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Soil Microbiomes: Crucial Contributors to Soil Health Conservation in a Changing Climate

Poonam Shrutee Sahoo[1], Chuncha Laxmi Prasanna[2], Janga Prasanth[3], Md Shadab Alam[4] and Rahul Soni[5]

Abstract: -

Maintaining soil health is crucial for agricultural sustainability and directly impacts the productivity of agroecosystems. However, soil resources are currently facing significant threats from various human activities, including climate change, which introduces additional uncertainties and complexities to agriculture, ecosystems, and their long-term sustainability. Plant-associated microbial communities play a vital role in promoting plant growth and enhancing resistance to both abiotic and biotic stresses. Understanding the relationship between microbial diversity distribution and ecosystem functioning is key to assessing how ecosystems respond to environmental changes. Soil microbes are critical in the context of global climate change as they are involved in biogeochemical cycling, plant growth, and carbon sequestration. Modern genomic techniques offer great potential for identifying uncultivated microbial diversity, tracking changes in bacterial communities linked to disease-resistant and sensitive plants, and understanding how microbes are influenced by climate change. This review discusses the impact of climate change on soil microbial communities and plant-microbe interactions, focusing on how metagenomics can help unlock the "black box" of soil microbiomes.

Poonam Shrutee Sahoo[1], Chuncha Laxmi Prasanna[2], Janga Prasanth[3], Md Shadab Alam[4] and Rahul Soni[5]

[1]M.Sc. Scholar, Department of Soil Science, Birsa Agricultural University, Ranchi

[2]Research Scholar, Department of Soil Science and Agricultural Chemistry, University of Agricultural Sciences, GKVK, Bangalore

[3]Farm Manager (Programme Assistant), Department of Microbiology, Krishi Vigyan Kendra, Nellore, Acharya N. G. Ranga Agricultural University

*[4]M.F.Sc. Scholar, Department of Aquaculture (Fisheries Science), College of Fisheries **Science,** OUAT, Rangeilunda-07*

[5]Research Scholar, Department of Botany (CMP), University of Allahabad, Prayagraj, Uttar Pradesh

Introduction

Current research priorities focus on conserving the environment, reducing global warming, and increasing food production to meet the growing global food demands. The Food and Agriculture Organization (FAO) estimates that global food production needs to rise by about 70% by 2050 to feed the expected world population of around 10 billion. As a result, food production must grow sustainably, considering the increasing competition for natural resources, particularly land and water, and the demand for food and biofuels, all while operating within a carbon-constrained economy (Thornton and Herrero 2010). Human activities have significantly impacted the environment, especially sustainable agriculture. The concept of "sustainable intensification" has emerged to describe the challenge of boosting agricultural productivity while minimizing environmental impact, particularly in the context of climate change. The industrial revolution, rapid population growth, and urban expansion have drastically altered human-environment relationships and contributed to global climate change (IPCC 2007). Climate change is known to affect both micro- and macro-organisms, including plants, and has become a major global issue affecting life on Earth (Compant *et al*. 2010). Climate changes also affect the structure, abundance, composition, and functional activity of plant-associated microbial communities. Climate change is thought to have both direct and indirect effects on plant-soil-microbe interactions. altering the community structure, abundance, and functions of soil microbial taxa, which vary in their physiology, growth rates, and sensitivity to temperature. Indirect effects on soil-microbial communities, mediated through plants, may be more significant than the direct effects on below-ground microbial communities. Changes in microbial community composition can alter ecosystem functioning, with shifts in the abundance of organisms regulating key processes directly influencing the rate of those processes. While much research has focused on plant species migration in response to climate change, fewer studies address the ability of plant-associated soil microbial communities to adjust their range to maintain their relationship with the soil and plant community (Van der Putten 2012).

Role of soil microbiome for improving soil health under changing climate

Soil microbiomes are a key factor in maintaining soil health, supporting plant growth, and enhancing agricultural productivity. They contribute to several vital soil functions, including:

1. **Nutrient Cycling**: Soil microbes are responsible for the cycling of essential

nutrients such as nitrogen (N), phosphorus (P), and carbon (C). Through processes like nitrogen fixation, decomposition, and mineralization, microbes ensure that nutrients are available to plants, thereby enhancing soil fertility.

2. **Soil Structure and Aggregation**: Microbes, particularly fungi, help form soil aggregates, improving soil structure. Aggregates enhance water infiltration, reduce soil erosion, and increase root penetration, which is vital for plant growth.
3. **Biological Disease Suppression**: Beneficial microbes in the soil outcompete or inhibit pathogenic microorganisms, thus reducing the occurrence of soil-borne diseases. This natural biocontrol is crucial for reducing the reliance on chemical pesticides and promoting organic farming practices.
4. **Plant Growth Promotion**: Many soil microbes produce plant growth-promoting substances like phytohormones (e.g., auxins and cytokinins), vitamins, and antibiotics that stimulate plant growth and enhance plant resistance to biotic and abiotic stresses.
5. **Carbon Sequestration**: Soil microorganisms play a critical role in carbon sequestration by decomposing organic matter and incorporating carbon into the soil. This process helps mitigate the impact of increased atmospheric CO2 levels and contributes to climate change mitigation.

Mechanism of interaction or communication of plants (roots) and microbes

Due to their stationary nature, plants must optimize their health within their biotic environments. Pathogenic and mutualistic microorganisms are key factors that influence plant fitness while also using host plants for their proliferation. Over time, plants and their associated microbes have coevolved, developing mechanisms that regulate the outcomes of their interactions (Jones and Dangl 2006). Plants depend on their roots to communicate with a variety of microbes. The diversity of bacteria and fungi in the rhizosphere is largely shaped by their interactions with plants, often controlled by the secretion of root exudates. Plant roots release a wide range of potentially valuable small molecules, such as p-hydroxy acids, quinones, cytokinins, and flavonoids, into the rhizosphere. The first step in root colonization is the chemotactic response of microbes to these root exudates. The exudates released by plant roots include amino acids and organic compounds. Terrestrial plants experience some of the most complex interactions, including physical, chemical, and biological processes between their roots and the rhizosphere. These interactions involve root-root, root-insect, and root-microbe dynamics. The root microbiome plays a critical role in plant growth and health by aiding nutrient uptake, providing protection against pathogens, and supporting tolerance to abiotic stresses (Berendsen *et al*. 2012).

Plant, microbe and climate change

Constant changes in climate patterns affect the distribution and behavior of species. The anticipated effects of climate change, such as rising temperatures and shifting rainfall patterns, introduce uncertainty and complexity to plant and agricultural systems, potentially threatening the sustainability of agricultural management. Climate change also significantly impacts crop quality and the dynamics of interactions between crops, pests, and diseases. Variations in climatic factors, such as rainfall, solar radiation, and temperature, have the potential to greatly influence crop production (Classen *et al*. 2015).

Direct impacts of climate change on soil communities and plants

Climate change impacts the functioning and relative abundance of microbial communities in soil. These microbes exhibit significant variation based on their growth rates, physiology, and sensitivity to temperature changes. DeAngelis *et al*. (2015) found that long-term warming of forest soils leads to changes in microbial communities in temperate forests. For instance, a 5°C increase in temperature in these forests alters the relative abundance of soil microbes, such as bacteria, resulting in a higher bacterial-to-fungal ratio. Global changes, such as global warming, directly influence the respiration rates of soil microbes, as the processes they mediate are temperature-sensitive. As a result, the impact of elevated temperatures on microbial metabolism has garnered significant attention in recent years (Bradford *et al*. 2008).

Indirect effects of climate change on plants and on soil microbiome

Climate change affects plant phenology and the distribution of microbes, leading to changes in plant species distribution. Many studies have not fully explored how soil-associated microbes might shift their ranges to maintain their relationships—either positive or negative—with plants. Soil microbes are considered poor dispersers, and thus, they respond to climate change at a slower rate compared to plants (Van der Putten 2012). However, it is understood that differences in dispersal abilities between microbes and plants can influence plant productivity, the establishment of new plant species, and their interactions. Plants that successfully establish in new areas are known to produce higher levels of defense-related compounds, such as polyphenols. The anticipated rise in global temperatures due to climate change affects crop species, insect pests, weeds, and crop diseases. Weeds are responsible for around 34% of crop losses, with insects causing 18% and diseases accounting for 16%. Climate change may exacerbate the already significant negative impacts of insects, weeds, and diseases on agricultural systems.

Microbes for soil health, plant productivity and disease management

Soil health refers to the ability of soil to support a variety of ecosystem and agronomic functions and services that maintain environmental quality, biological productivity, and promote the health of plants and animals. Healthy soils are the foundation of sustainable and productive agroecosystems, and their maintenance can be achieved through principles such as minimizing soil disturbance, protecting surface soils by growing more plants, increasing plant diversity through crop rotation, polycultures, and cover crops, and enhancing the soil microbiome (Brussaard *et al*. 2007). The successful use of microbes helps maintain soil health by improving water retention, carbon storage, root growth, nutrient availability and cycling, pollutant filtration, and biodiversity conservation. Maintaining and enhancing soil health and fertility is crucial for agricultural productivity. While soil-borne beneficial microbes have been extensively studied and applied in many important crops worldwide, their integration into agriculture remains limited, hindering the development of effective disease management strategies. Beneficial microbes offer new opportunities for long-term pathogen control, highlighting the importance of plant-associated microbiomes for crop productivity (Bonanomi *et al*. 2018). Since soil microbes are a key component of soil organic matter, they provide essential nutrients to plants and protect against pest and disease outbreaks through their diverse community.

Harnessing Microbial Communities for Climate Change Mitigation

Given the critical role of soil microbiomes in ecosystem functioning, harnessing their potential for climate change mitigation is an essential strategy. The use of beneficial soil microbes offers promising opportunities for sustainable agriculture and ecosystem management. Some key approaches include:

1. **Microbial Inoculants**: The application of beneficial microbial inoculants, such as nitrogen-fixing bacteria or plant growth-promoting rhizobacteria (PGPR), can enhance soil health and improve crop yields under changing climatic conditions. These microbes can help increase nutrient availability, improve plant stress tolerance, and enhance soil structure, contributing to more resilient agricultural systems.

2. **Microbial-Plant Interactions for Stress Tolerance**: Research on plant-microbe interactions is essential for identifying microbial strains that can enhance plant resistance to environmental stressors such as drought, salinity, and heat. This knowledge can be used to develop climate-resilient crops that rely on their microbial partners for improved performance under adverse conditions.
3. **Soil Carbon Sequestration**: By promoting microbial communities that facilitate the decomposition of organic matter and carbon storage, soil health management practices can enhance soil carbon sequestration, mitigating the effects of climate change. Practices such as cover cropping, reduced tillage, and organic amendments help maintain and improve microbial diversity, supporting long-term carbon storage in soils.
4. **Soil Health Monitoring**: Using genomic and metagenomic tools to monitor soil microbial communities offers a powerful approach for tracking soil health and understanding the impacts of climate change on microbial dynamics. Molecular techniques can identify key microbial taxa that are sensitive to climate factors, enabling predictive models of ecosystem functioning and informing soil management strategies.

Conclusion

To achieve long-term success, it is essential to develop sustainable and sufficiently productive agricultural systems that can keep pace with the growing human population and the challenges posed by climate change. The rhizosphere remains one of the most diverse and dynamic zones, estimated to host tens of thousands of microbial taxa, making it a complex and active area. Within this zone, numerous interactions occur between plants, soil, and microbes, with these microbial communities playing an indispensable role in promoting sustainable agricultural development. Given the uncertainties caused by global climate change, the potential of microbial communities can be leveraged to monitor and mitigate its effects. Innovative genomic approaches will be crucial for microbe-focused studies, helping identify microbial taxa sensitive to climate change and understanding how their responses alter microbial community structure and function. Overall, these molecular techniques will be vital for predicting ecosystem functions, understanding the impact of extreme conditions, and assessing the stability of microbial communities in a changing climate. Modeling soil and plant microbial communities, along with their interactions, is essential for forecasting future ecosystem functions.

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