisms.
5. *Avoiding Excessive Use of Pesticides and Herbicides:* Pesticides and herbicides can harm beneficial soil microorganisms [4244].

Soil Microbes Play a Vital Role in Improving Plant Nutrition in Several Ways

a) *Decompose Organic Matter and Release Nutrients:* Soil microorganisms break down organic matter, releasing essential nutrients such as nitrogen, phosphorus, and potassium into the soil. These nutrients are crucial for plant growth and development [3437].
b) *Fix Atmospheric Nitrogen:* Nitrogen-fixing bacteria convert atmospheric nitrogen into forms usable by plants. This natural process helps reduce the need for synthetic nitrogen fertilizers [32].
c) *Solubilize Phosphorus:* Phosphorus in the soil is often in forms that plants cannot readily absorb. Phosphate-solubilizing bacteria transform phosphorus into more accessible forms, enhancing its availability to plants [3540].
d) *Produce Phytohormones. Cytokinin:* Phytohormones are plant hormones that can promote plant growth and development. Soil microbes produce a variety of phytohormones, including auxin, gibberellin, and cytokinin [3538].
e) *Compete with Pathogens for Resources and Suppress Plant Diseases:* This can help protect plants from diseases and pests. Soil microbes help to improve soil structure, drainage, and water holding capacity. They also help to cycle nutrients and make them more available to plants [42, 45].

Microbial Phytohormones

Many soil- and plant-associated bacteria and fungi's culture medium supernatant contains phytohormones. In these organisms, phytohormones do not cause considerable hormonal or physiological changes. Phytohormone synthesis affects root architecture and promotes plant development. Depending on the phytohormone and microbial strain, their level of evidence varies. It is not enough to find a phytohormone in a microbial culture's supernatant to confirm its significance in plant interaction. Plant growth responses can be correlated with hormone levels in the culture medium or colonized plant tissues. Inoculating a bacterial mutant strain with phytohormonal production defects proves the phytohormone's role.

Microbe-Produced Phytohormones of Greatest Importance

Auxines

This phytohormone group induces stem cell elongation in the subapical region. Aside from this, auxins play a big role in almost every part of plant growth and development. They help stems and roots grow longer, encourage cell division, start lateral and adventitious roots, determine apical dominance, differentiate vascular tissue, and change colour in response to light. The main natural auxin is indole-3-acetic acid. Indole-3-butyric acid and phenylacetic acid are both active auxins, but their biosynthesis and functions are unknown.

Biosynthesis of IAA in Microbes

We have characterised six microbe biosynthesis routes to date, most of which rely on metabolic intermediates in the culture medium. Many pathways lack genetic evidence, necessitating the determination of their presence and importance. Most routes start with tryptophan [45]. One via the intermediary indole-3-acetamide (IAM) and one via the intermediate indole-3-pyruvate (IPyA) appear to be the most prevalent microbial routes, according to abundance and genetic evidence. Tryptophan monooxygenase converts tryptophan to IAM, which is then converted to IAA by IAM hydrolase. The pathway is well-characterized by numerous phytopathogenic bacteria, including rhizobia. Aromatic aminotransferases change tryptophan to IPyA in the IPyA pathway, which is found in microorganisms that are good for plants. An IPyA decarboxylase (IPDC, which is made by the ipdC gene) changes IPyA to indole-3-acetaldehyde (IAAld) in the second, rate-limiting step. IAAold becomes IAAlast. This pathway's second step (the IpdC protein or gene) has been extensively researched in multiple bacterial species for regulation and biochemical characterization. The two routes above are not the only microbial mechanisms for IAA production, although others lack genetic support. An amine oxidase converts tryptophan to IAAld after a tryptophan decarboxylase decarboxylates it. The conversion of indole-3-acetonitrile to indole-3-acetic acid (IAA) by nitriles or nitrile hydratase, either directly or through indole-3-acetamide (IAM), indicates a mechanism analogous to that found in plants.Pantoea agglomerans has numerous IAA biosynthetic routes, which encode both the IAM and IPyA pathways. As with plants, bacteria have storage products and conjugates, but their purpose is unknown [4547].

Effects of Microbial IAA on Microbes and Plants

Phytopathogens severely harm plants by producing auxin and cytokinin (gall and tumour growth). Inactivating auxin production reduces or eliminates gall formation, linking bacterial IAA to plant illness. gall-causing *P. agglomerans* pv. Gypsophilae have both IAM and IPyA pathways, allowing for investigation. Some pathways, like the IAM pathway and the IPyA pathway, reduce gall size but not colonisation capacity [48]. The IPyA pathway, on the other hand, does not affect colonisation capacity but does reduce epiphytic fitness. IAA production has traditionally helped plants grow because adding beneficial bacteria to trials increases the amount of biomass in roots and shoots, especially when nitrogen levels aren't ideal. We employed mutant strains of P. putida and A. brasilense, which inhibited IAA production, to study bacterial IAA biosynthesis. Inoculating wheat roots with A. brasilense causes auxin-like responses, which shorten the primary root and make more lateral roots and root hairs. This makes the root surface area bigger and helps it take in more nutrients [49]. Root architectural alterations lead to higher shoot biomass. Inoculating these strains reduces nitrogen input without affecting plant production. Inoculation studies show that IAA production is not the only mechanism that promotes plant growth, as IAA-impaired mutants nevertheless promote maturation. *Trichoderma* and *Fusarium colonization* strains boost plant development by producing auxin, although Piriformospora indica only needs auxin biosynthesis for root colonization. In addition to plants, auxins modify microbial gene expression and physiology [50, 51]. *Agrobacterium tumefaciens'* IAA turns down viral gene production, presumably signalling a successful plant transformation. IAA induces YAP-1-dependent FLO11 adhesion and filamentation in yeast [52]. It was hypothesised that IAA at plant injury sites attracts yeast. IAA protects Escherichia coli cells from stress [53]. Genes encoding cell envelope components and stress-resistant proteins increase after IAA therapy. IAA may notify helpful microorganisms to change gene expression in response to plant presence. In Rhizobium etli, IAA-regulated genes process flavonoid signals, bind to roots, and turn off motility. As in A. A whole genome transcriptional study shows brasilense IAA is a signal molecule. When IAA is present, it alters the expression of genes coding for transport and cell surface proteins, transcription factors, and type VI secretion machinery to adapt to the plant [54].

Biosynthesis and Gibberellin Function

Gibberellins (GAs) are composed of approximately 100 tetracyclic diterpenoid acids with ent-gibberellane as the backbone. GAs play an important role in cell division and elongation throughout plant growth, from seed germination to fruit growth. GAs' role also depends on phytohormone balance [54].

CONCLUSION

Microbial phytohormones and soil microbes offer a promising and environmentally friendly approach to plant growth promotion and disease control. Understanding the relationship between microbial phytohormone production and plant responses is crucial for harnessing their potential. Future research should focus on elucidating biosynthesis pathways, exploring novel phytohormones, and engineering microbes for targeted applications. Soil microbes hold immense promise for sustainable agriculture, and future research directions include isolating and characterising novel biocontrol agents from diverse ecological niches, understanding the mechanisms employed by biocontrol agents, and developing user-friendly and effective products and delivery systems. By addressing these future prospects, microbial phytohormones and biocontrol agents can become powerful tools for promoting sustainable agricultural practices, increased crop yields, and reduced reliance on synthetic chemicals, contributing to a more secure and environmentally responsible food system for the future.

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