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Microbes, Minerals, and Salinity: A Triangular Stress Response in Soils

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Abstract

Soil salinization is a serious problem in arid and semi-arid farming regions, where it undermines soil health, reduces crop yields, and throws off the ecological balance. Over time, salts build up in the soil often due to excessive irrigation, poor drainage, and heavy use of chemical inputs. This not only changes the soil's physical and chemical nature but also disrupts its living systems, especially the microbes that are essential for healthy soil function. Microbial communities responsible for breaking down organic matter, recycling nutrients, and supporting plant root systems are particularly vulnerable to salt stress. High salinity creates osmotic pressure, introduces toxic ions like sodium and chloride, and disrupts the balance of nutrients. Together, these stressors weaken microbial activity, leading to noticeable drops in biomass, diversity, and enzyme production. Beneficial microbes, such as nitrogen-fixers, phosphate-solubilizers, and mycorrhizal fungi, are among the most sensitive. Their decline makes it harder for the soil to provide plants with essential nutrients like nitrogen, phosphorus, and potassium disrupting critical processes such as nitrification, denitrification, and nutrient mobilization. As a

result, soil fertility suffers. However, practices like adding organic matter and improving irrigation and drainage can help restore microbial life and revive nutrient cycling. This review brings together recent findings on how salinity affects soil microbes and nutrient dynamics.

1. Introduction

Soil salinity is one of the most pressing threats to global agricultural productivity and soil health (Singh *et al*., 2022). Current estimates indicate that more than 20 per cent of irrigated lands and nearly 50 per cent of cultivated areas worldwide are affected by salinity, a figure expected to rise due to climate change, intensified agriculture, and land mismanagement (Khondoker *et al*., 2023). Salinity stress, primarily characterized by the accumulation of soluble salts especially sodium chloride (NaCl) within the soil profile, leads to degradation of soil structure, impaired water uptake, and reduced plant growth and yield (Hailu *et al*., 2021). Beyond its direct effects on plant systems, salinity significantly disrupts soil microbial communities, which play a crucial role in maintaining soil ecosystem functions. Soil microbial populations comprising bacteria, fungi, actinomycetes, and archaea are fundamental to the regulation of key biogeochemical cycles, including organic matter decomposition, nutrient mineralization, nitrogen transformations, and phosphorus solubilisation (Zhang *et al*., 2024). Moreover, microbial interactions enhance plant health through symbiosis and pathogen suppression. However, elevated salt concentrations in soil adversely affect microbial diversity, composition, and functionality. Salinity induced osmotic stress, ionic toxicity (mainly from Na^+ and Cl^-), and nutrient imbalances inhibit microbial metabolism and enzymatic activities (Saleem et al., 2025). As a result, microbial-mediated processes particularly nitrogen and phosphorus cycling are disrupted, further deteriorating soil fertility and productivity.

Understanding the responses and adaptive mechanisms of microbial communities to salinity stress is essential for developing resilient agricultural systems. Certain halotolerant and halophilic microorganisms have evolved to thrive under high-salt conditions, maintaining their functional roles in nutrient cycling and soil health improvement. These microbes show promise as bioinoculants for enhancing soil quality in saline environments (Santhosh *et al*., 2025). It reviews the origin, mechanisms of soil salinity, its effects on microbial structure and function, and the implications for nutrient cycling. Additionally, it highlights mitigation strategies including the application of halophilic bioinoculants, phytoremediation, organic waste recycling, and improved irrigation practices. The review also identifies research gaps and proposes future directions aimed at deepening our understanding of microbial adaptations to salinity, with a view toward practical applications in sustainable soil and crop management (Bhardwaj *et al*., 2025).

2. Sources and causes of soil salinity

Soil salinity refers to the accumulation of soluble salts, primarily sodium (Na^+), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-) in the soil profile at concentrations detrimental to plant growth and microbial activity (Almudhafar *et al*., 2025). Salinization arises from both natural and anthropogenic sources and is particularly prevalent in arid and semi-arid regions, where high evapotranspiration rates exceed precipitation, leading to salt accumulation in the root zone (Gao *et al*., 2025).

3. Natural Facts of Soil Salinity:

3.1. Parent Rock Material Weathering

Weathering of the rocks deposits salts over geological scale that are later accumulated to the soil. Under zones of low precipitation, these salts do not get washed through but rather were left in the top soil levels.

3.2. Capillary Rise of Groundwater

The salty water underneath can flow up by the help of the capillary pressure in the places where the depth of rising water table is lowered. The process of evaporating water makes the surface of the soil dry leaving the surface salts and the surface salinization happens.

3.3. Seawater intrusion

Seawater can intrude the fresh water table as a result of over usage of ground water in the coastal zone as a result of which the salt concentration level of the land, as well as in the water used in irrigation, increases making this water harmful to the crops.

4. Anthropogenic (Human -Induced) Causes

4. 1. Saline Water-Based Irrigation

Poor quality of irrigation water is one of the leading cases of secondary salinization when the water used in the process has a high concentration of dissolved salts. Excessive usage results into salt accumulation within the root zone.

4.2. Poor Drainage Systems

In poorly drained soils, rain or irrigating water are incapable of percolation deep into the soils hence leading to waterlogging. This condition accelerates concentration of salt since evaporating water moves the salts to the surface.

4.3. Over-Irrigation and Flood Irrigation activities

Excessive use of water, more so in fields that have poor drainage, tends to increase ground water table and enable the upward transfer of salts.

4.4. Chemical Fertilizers

There are fertilizers that have sodium content or indirectly lead to salinization when over applied without regulation of usage.

Primary and secondary soil salinity significantly impact soil structure, microbial populations, and long-term agricultural sustainability. Understanding its root causes is essential for implementing effective mitigation strategies. Soil microbial communities highly diverse and influenced by soil type, vegetation, and management are crucial for maintaining soil health and ecosystem balance.

5.Important categories of Soil Microorganisms:

5.1. **Bacteria**

The most common of the microorganisms found in the soil are the bacteria. They take part in many biochemical activities like the decomposition of organic matter, fixation of nitrogen (e.g. Rhizobium), nitrification (e.g. Nitrosomonas, Nitrobacter) and denitrification. They are highly adaptive to varied conditions of soil, and a major player in conversion of nutrients.

5.2. **Fungi**

Fungi play a vital role in the breakdown of complex types of organic materials such as cellulose and lignin. The growth of mycorrhizal fungi including arbuscular mycorrhizae (AMF) on the roots of a plant provides a symbiosis system that increases nutrient absorption, especially phosphorus. The organic matter is also broken down by saprophytic fungi.

5.3. Actinomycetes

Certain decomposing bacteria that are filamentous, and they destroy resistant organic compounds and provide the soils with earthy odor. They contribute to formation of humus and are also producers of antibiotics in relation to suppression of soil-borne pathogens.

5.4. Archaea

Archea are also widely represented in soils although they are less researched but they are predominant in the extreme environment. They can take part in the oxidation of ammonia and methane production contributing to nitrogen and carbon cycles.

6. Impact of Salinity on the Microbial Dynamics of soils

Microbial communities and their functionality, composition, and diversities are strongly determined by soil salinity. The high salt concentrations provide harsh environments because it causes osmotic stress, ion toxicity, and nutrient imbalance, which have a negative impact on the microbial life. Due to this, salinity may cause a change in the structure of microbial population, may result in a decline in the microbial biomass, and may cause the degradation of microbial functions of the soil that are vital to maintaining the sustainability of the ecosystem.

6.1. Microbial Biomass and Diversity Reduction

The overall effect of salinity stress is the reduction of microbial biomass. The taxa that are sensitive to salt stress become inhibited first (under saline conditions), including nitrogen-fixing bacteria and phosphate-fixing organisms. The outcome is the loss of microbial diversity especially non-halotolerant species. Evidence has revealed that salinity depressed other beneficial genera like Rhizobium, Azospirillum and Pseudomonas (Ren *et al*., 2016).

6.2. Community Structure Shifts

Due to saline conditions, there will be changes in the compositions of microbial communities. Halotolerant and halophilic microorganisms, including some species of Halobacterium, Bacillus and Streptomyces, are usually the dominant ones. These organisms have adaptive strategies that allow them to endure high-salt conditions, but is not able to provide all of the structurally important ecosystem services that more diverse microbial consortia do.

6.3. Impairment of Enzyme Activity

Urease, dehydrogenase, phosphatase, and Beta-glucosidase are enzymes found in the soil and are important in the recycling of nutrients and decomposition of organic matter. Salinity minimizes the activity of such enzymes, thus slows down microbial metabolism and nutrient transformations. This deteriorates important processes such as nitrogen mineralization, nitrification and phosphorus solubilisation (Xiao *et al*., 2025).

6.4. Breakage of Microbial Interaction

Salinity interferes with the interaction between plants and microbes, including interaction with mycorrhizal fungi and rhizobia. These symbioses play critical roles in plant nutrient acquisition and plant tolerance; the interference of these symbioses helps in explaining diminished plant growth and productivity on salty soils (Ren *et al*., 2016).

6.5. Ecological and Agricultural Implications

There is an overall impact in terms of all these effects of salinity on microbial dynamics by reducing the fertility of soils, poor nutrient availability and poor soil structure. Such alterations do not only influence microbial ecosystem services; they also reduce productivity and sustainability of agriculture. To sum up, salinity stress has a highly adverse effect on the dynamics of soil microbes. These changes are critical in strategizing the management processes to recover the microbial activities in the salt-affected ecosystems to regain soil recovery and resilience.

7. Salinity and Soil Nutrient Cycling

The process of soil nutrient cycling is complex and much the nutrient cycling is performed by means of a microbial community, which degrades all the organic material and the transformation of nutrients in a form which plants can absorb. Salinity stress, however, interferes with such microbial activities and it has negative implications in cycling of essential nutrients including nitrogen, phosphorous, potassium, and micronutrients. This imbalance does not only lower fertile soil, but it also blocked plant growth and agricultural output.

7.1. Nitrogen Cycle

The impact of salinity on the nitrogen cycle is vivid. High concentration of salt can kill processes such as nitrogen fixation, nitrification and denitrification. Salinity especially to the nitrogen-fixing bacteria like Rhizobium and Azospirillum makes them too susceptible to the salinity and this increases the loss of nitrogen input in soils. Saline nutrient conditions also inhibit nitrifying bacteria (Nitrosomonas and Nitrobacter) which causes a decrease in ammonia to nitrate conversion. Moreover, the denitrifying bacteria can be inhibited or even synthesize excessive amounts of nitrous oxide (N_2O), which happens to be an effective greenhouse gas during the salinity pressure (Vamshi *et al*., 2023).

7.2. Phosphorus Availability

A lack of phosphorus in salty soils is a significant issue because of a lesser microbial solubilization and a larger binding with calcium and magnesium salts. Salinity sensitivity of phosphate-solubilizing microorganisms (PSMs), that transform insoluble phosphorus into the plant-available, is recognized. Consequently, the cycling of phosphorus is reduced, minimizing the ability of plants to absorb them and leading to cases of nutrient deficiencies (Thampi *et al*., 2023).

7.3. Micronutrients and Potassium

Saline soils contain high concentrations of sodium ions (Na^+) which can cause displacement of potassium (K^+) occur on the soil exchange sites, reducing the availability to growing plants. Salt stress induces the ionic imbalance, which also leads to the shortage of those micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) since salt stress changes the soil pH and redox state that further decreases solubility and uptake of nutrients.

7.4. Activities by Microbial Enzymes

The salinity of the soil inhibits the enzymatic action of processes which transform the nutrients i.e. the urease (urea source of nitrogen), phosphatase (phosphorus source), and dehydrogenase (general activity of all microbes). These enzymes are lessened and stimulate the attenuation of nutrient mineralization and the re-use of nutrients which have a direct correlation with the efficiency of nutrient cycling (Goszcz *et al*., 2025).

8. The mechanisms of adaptation and tolerance of microbes

Although most soil microorganisms are negatively affected by salinity, some microbes developed several physiological and biochemical processes enabling them to tolerate and adapt

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to salinity. Such halotolerant and halophilic microorganisms are important in keeping the soil functioning despite the salinity stress since they keep cycling of nutrients, decomposition of organic matter and growth of the plants.

8.1. Compatible Solutes Osmotic Adjustment

The accumulation of compatible-solutes or osmo protectants like proline, glycine betaine, trehalose and ectoine is one of the most widespread ways of response to salinity stress produced by microbes. Such molecules can assist to generate cellular osmotic balance without disturbing the normal metabolic pathways. microbes can maintain the internal and the external pressure of osmosis, which prevents a dehydration in their cells as well as prohibits any inactivation of the enzymes (Goszcz *et al*., 2025).

8.2. Transport of Ions and Homeostasis

There are ion transport systems specialized to elaborate intracellular concentrations of ions on salt-tolerant microbes. These consist of Na^+/H^+ antiporters, K^+ transport systems and Cl^- channels that aid in the removal of excess sodium as well as provision of adequate amounts of potassium and the other important ions. This process prevents disruption of cell structure and disruption of enzyme action in salty environments (Joshi et al., 2025).

8.3. Protein Modifications and Cell Membrane

Microbes will change their membrane lipid to keep the fluidity and escape the situation of salt damage under salt stress. Further, the salt shock proteins and the heat shock proteins cause the stabilization of cellular proteins and enzymes and lead to an increase in tolerance to stress.

8.4. Exopolysaccharides (EPS) production

Substantial quantity of halotolerant bacteria and fungi establish exopolysaccharides, safeguarding a cell with a protective film of biofilm. A favorable microenvironment, which alleviates salt stress due to water entrapment, binding of toxic ions, and the generation of an ideal microenvironment is produced by EPS. (Lalitha *et al*., 2022).

8.5. Salinity-Evidence of Symbiotic Efficiency

There are those that are not lost in salty environments such as salt tolerant Rhizobium strains and arbuscular mycorrhizal fungi. Such associations are able to benefit the growth of plants by enhancing nutrient acquisition and tolerance (Bhardwaj *et al*., 2025).

Conclusion

Soil salinity poses a significant threat to the biological integrity of soil ecosystems, particularly by disrupting microbial communities essential for nutrient cycling and soil fertility. The suppression of key microbial functions such as nitrogen fixation, nitrification, and phosphorus solubilization under saline conditions compromises plant growth and long-term agricultural sustainability. However, halotolerant and halophilic microorganisms exhibit promising adaptive traits, including osmo-protectant synthesis, ion regulation, and stress-responsive gene expression, making them viable candidates for use as bioinoculants in saline soils. Integrated strategies involving microbial biotechnology, organic amendments, improved irrigation, and phytoremediation hold potential to mitigate salinity impacts and restore microbial functionality. Advancing our understanding of microbial ecology under saline stress especially through metagenomic and molecular tools will be pivotal in identifying resilient taxa and designing microbial-based interventions for climate-resilient and sustainable agriculture.

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