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PGPR and Soil Carbon Cycling

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Soil is one of the most vital natural resources on Earth, forming the foundation of terrestrial ecosystems and agricultural productivity. Far more than just a medium for plant growth, soil is a living, dynamic system that supports a wide range of biological, chemical, and physical processes. It plays a crucial role in nutrient cycling, water filtration, carbon storage, and habitat provision for countless organisms. The health and fertility of soil directly influence food security, environmental quality, and climate regulation. It is composed of several essential components as Soil Organic Matter (SOM), Minerals, Soil Carbon, Water, Air, Microorganisms, and Nutrients that work together to support plant growth, regulate environmental processes, and sustain life.

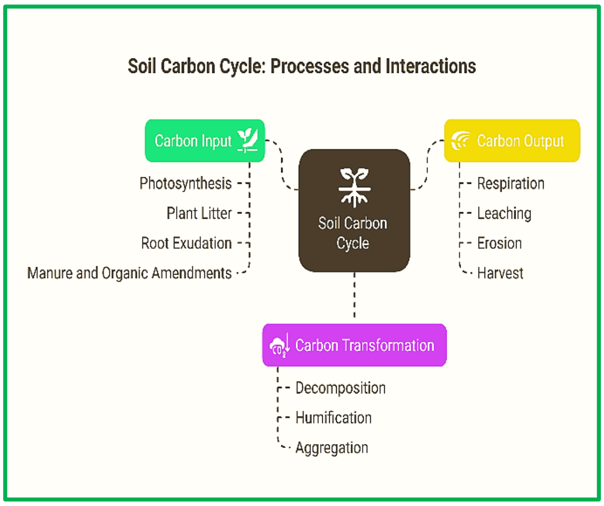
Among these, carbon is one of the most critical elements, playing a central role in maintaining soil fertility, structure, and microbial activity. Carbon in soil is a fundamental component that underpins soil health, fertility, and ecosystem stability. Present in both organic and inorganic forms, soil carbon plays a central role in maintaining the biological, chemical, and physical functions of soil. Soil is far more than a passive medium for attaching plants it's a dynamic, living ecosystem overrun with diverse microorganisms that play essential roles in regulating key ecological processes. Among these microbial communities, Plant Growth-Promoting Rhizobacteria (PGPR) are particularly significant due to their multifaceted contributions to soil health and plant development.

These beneficial bacteria colonize the rhizosphere the soil region surrounding plant roots and promote plant growth through mechanisms such as nitrogen fixation, nutrient solubilization, phytohormone production, and induced systemic resistance. By stimulating plant growth, PGPR contribute to increased carbon input into the soil through root exudates and plant residues, while also enhancing the decomposition and stabilization of soil organic matter. This contributes to the transition of carbon from labile (easily decomposed) to recalcitrant (stable) forms, thereby improving long-term carbon storage. Furthermore, PGPR support sustainable agricultural systems by reducing the reliance on chemical inputs, improving soil structure, and acting as bio control agents against plant pathogens. Though, challenges such as inconsistent field performance and limited shelf-life of microbial formulations remain barriers to their widespread adoption.

Soil Carbon Cycling

Soil carbon cycling is the process by which carbon moves through the soil ecosystem, involving inputs from plants, transformations by soil organisms, and exchanges with the atmosphere. Carbon enters the soil primarily through plant residues, root exudates, and organic amendments, such as compost and manure. These carbon-rich materials provide food for soil microorganisms, initiating a series of biological and chemical processes that influence soil fertility and structure. Microorganisms, including bacteria and fungi, play a central role in decomposing organic matter, breaking down complex compounds into simpler forms in a process called mineralization. Some of the carbon is released as carbon dioxide (CO_2) through microbial respiration, while the rest is transformed into stable organic matter known as humus through humification. This stable organic matter contributes to long-term carbon storage and enhances soil's water-holding capacity, nutrient availability, and biological activity. The balance between carbon inputs and outputs determines whether the soil acts as a carbon sink or a carbon source.

Soil carbon cycling is essential not only for maintaining soil health and plant productivity but also for mitigating climate change. Practices such as crop rotation, reduced tillage, cover cropping, and the use of PGPR inoculum can enhance soil carbon sequestration. By increasing biomass production and promoting the formation of stable organic matter, these practices improve carbon retention in soils. Soil carbon cycling refers to the transformation and movement of carbon within the soil. It involves:



- **Carbon Inputs**: Through plant litter, root exudates, and microbial biomass.
- **Carbon Transformation**: Via microbial decomposition, humification, and mineralization.
- **Carbon Outputs**: CO_2 emissions from microbial respiration and erosion losses.

Carbon in the soil exists in various pools:

- **Labile Carbon**: Easily decomposed; short-term storage.
- **Recalcitrant Carbon**: Resistant to decomposition; long-term storage.
- **Microbial Biomass Carbon**: Living microbial cells; dynamic and responsive.

PGPR influence all three pools through their direct metabolic activity and by altering plant inputs and microbial community composition. Carbon is present in soil in two primary forms: organic carbon and inorganic carbon. Soil Organic Carbon (SOC) originates from plant and animal residues, root exudates, and microbial biomass. It exists in varying degrees of decomposition, from fresh organic matter to stabilized humus. Soil Inorganic Carbon (SIC) is mainly found in the form of carbonates (like calcium carbonate), especially in arid and semi-arid regions. The total carbon content in soil is the sum of both forms, but organic carbon is more dynamic and plays a more active role in soil biological processes and ecosystem functions.

Importance of Carbon in Soil

1. **Soil Fertility and Structure**: Organic carbon improves soil texture, increases water-holding capacity, and enhances nutrient retention and availability, making it vital for plant growth.
2. **Microbial Activity**: Soil carbon serves as the primary energy source for soil microorganisms, which are essential for nutrient cycling, organic matter decomposition, and disease suppression.
3. **Carbon Sequestration and Climate Regulation**: Soils act as major carbon sinks. Storing carbon in soil helps mitigate climate change by reducing atmospheric CO_2 levels.
4. **Erosion and Degradation Control**: Soils rich in organic carbon have better aggregation and are less prone to erosion and compaction, maintaining long-term soil productivity.

Role of Plant Growth-Promoting Rhizobacteria Influence Soil Carbon Cycling

Plant growth-promoting rhizobacteria (PGPR) play a crucial role in enhancing soil health and agricultural sustainability. PGPR are a diverse group of bacteria that establish close associations with plant roots and benefit plant growth. These organisms can be free-living, associative, or symbiotic and include genera like ***Pseudomonas***, ***Bacillus***, ***Azospirillum***, ***Rhizobium***, and ***Enterobacter***. These beneficial microorganisms contribute to nutrient cycling, pathogen suppression, and plant growth stimulation through various mechanisms. They promote plant growth through: Biofertilization: Fixing atmospheric nitrogen, solubilizing phosphorus. Phytohormone Production: Synthesizing auxins, cytokinins, gibberellins. Biocontrol: Suppressing pathogens via antibiotics, enzymes, or induced systemic resistance. Stress Alleviation: Helping plants tolerate drought, salinity, and heavy metals. PGPR can directly promote plant growth by producing phytohormones, fixing atmospheric nitrogen, and solubilizing phosphates. They also indirectly benefit plants through induced systemic resistance and competition with pathogens. The use of PGPR as inoculants offers a promising alternative to chemical fertilizers and pesticides, contributing to more sustainable agricultural practices and improved soil health.

Impact of PGPRs on soil and Plants

A. Enhancement of Root Biomass and Exudation

PGPR stimulate plant growth, particularly root development. More extensive root systems produce and increased root biomass (a major carbon input), when more root exudates (sugars, amino acids, organic acids) that fuel microbial activity. These exudates act as signalling molecules and energy sources, stimulating microbial communities and driving carbon turnover.

B. Stimulation of Microbial Activity and Diversity

PGPR often act as important taxa in the rhizosphere, shaping microbial networks. Their presence can promote beneficial fungi (e.g., mycorrhizae) that aid in carbon sequestration, inhibit pathogens that could otherwise reduce plant productivity and carbon input, stimulate microbial carbon-use efficiency (CUE) and affecting the carbon is retained as biomass contrasted with lost as CO_2.

C. Soil Aggregation and Carbon Protection

Some PGPR produce **extracellular polymeric substances (EPS)** that help form and stabilize soil aggregates. Well-aggregated soil protects organic matter from decomposition, enhances soil structure, porosity, moisture retention, and upsurges the potential for long-term carbon storage.

D. Influence on Carbon Mineralization

PGPR can accelerate or suppress carbon mineralization depending on perspective of positive stimulation occurs through enzyme production and priming effects and suppression may occur through competitive exclusion or by forming physical barriers around organic matter. The net effect depends on soil type, plant species, and microbial community interactions.

Applications and Implications

1. PGPR enhance Soil Carbon Sequestration by increases root biomass and exudation, adding organic carbon to the soil.
2. By promoting microbial growth, PGPR boost the active Microbial Biomass Carbon (MBC) carbon pool in soils.
3. PGPRs produce exopolysaccharides that bind soil particles, reducing erosion, preserving organic carbon and improve soil aggregation.
4. PGPRs stimulate Rhizodeposition by releases of carbon-rich compounds from plant roots, enriching soil carbon inputs.
5. PGPRs fix minerals and mobilize nutrients, lowering the need for synthetic fertilizers that can degrade organic matter.
6. They Promote Stable Carbon Compounds by assistance in the formation of humus, increasing long-term carbon storage in soils.
7. By improving soil carbon capture and reducing chemical inputs, PGPR help reduces CO_2, N_2O, and CH_4 emissions and helps in mitigating greenhouse gas emissions**.**
8. They boost nutrient cycling by accelerate decomposition and transformation of organic materials, optimizing carbon and nutrient turnover.

9. Carbon-rich soils supported by PGPR are more fertile, bio diverse, increase soil fertility, soil health and resilient.
10. Support climate-smart agriculture, where microbes offer eco-friendly solutions that link soil carbon management to sustainable crop production.

Conclusion

Plant Growth-Promoting Rhizobacteria (PGPR) play a crucial role in enhancing soil carbon cycling by stimulating plant root growth, increasing organic matter inputs, and improving microbial activity in the rhizosphere. Through their ability to fix nitrogen, solubilize nutrients, and produce growth-promoting substances, PGPR not only boost plant productivity but also contribute significantly to soil carbon sequestration and stabilization. Their impact on microbial biomass, soil aggregation, and Rhizodeposition enhances both short-term and long-term carbon storage, promoting soil fertility and ecosystem resilience. Harnessing this potential will require interdisciplinary approaches bridging microbiology, soil science, agronomy, and climate policy. Integrating PGPR into sustainable agricultural practices offers a promising strategy for improving soil health, mitigating climate change, and ensuring food security through effective management of the soil carbon cycle.

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