



SOIL SALINITY AND THE ROLE OF PLANT-ASSOCIATED MICROBES IN PULSE-BASED SUSTAINABLE AGRICULTURE



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INTRODUCTION

Soil salinity has emerged as one of the most severe abiotic stresses threatening global agriculture, particularly in the face of climate change and unsustainable irrigation practices. It is estimated that over 20% of the world's irrigated lands and about 7% of total land area are affected by salinization, with an increasing trend each year due to secondary salinization processes. High salt concentrations in the root zone lead to osmotic stress, ion toxicity (primarily from Na^+ and Cl^-), nutrient imbalances, and physiological drought, ultimately suppressing plant growth and productivity. This challenge is particularly significant in arid and semi-arid regions of Asia and Africa, where pulse crops such as lentil (*Lens culinaris*), chickpea (*Cicer arietinum*), and mungbean (*Vigna radiata*) are staple sources of protein and play a vital role in maintaining soil fertility through nitrogen fixation. However, the productivity of these legumes is highly sensitive to salinity, especially during germination and early seedling stages.

Plant-Associated Microbes: A Biological Strategy for Salt Stress Management

A promising and environmentally sustainable approach to tackle salt stress is the use of plant-associated beneficial microbes, including plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and nitrogen-fixing rhizobia, as bio-inoculants. These microbial allies offer several benefits under saline conditions: Alleviation of salt-induced stress through mechanisms such as osmolyte production, indole acetic acid (IAA) synthesis, and ACC deaminase activity, which reduces ethylene-induced growth inhibition. Improved nutrient uptake, particularly phosphorus, potassium, and iron, through solubilization and siderophore production. Ion homeostasis by enhancing K^+/Na^+ selectivity and limiting the accumulation of toxic ions in plant tissues. Stimulation of antioxidant defense systems, reducing oxidative damage

caused by salinity-induced reactive oxygen species (ROS).

Soil Salinity: Impact and Challenges

Salinity results in osmotic stress, ion toxicity (especially from sodium and chloride ions), and disruption of soil structure. These effects hinder microbial activity, root development, and nutrient uptake. Saline soils often show poor microbial diversity and reduced functional groups involved in nitrogen fixation, phosphorus solubilization, and organic matter decomposition. Traditional chemical and mechanical amelioration methods are costly and often unsustainable.

Pulses as a Tool for Saline Soil Reclamation

Pulses, members of the Leguminosae family, are increasingly recognized for their potential in rehabilitating saline and degraded soils. Their unique nitrogen-fixing ability, established through a symbiotic relationship with *Rhizobium* and other rhizobia, allows them to thrive even in nutrient-poor environments and enhance soil fertility by contributing biologically fixed nitrogen. Several pulse species, such as lentil (*Lens culinaris*), chickpea (*Cicer arietinum*), mungbean (*Vigna radiata*), and pigeon pea (*Cajanus cajan*), have demonstrated moderate tolerance to salinity. They can germinate and establish in soils with electrical conductivity (EC) ranging from 4 to 8 dS/m, depending on the species and genotype. Their ability to establish root systems in such environments plays a crucial role in physically stabilizing the soil and initiating biological processes that gradually reduce salinity levels.

Microbial Interactions and Soil Health Improvement

The rhizosphere of pulses supports diverse microbial communities, including plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), which play essential roles in nutrient solubilization, hormone production, and stress mitigation. Pulse roots release exudates rich

in amino acids, organic acids, and sugars, which selectively enhance the proliferation of beneficial microbes. These microbial communities can mobilize essential nutrients such as phosphorus, potassium, and micronutrients, and produce ACC deaminase and osmoprotectants, which help the host plant cope with salt stress.

In addition, the biomass and residues of pulses, when incorporated into the soil, significantly improve organic matter content. This boosts soil aggregation, water retention capacity, and cation exchange capacity—critical factors in restoring soil structure and reducing salt accumulation.

Microbial Interactions in Saline Environments

Microbial interactions in saline soils are governed by the ability of microbes to tolerate high osmotic stress. Plant Growth-Promoting Rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and halotolerant microbes have emerged as key players. These microbes possess mechanisms such as production of osmoprotectants, exopolysaccharides, antioxidant enzymes, and stress-related phytohormones. Such traits help both the host plant and soil microbial ecosystem to cope with salinity.

Plant Growth-Promoting Rhizobacteria (PGPR)

PGPR are free-living bacteria that colonize the rhizosphere and enhance plant growth through direct and indirect mechanisms. Under salinity stress, PGPR strains (e.g., *Pseudomonas*, *Bacillus*, *Azospirillum*, *Rhizobium*) help by: Fixing atmospheric nitrogen, Producing indole-3-acetic acid (IAA) to promote root growth, Solubilizing phosphorus and potassium, Producing ACC deaminase to lower ethylene levels under stress, and Enhancing uptake of essential nutrients. In pulses, PGPR improve seed germination, root elongation, nodulation, and biomass accumulation in saline soils.

Arbuscular Mycorrhizal Fungi (AMF)

AMF form symbiotic relationships with most terrestrial plants, including pulses. They improve water and nutrient uptake by increasing root surface area and accessing micro-pores in the soil. AMF: Enhance plant tolerance to salinity by regulating ionic balance, Increase antioxidant enzyme activity, Support nutrient cycling and soil aggregation, and Reduce soil pH and improve microbial diversity.

Studies in chickpea, pigeon pea, and lentil have shown that AMF inoculation leads to

improved yield and soil quality under saline conditions.

Symbiotic Nitrogen-Fixing Bacteria (Rhizobia)

Rhizobia establish symbiosis with pulses, forming root nodules that fix atmospheric nitrogen into ammonia. Salinity negatively affects nodulation and nitrogen fixation. However, inoculation with salt-tolerant rhizobia strains can mitigate this by: Enhancing nodule formation and nitrogenase activity, Producing stress-adaptive exopolysaccharides, Maintaining host plant growth under salt stress. Improved rhizobial inoculants have been developed for saline soils, offering dual benefits of crop productivity and soil enrichment.

Halotolerant and Halophilic Microbes

These microbes naturally thrive in saline environments and offer unique metabolic traits useful in soil reclamation. Halotolerant bacteria produce osmoprotectants (e.g., proline, glycine betaine) and antioxidant enzymes to alleviate oxidative stress. They also improve soil structure by secreting exopolysaccharides that bind soil particles and reduce sodium mobility.

Microbial Consortia and Formulations

A single microbial strain may not be sufficient for effective amelioration. Microbial consortia, comprising compatible strains of PGPR, rhizobia, and AMF, offer synergistic effects. These formulations: Improve rhizosphere activity, Enhance plant physiological responses to salinity, and Contribute to sustainable soil health management. Field trials with consortia on mungbean and lentil have demonstrated better growth and yield under salinity than single inoculants. Microbial Consortia and Formulations for Saline Soil Amelioration. While individual microbial strains like *Rhizobium*, *Bacillus*, or *Pseudomonas* have shown promise in mitigating salt stress, a single inoculant is often insufficient to fully exploit the complex interactions required for plant growth in saline conditions. Microbial consortia, consisting of compatible and synergistic strains of plant growth-promoting rhizobacteria (PGPR), rhizobia, and arbuscular mycorrhizal fungi (AMF), have emerged as a more robust and sustainable approach for soil reclamation and crop productivity in salt-affected areas.

These consortia are specifically designed to:

- Enhance microbial colonization and activity in the rhizosphere by providing complementary benefits such as biofilm formation, quorum

sensing, and enhanced root attachment (Bashan et al., 2004).

- Modulate plant physiological processes, including increased production of osmoprotectants (like proline), antioxidant enzymes (like SOD and CAT), and hormonal balance (auxins, cytokinins) under saline stress.
- Improve soil health, including organic matter mineralization, enzyme activity (e.g., dehydrogenase, urease), and nutrient cycling, thereby contributing to long-term fertility and structure restoration.

Case Studies and Success Stories

- In Punjab, India, co-inoculation of *Rhizobium* and AMF in chickpea improved yield by 25% under saline irrigation.
- In Egypt, lentil treated with halotolerant *Bacillus* spp. showed improved nodulation and higher seed protein content in salt-affected soils.
- A metagenomic study in Gujarat, India revealed enrichment of Actinomycetota and Proteobacteria in salt-tolerant lentil roots, highlighting the potential for functional microbiome utilization.

CONCLUSION

Microbial interventions through pulses offer an eco-friendly, cost-effective, and sustainable strategy for saline soil amelioration. Harnessing microbial diversity not only improves pulse productivity under salt stress but also rejuvenates degraded soils. Integrating traditional knowledge with modern tools like metagenomics, microbial formulations, and bioinformatics will pave the way for large-scale implementation in salt-affected regions.

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