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Sustainable Soil Reclamation: The Twin Role of Biochar and Microbial Culture

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Abstract

Soil salinity is a growing challenge across many parts of the world, affecting millions of hectaresof farmland. The excessive accumulation of soluble salts in the soil interferes with water and nutrient absorption, damages soil structure, reduces crop yields, and disrupts beneficial microbial communities. These impacts are particularly severe in arid and semi-arid regions, where managing salinity is critical to maintaining productive agriculture. Among the more sustainable approaches to this problem, the combined use of biochar and microbial inoculants has shown strong potential. Biochar, a carbon-rich substance produced through the pyrolysis of organic material, improves the physical and chemical properties of soil. It enhances porosity, water retention, cation exchange capacity, and pH buffering. Its porous structure also provides a stable habitat for soil microbes, encouraging their survival and activity even under salty conditions.

Microbial inoculants such as plant growth-promoting rhizobacteria (PGPR), halotolerant

bacteria, and arbuscular mycorrhizal fungi (AMF) help plants cope with salinity by improving nutrient availability, producing growth-promoting hormones, enhancing root development, and strengthening antioxidant defenses.When applied together, biochar and microbial cultures create a synergistic effect. They improve soil enzyme activity, boost microbial biomass, enhance nutrient uptake, and support better plant growth in saline environments. Research from both greenhouse and field trials has shown that this combination significantly reduces salt toxicity and helps restore soil microbial function. The integration of biochar and microbial inoculants represents a practical and sustainable strategy for reclaiming salt-affected soils, improving crop productivity, and promoting long-term soil health

1. Introduction

Salinity in the soil has become one of the critical challenges of the world, negatively influencing agricultural productivity, ecological balance, and food security Globally, more than 833 million hectares, accounting for approximately 8.7% of the Earth's land surface, are reported to be affected by salt stress (FAO, 2021). Salinization may be a natural event but also a human-made process caused by factors such as immoderate watering, improper drainage, and unbalanced land use. Solution of salts in the root zone changes the structure of the soil, hinders water penetration, and restricts nutrient availability, affecting plant growth and biological activity of soils. Conventional ways of controlling soil salinity like leaching, use of chemicals (e.g., gypsum), and improved irrigation methods are often costly, time-consuming, and not long-term sustainable (Faisal *et al*., 2024).

This has led to increased interest in cost-effective, environmentally friendly soil management strategies. Among them, biochar and beneficial microbial cultures important due to their multifunctionality in enhancing soil fertility, structure, and biological activity. Biochar, produced by pyrolysis of biomass, improves aeration, water retention, and nutrient holding capacity (Pandao *et al*., 2023). Its surface chemistry also helps reduce salt mobility and toxicity. In contrast, microbial inoculants, particularly PGPR, halotolerant bacteria, and mycorrhiza fungi, play critical roles in hormone production, nutrient uptake, and osmotic adjustment. When combined, biochar and microbial cultures may create a synergistic microenvironment that enhances microbial survival and mitigates salinity stress offering a long-term solution to saline soil reclamation (Al-Turki *et al*., 2023).

2. Related Causes and Consequences of Soil Salinity

Soil salinity is the build-up of soluble salts, mostly sodium (Na^+), chloride (Cl^-), sulfate (SO_4^{2-}), and carbonate ions in the soil profile to levels that adversely affect plant growth and soil health. Saline soil development may be caused by both natural and human-induced factors (Chhabra *et al*., 2022). Natural factors include weathering of salt-bearing rocks, oceanic salt deposition through wind and rainfall (especially in coastal zones), and capillary rise of salty groundwater in arid and semi-arid regions. Low rainfall and high evaporation impede the leaching of salts, intensifying salinity. Anthropogenic causes include over-irrigation, use of saline water, lack of drainage, intensive cropping, deforestation, and excessive fertilizer use. Poorly managed irrigation increases the water table and salt accumulation, while monoculture reduces vegetation cover, further enhancing salinization (Mohanavelu *et al*., 2021).

Salinity causes osmotic stress, preventing plant roots from absorbing water. It leads to sodium toxicity, nutrient imbalance, and metabolic disruptions, with symptoms like stunted growth, leaf burn, and poor germination. Microbial communities also suffer, with reduced diversity and enzymatic activity. Saline soils become compacted, lose porosity, and hinder root and water penetration, deteriorating soil structure (Chhabra *et al*., 2022). Economically, this results in crop failure, increased reclamation costs, land abandonment, and contributes to desertification and biodiversity loss. Understanding causes and effects is essential for developing sustainable strategies such as biochar application and microbial inoculants, which offer effective, green alternatives to restore biological soil activity and profitability.

3. Biochar: Characteristics and Its Implications in Remediating Salty Soils

Biochar is a carbon-rich, porous biomaterial generated through pyrolysis the thermal degradation of organic biomass in limited or no oxygen. It is widely regarded as a soil amendment due to its potential to improve soil fertility, structure, and strength, especially in salinized soils.

Key properties of biochar useful for saline soil remediation include:

- **High surface area and porosity**: Increases water retention, aeration, and microbial colonization.
- **Cation exchange capacity (CEC)**: Allows adsorption and retention of nutrients and excess toxic ions like sodium.
- **High pH**: Helps neutralize acidic soils, affecting nutrient availability and microbial activity.
- **Stable carbon content**: Remains in the soil for decades, enhancing the organic matter pool (Tomczyk *et al*., 2020).

Biochar immobilizes salt ions through adsorption, reducing their availability and toxicity. This relieves osmotic and ionic stress on plants in saline soils. Its role in improving soil aggregation and reducing bulk density also supports better water percolation and root growth (Ghassemi-Golezani *et al*., 2023). Its high water-holding capacity is especially vital in arid and semi-arid areas prone to water scarcity and salinity. Biochar also prevents nutrient leaching, especially of nitrogen and phosphorus, making nutrients more plant-available. Additionally, it supports beneficial microbes by offering a stable habitat and energy source key in microbial restoration in salty soils. Biochar is a versatile amendment that mitigates salt stress, improves physical and chemical soil properties, enhances nutrient availability, and supports microbial growth. When combined with microbial inoculants, its effectiveness is further amplified making it a long-term solution to saline soil rehabilitation.

4. Microbial Culture for Saline Soil Management

Salinity heavily disrupts microbial balance and biological activity in soils. However, certain halotolerant and halophilic microbial strains show promise in improving plant and soil tolerance to salinity (Kumar *et al*., 2023). These microbes can be used as bio-inoculants to rehabilitate saline soils and support sustainable crop production. Key microbial groups include PGPR, AMF, cyanobacteria, and halotolerant bacteria such as *Azospirillum*, *Bacillus*, *Pseudomonas*, *Rhizobium*, and *Enterobacter*. They assist plants under salt stress by producing phytohormones (auxins, cytokinins, gibberellins) that promote root growth (Lalitha *et al*., 2022). They also facilitate osmotic adjustment by enhancing production of osmoprotectants like proline, glycine betaine, and trehalose.

Microbial cultures improve uptake of essential nutrients (N, P, K) that are typically unavailable in saline conditions. ACC deaminase production reduces ethylene levels, mitigating stress symptoms. AMF symbiosis enhances water and nutrient absorption, while also contributing to soil aggregation and stabilization (Wahab *et al*.,2023). They restore soil microbial richness and induce enzymes like dehydrogenase, urease, and phosphatase, which are suppressed under salinity. This rejuvenates soil biological activity and improves fertility.

5. Additive Biochar to Bacterial Inoculants

Combining biochar with microbial inoculants is a very effective method for saline soil remediation. Biochar physical-chemical properties and the biological activity of beneficial microbes together improve soil health, plant growth, and salt stress mitigation. As a porous material, biochar is an ideal carrier for microbial inoculants, providing shelter and protection against stressors like UV light, dehydration, and salt (Arshad *et al*., 2024). This combination supports rhizosphere colonization and activity of salt-tolerant microbes (e.g., *Pseudomonas*, *Bacillus*, *Azospirillum*), boosting hormone production, nutrient solubilization, and stress tolerance in plants.

Biochar-microbe interaction also stimulates key enzymes (dehydrogenase, urease, phosphatase), promoting nutrient cycling and microbial biomass. This increases soil respiration and biological stability (Taheri *et al*., 2024). Biochar's sodium adsorption reduces salt toxicity, while microbes mobilize essential nutrients like nitrogen and phosphorus, correcting typical saline soil nutrient imbalances. Together, they improve soil structure, water retention, and reduce oxidative stress in plants. Experiments show combined application leads to better crop germination, growth, and yield than either amendment alone (Niu *et al*., 2024). It also restores microbial diversity and long-term soil productivity. This integrated approach aligns with climate-smart and resource-efficient agriculture, offering a sustainable and scalable solution. Future research should focus on optimized combinations based on salinity levels, soil types, crops, and microbe–biochar compatibility.

6. Conclusion

Soil salinity poses a major threat to sustainable agriculture, especially in arid and semi-arid regions. Conventional management practices, including gypsum application, leaching, and subsurface drainage, though effective, are not always feasible in resource-limited systems due to high water and input demands. Hence, there is increasing interest in alternative biological approaches that are cost-effective, eco-friendly in contrast, the combined use of biochar and microbial cultures provides a sustainable and eco-friendly solution for restoring salty soils. Biochar improves soil physical and chemical properties, binds toxic salts, enhances water and nutrient dynamics, and fosters microbial colonization. Meanwhile, halotolerant microbes support nutrient uptake, enzyme activity, and hormone production stimulating plant health and soil properties. Evidence from researches, confirms that their combined effects are greater than individual applications, promoting soil fertility and plant growth & development. Standardized formulations, long-term studies, and cost-effective field models are essential for large-scale adoption. The use of biochar along with microbial inoculants presents a sustainable and climate-friendly strategy to manage soil salinity, boost food production, and preserve ecosystems. To make this effective, increased investment in research, farmer training, and strong policy back-up is essential.

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