Harnessing Soil Microbiome for Enhancing Soil Health, Crop Productivity and Environmental Sustainability

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ABSTRACT

The global population is projected to reach 9.7 billion by 2050 and the food production must effectively increase by about 70% so as to feed the growing population. But as the world's population is growing rapidly, food insecurity issues are rising. Agricultural intensification activities have increased crop yields in the short term but these practices have led to soil degradation and poor soil quality, highlighting the urgent need for sustainable strategies. This paper explores advantages of utilizing beneficial microorganisms, such as plant growth-promoting rhizobacteria, mycorrhizal fungi and biocontrol agents that offers sustainable and eco-friendly alternatives to conventional agricultural practices. The soil microbiome, comprises of diverse community of microorganisms including bacteria, fungi, actinomycetes, algae, pathogens and nematodes. These microorganisms form intricate networks and engage in a myriad of interactions that drive essential soil functions and processes. Soil microorganisms enhance plant growth by fixing atmospheric nitrogen, solubilizing phosphorus and producing growth-promoting hormones. Additionally, soil microbes play a key role in bioremediation by breaking down pollutants and detoxifying heavy metals.

Beneficial microbial interactions with plant roots, such as mycorrhizal associations, improve water and nutrient uptake, thereby enhancing crop productivity. By combining microbial solutions with compost, organic fertilizers and minimal synthetic inputs, farmers can enhance soil fertility, improve plant resilience and optimize nutrient uptake while maintaining balanced microbial communities.

INTRODUCTION

As the world grapples with increase in population the Food and Agriculture Organization of the United Nations estimated that the global food production needs to be increased by about 70% by 2050, so as to feed the projected world population of about 10 billion. As the population is increasing at fast rate, to keep pace, the total area of cultivated land worldwide has increased over 500% in the last five decades with a 700% increase in fertilizer use and a several-fold increase in pesticide use (Banerjee *et al*., 2019). Various agricultural intensification activities like tillage fertilizer pesticide improper crop rotation especially monoculture cropping, has increased crop production over a short term by suppressing interactions between plants and microorganisms. these practices have led to colossal yield increases over the short term. However, such approaches have increased agrochemical pollution, land degradation, and spread of resistant pests. These drawbacks are increasingly offsetting the initial yield gains, calling for more sustainable strategies among which harnessing soil microbiome is one of the key approaches.

The soil microbiome refers to the diverse community of microorganisms i.e. bacteria, fungi, algae, fungi, actinomycetes and nematodes that inhabit the soil. This complex and dynamic ecosystem plays a crucial role in nutrient cycling, plant growth promotion, disease suppression, and ecosystem stability. These microorganisms form intricate networks and engage in a myriad of interactions that drive essential soil functions and processes. These microbial communities are constantly working behind the scenes, breaking down complex organic compounds, fixing nitrogen, and forming symbiotic relationships with plant roots. Without them, soil would lose its fertility, and agriculture as we know it would not be possible.

Role of soil microbiome for enhancing soil health

1. **Decomposition:** Dead leaves that fall from the trees represent organic material entering the soil as plant litter which includes leaves barks and other plant debris then earthworm insects and microbes breaks the organic matter into smaller particles then soluble organic and inorganic substances are dissolved by water transporting nutrients deeper into the soil by the process of leaching. Humification leads to formation of a stable organic compounds i.e. humus which enhance soil fertility and water retention then organic nutrients are converted into inorganic nutrients by the process of mineralization which is available to the plant for their growth.

2. **Nutrient cycling:** Nutrient cycling in soil encompasses the complex series of biological, chemical, and physical processes by which essential elements are transformed and made available to plants and other organisms. Various nutrients macronutrients and micronutrients enters the soil mostly in organic form which needs to be converted into inorganic forms which is available to plants for absorption hence

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increasing nutrient content in soil too. Micronutrients like Zn, Mn, Fe, Cu are available with the help of chelators and siderophores which are specialized organic molecules.

3. **Soil structure and stability:** Fungal hyphae (the thread-like filaments of fungi) intertwine with plant roots and soil particles bridging across root surface helps bind soil particles, enhancing soil structure. Fungal threads act like a biological glue, holding soil crumbs (aggregates) together. Fungi bridge gaps between soil particles, reinforcing the soil's physical structure. This network can also retain water and nutrients more effectively (Ritz and Young, 2004).

4. **Suppression of soil borne pathogen:** Soil microorganisms create environment unfavorable for pathogens like altering soil pH, oxygen level making it difficult for pathogen to survive. Microbes compete for space, water and nutrient by rapidly colonizing root surface, consume nutrients before pathogen could access them and form biofilms which prevent establishment. They produce antibiotic compounds like streptomycin, bacteriocin etc. produced by actinomycetes which directly kill or inhibits pathogen.

Role of soil microbiome for enhancing crop productivity

1. **Nutrient uptake:**

Microbial role	Nutrients	Examples
Phosphate solubilization	Phosphorus	*Pseudomonas*, *Bacillus*, *Aspergillus*
Potassium mobilization	Potassium	*Bacillus mucilaginosus*, *Frateuria aurantia*
Mycorrhizal symbiosis	Phosphorus, Nitrogen	*Glomus* (AMF – Arbuscular Mycorrhizal Fungi)
Production of growth hormones	All nutrients	*Azospirillum*, *Bacillus*, *Pseudomonas*

2. **Stress tolerance:** It is defined as organism's ability to survive and maintain normal physiological functions under unfavourable environmental conditions. For overcoming biotic stress, the microbes produce volatile organic compounds, produce antimicrobial and antiviral compounds and fight for space and water outcompeting harmful organisms. For abiotic stress, microbes enhance water uptake by extending root system and produce exopolysaccharides, they produce osmolytes and decrease sodium uptake under salinity and produces heat shock proteins and cryoprotectants to overcome temperature stress.

3. **Biological Nitrogen fixation:** Legume roots release flavonoids which act as chemical signals to attract nitrogen-fixing bacteria. Bacteria recognize these signals and produce Nod factors, signalling molecules that trigger root hair curling in the plant. The bacteria penetrate the root hair by forming an infection thread, allowing bacteria to move toward the plant's cortical cells. Once inside the root cortex, bacterial cells are released into membrane-bound compartments called symbiosomes. The plant forms nodules, specialized root structures where nitrogen fixation occurs. Inside nodules, bacteria differentiate into bacteroids, the functional nitrogen-fixing form. The enzyme nitrogenase catalyzes the conversion of atmospheric nitrogen (N_2) into ammonia. Nitrogenase Enzyme functions only under anaerobic conditions. The plant produces leghaemoglobin, a protein that binds oxygen to protect nitrogenase from inactivation and gives active nodules red

colour. The fixed ammonia is converted into glutamine and other nitrogenous compounds, which are transported to the plant for growth.

4. **Resistance:** The ability of a plant to identify, prevent, and restrict the establishment or spread of diseases and pests—often before serious harm is done. A pathogen infects a leaf, causing localized tissue damage; the plant recognizes the pathogen through pattern recognition receptors (PRRs). The infected leaf initiates SAR (Systemic Acquired Resistance) by producing signaling molecules like salicylic acid (SA), methyl salicylate (MeSA), and reactive oxygen species (ROS). These molecules travel through the vascular system (phloem/xylem) to uninfected parts of the plant. Upon reaching distant parts of the plant, SAR signals prime the cells to enhance defense. ISR (Induced Systemic Resistance) is activated by Plant Growth-Promoting Rhizobacteria (PGPR). The plant releases selective compounds into the rhizosphere to recruit ISR-eliciting microbes. ISR and SAR work together to protect newly emerging leaves, roots, and neighboring plants from future attacks. This provides long-term immunity without requiring direct pathogen exposure.

Role of soil microbiome for enhancing environmental sustainability

1. **Carbon sequestration:** the process by which carbon dioxide (CO_2) is captured from the atmosphere and stored in long-lived carbon pools—such as soil organic matter, vegetation biomass, and geologic formations—thereby reducing greenhouse-gas concentrations and mitigating climate change. Steps include: Carbon fixation by plants, decomposition, humification, microbial biomass storage, carbon protection, methane oxidation and long-term carbon storage. This ensures carbon remains stored for thousands of years, contributing to climate stability.

2. **Bioremediation:** the process of using living organisms like bacteria, fungi or algae to clean up environmental pollutants like oil spills, contaminated soil, and groundwater. These microbes degrade or transform pollutants into less harmful substances, making it an eco-friendly and effective way to address contamination. These processes include biodegradation, biotransformation, and mineralization, where microbes act as catalysts to convert complex pollutants into less harmful substances or essential nutrients (Razak, 2024).

3. **Waste decomposition:** Decomposition is a natural biological process occurring naturally in organisms whereby organic waste materials (such as crop residues, food scraps, manure, and dead organisms) are broken down into simpler components by microorganisms such as bacteria, fungi, and actinomycetes. This process takes place in multiple stages: complex molecules (such as cellulose, proteins, fats) are enzymatically degraded into simpler components (such as sugars, amino acids) and then further mineralized into carbon dioxide, water, and plant available nutrients, such as nitrogen and phosphorus. Waste decomposition is essential for recycling of nutrients in soil, for soil fertility, and for prevention of environmental pollution.

CONCLUSION

Beneficial microbes play a crucial role in enhancing soil fertility by facilitating nitrogen fixation, phosphorus solubilization and organic matter decomposition thereby reducing dependence on chemical fertilizers. The use of microbial inoculants boost plant growth, strengthens root systems and enhances crop

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yield. Soil microbes improve plant resilience to biotic and abiotic stresses. Biofertilizers enhance nutrient availability leading to improved nutrient uptake and enriched nutrient content in crops. Soil microbes aid in carbon sequestration and reduce greenhouse gas emissions promoting sustainability. They assist in pesticide degradation and help mitigate heavy metal toxicity in the rhizosphere. Integrating microbial solutions with organic and inorganic amendments ensures long-term soil health, fostering sustainable agriculture, food security and ecosystem resilience.

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