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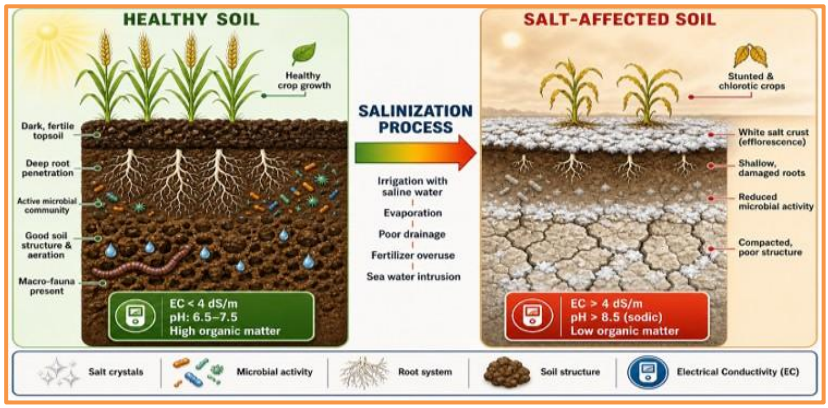
When Salt Takes Over the Soil: Can Friendly Microbes Help?

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Soil salinity poses a growing threat to sustainable agriculture by disrupting water absorption, nutrient balance, root development, and soil biological activity. Alongside conventional practices, plant growth-promoting rhizobacteria (PGPR) offer a promising approach to enhancing crop growth and salinity tolerance in salt-affected soils. Plant growth-promoting rhizobacteria, Rhizobium, arbuscular mycorrhizal fungi, and other halotolerant microbes support plant resilience through key mechanisms including phytohormone synthesis, ACC deaminase activity, exopolysaccharide secretion, and improved ionic homeostasis. These microbial technologies hold significant potential to complement existing approaches, ultimately helping to restore the productivity and ecological health of salt-stressed agricultural soils.

Keywords: Halotolerant bacteria; Plant growth-promoting rhizobacteria; Rhizosphere; Salinity stress

Soil salinity often develops unnoticed, with rising salt concentrations in the root zone progressively impairing germination, plant growth, and yield. The occurrence is especially common in areas where saline waters are used for irrigation, poorly drained, subjected to high evaporation rates, or subject to seawater intrusion. The build-up of salts in the soil renders it difficult for plants to absorb water, while the high concentration of sodium and chloride ions impedes the plants' ability to uptake nutrients and the overall functionality of their cellular machinery, thus diminishing the efficacy of the soil's biological activity (Choudhary *et al*., 2022; Kumawat *et al*., 2023). Thus, the question posed to agriculture is the one of salt tolerance in saline soils. The current set of saline soil management practices, which include enhanced drainage, the use of high-quality irrigation water, leaching of saline soils, the use of soil amendments, and salt-tolerant crops, remains integral in most approaches to saline soils. However, there is a growing interest in the scientific community to explore the potential of beneficial microorganisms in the rhizosphere as a possible solution to the salt build-up in soils.



How increasing soil salinity changes the soil environment and affects crop growth

The Invisible Workforce of Saline Soils

A single handful of healthy soil contains an incredibly large number of microorganisms that interact with each other and with plant roots, breaking down organic matter and returning it to the environment. There are also bacteria, fungi, and other types of microorganisms in the rhizosphere, the narrow soil region around plant roots. A rhizosphere contains plant root exudates, which attract microorganisms capable of improving the plant's nutrition, root system development, and resistance to environmental stressors. The salt effect on the soil microstructure is devastating. An increase in salinity may cause a decrease in the number of microbial species and populations and a reduction in their activity. On the other hand, there is an increase in the relative content of salt-resistant microbes. In saline soils, there is also a deterioration in the processes of organic matter formation and transformation and a decrease in the overall biological potential of the soil (Kumawat et al., 2022; Shah et al., 2022). Therefore, there is a need to modify salt-affected soils with halotolerant and halophilic microorganisms, which are of great interest to biotechnology and can act as bioinoculants. These microorganisms can tolerate high concentrations of salt and are therefore of great importance for the study and improvement of saline soils.

How Salt Stresses the Crop

Salinity influences plants in three ways. The first is that high salt levels reduce the amount of water taken up by the plant due to the high concentration of salt outside the roots, thereby inducing drought stress. The second mechanism by which salinity stresses plants is by ion toxicity. An excess of sodium and chloride ions in plant tissues disrupts enzyme activity, membrane function, and nutrient balance, inhibiting growth. The third way is by creating oxidative stress in plants. High levels of salt increase the production of reactive oxygen species that damage proteins, membranes, and other cellular components. As a result, germination rates are low, plants are stunted, and chlorophyll content, biomass, and yield are decreased (Shultana et al., 2022; Ali et al., 2022). Beneficial microorganisms cannot remove the sources of salinity but can improve several physiological processes in plants, including the mechanisms involved making the whole plant salt-tolerant.

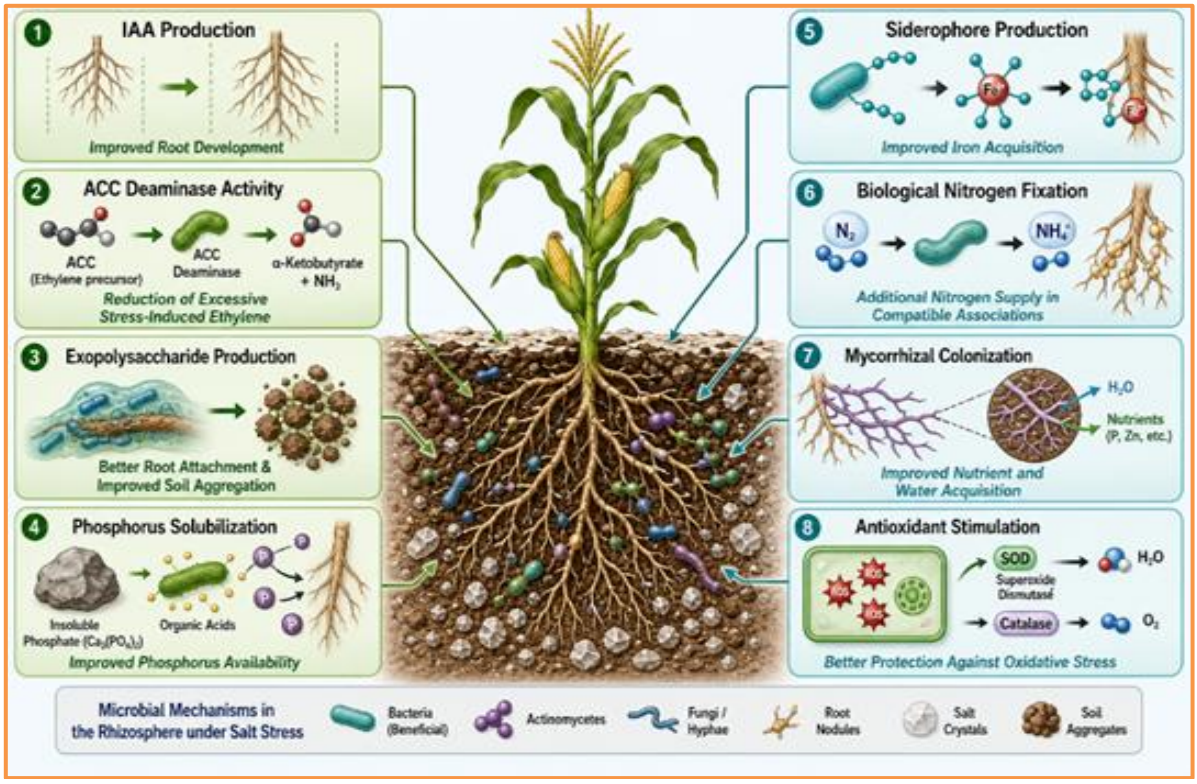
Effects of soil salinity on soil–plant processes and the potential role of beneficial microbes

Soil/Plant Problem under Salinity	What May Happen	How Beneficial Microbes May Help
High salt concentration	Water uptake by plants becomes difficult	Improve root–soil interactions and support water uptake
Nutrient imbalance	Reduced availability and uptake of essential nutrients	Mobilize nutrients and improve nutrient availability
Reduced microbial activity	Slower decomposition and nutrient cycling	Salt-tolerant microbes may remain active under saline conditions
Poor root development	Reduced root growth and overall plant development	Some plant-growth-promoting rhizobacteria (PGPR) can stimulate root growth
Nitrogen limitation	Poor nodulation and reduced nitrogen supply	Compatible *Rhizobium* can fix atmospheric nitrogen and support plant N nutrition
Oxidative stress	Accumulation of reactive oxygen species (ROS) and cellular damage	Some beneficial microbes can stimulate plant antioxidant and defence mechanisms

Friendly Microbes and Their Work

Plant growth-promoting rhizobacteria (PGPR) have been among the most extensively studied groups of microbes for improving crop performance under saline stress. These bacteria can improve plant tolerance through several key mechanisms. The production of indole-3-acetic acid (IAA), a hormone regulating cell division and root development, enables plants to

explore greater soil volumes for water and nutrients, with numerous studies reporting improved root and shoot growth under salinity. Another key mechanism is ACC deaminase activity, whereby bacteria breakdown the ethylene precursor, reducing stress-induced ethylene accumulation that would restrict plant growth (Shultana et al., 2022; Sayyed and Sagar, 2022). Furthermore, some PGPR produce exopolysaccharides (EPS), sticky biological compounds that improve root attachment, improve soil aggregation and water retention, and regulate ion movement around the root zone, creating a protective microbial environment for plants (Azeem et al., 2022). Nutrient acquisition is another valuable service, as salinity disrupts nutrient availability and uptake. Beneficial microorganisms offer a solution by producing siderophores that improve iron acquisition, while others contribute to phosphorus solubilisation and biological nitrogen fixation depending on the organism and soil conditions (Kumawat et al., 2023). Collectively, these mechanisms make PGPR excellent candidates for mitigating salt stress in crops.

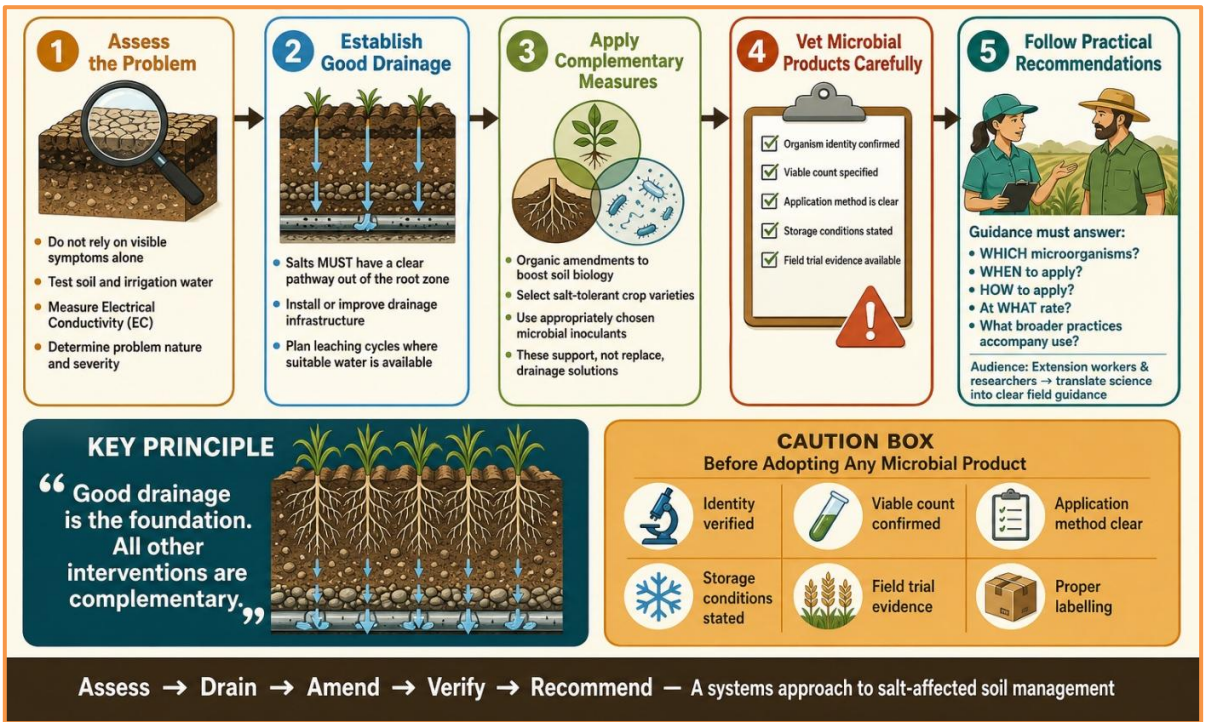


Major microbial mechanisms that may help crops under salinity

What Does the Evidence Tell Us?

Research with major crops including rice, wheat, maize, legumes and other plants has found certain strains of microbes to significantly improve germination, growth, nutrient status and yields under saline conditions. These include the genera Bacillus, Pseudomonas, Azospirillum, and mycorrhizal fungi (Gao et al. 2022; Kumawat et al. 2023). For instance, studies have reported an improvement in rice growth and nitrogen performance following inoculation with strains of salt tolerant bacteria (Khumairah et al. 2024), increased antioxidant activity of maize following treatment with Bacillus safensis (Azeem et al. 2022), and improved the growth and yield of salt stressed legumes colonized by mycorrhizal fungi (Sharma et al. 2017). Nevertheless, the performance of bacterial strains is inconsistent under different environmental conditions, as a number of factors including strain, genotype, salt concentration, soil moisture and application technique contribute to the outcome (Shahid et al. 2024). As such, strains that have been found to perform well under laboratory conditions may not necessarily have the same effect under field conditions.

What Farmers Can Do Now



Summary

Farmers managing salt-affected soils should first assess the nature and severity of the problem through soil and irrigation-water testing to determine electrical conductivity and other relevant properties, rather than relying solely on visible symptoms. Good drainage and planned leaching are essential for removing salts from the root zone, while organic amendments, salt-tolerant crop varieties, and selected microbial inoculants serve as complementary measures to support soil biological activity and crop performance Farmers should exercise caution when selecting microbial products, verifying the organism's identity, viable count, application method, storage conditions, and field trial evidence before adoption. Extension workers and researchers must translate microbial technologies into clear, practical guidance, informing farmers on which microorganisms to use, when and how to apply them, and what complementary management practices should accompany their use.