Breaking the Salt Barrier: Integrated Agronomic Pathways for Enhancing Crop Resilience

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ABSTRACT

Salinity and alkalinity are major abiotic constraints limiting crop productivity, particularly in arid, semi-arid, irrigated and poorly drained environments. Excess soluble salts cause osmotic stress, ionic toxicity and oxidative damage, while sodicity and high soil pH impair soil structure and nutrient availability. Plants mitigate salt stress through osmotic adjustment, ion exclusion, vacuolar compartmentation, antioxidant defence and maintenance of ion homeostasis. However, intrinsic tolerance alone may be insufficient to sustain productivity under field conditions. Agronomic management therefore provides an essential complementary approach through improved drainage, leaching, efficient irrigation, soil amendments, salt-tolerant crops, appropriate planting methods, balanced nutrient management, seed priming and biological interventions. This review summarizes the major impacts of salinity and alkalinity on plants and evaluates key agronomic strategies for improving crop establishment, growth and productivity in salt-affected environments.

INTRODUCTION:

Agricultural intensification, mismanagement of irrigation water, inadequate drainage and climatic variability are major drivers of increasing salt accumulation in agricultural soils. Salinity is particularly widespread in arid and semi-arid regions, where high evaporative demand and limited rainfall promote salt concentration in the root zone. Poor-quality irrigation water, shallow water tables and inadequate drainage further aggravate salt accumulation. Globally, approximately 1.381 billion ha are affected by salinity and/or sodicity, posing a substantial threat to soil health and agricultural productivity.

Salt-affected soils are broadly classified as saline, sodic/alkaline and saline-sodic soils. Saline soils contain high concentrations of soluble salts, whereas sodic soils are characterized by excessive exchangeable sodium, elevated pH, clay dispersion, surface crusting and reduced infiltration. Saline-sodic soils exhibit features of both conditions. Effective management therefore requires diagnosis based on electrical conductivity (EC), soil pH and exchangeable sodium percentage (ESP). Salinity tolerance involves coordinated morphological, physiological and biochemical responses that maintain water status, photosynthetic function and cellular integrity (Acosta-Motos *et al*., 2017). Ion homeostasis, osmoprotectant accumulation, antioxidant defence and molecular signalling further contribute to plant adaptation to salinity (Gupta and Huang, 2014).

Physiological Impacts of Salinity and Alkalinity Stress

Salinity affects plants through two overlapping phases: an initial osmotic phase, which rapidly reduces water uptake, stomatal conductance and cell expansion, followed by an ionic phase associated with the progressive accumulation of Na^+ and Cl^- in leaf tissues. Prolonged ion accumulation causes chlorosis, necrosis, premature senescence and reduced photosynthetic capacity. Excess Na^+ disrupts K^+ acquisition and the K^+/Na^+ balance, impairing enzyme activity, protein synthesis and cellular metabolism, while salinity and high soil pH can also restrict the availability of Ca, N, P and micronutrients such as Fe, Zn and Mn.

Plant salt tolerance primarily involves osmotic tolerance, ion exclusion and tissue tolerance. Osmotic adjustment is achieved through the accumulation of compatible solutes such as proline, glycine betaine and soluble sugars; ion exclusion limits Na^+ and Cl^- uptake and transport to shoots, while tissue tolerance enables toxic ions to be compartmentalized within vacuoles or specialized tissues.

Agronomic Manipulations for Salinity and Alkalinity Management

Effective management of salt-affected soils requires an integrated soil-water-crop nutrient approach rather than reliance on a single practice. Management should be guided by soil EC, pH and ESP and irrigation-water quality, particularly EC, SAR and RSC.

1. Soil and Water Management

Drainage and leaching are the primary interventions for saline soils. Drainage prevents salt redistribution within the profile, while leaching moves soluble salts below the effective root zone. In sodic soils, exchangeable Na^+ must first be displaced, generally using Ca-based amendments, before effective leaching. Land levelling improves the uniformity of water distribution, while drip, alternate-furrow and conjunctive irrigation can improve water-use efficiency and modify salt distribution. Bio-drainage may also be useful under suitable conditions.

2. Chemical and Organic Amendments

Gypsum ($CaSO_4.2H_2O$) is widely used for sodic soil reclamation because Ca^{2+} replaces exchangeable Na^+, facilitating its subsequent removal through leaching. Elemental sulphur and other acid-forming amendments may be used where appropriate. Organic materials such as farmyard manure, compost, crop residues, vermicompost and green manure improve soil aggregation, water retention and nutrient availability. Biochar represents an emerging amendment, although further field validation is required.

3. Crop and Variety Selection

Selection of salt-tolerant crops and cultivars provides a practical means of maintaining productivity during reclamation. Barley, cotton and sugar beet are relatively tolerant crops, while CSR-series rice and KRL-series wheat are examples of salt-tolerant cultivars. Crop rotation incorporating tolerant crops and suitable deep-rooted species can further support soil productivity and water-table management.

4. Sowing and Seed Priming

Salt distribution within the seedbed should be considered when selecting planting positions. Ridge-furrow planting, particularly sowing on the ridge shoulder or flank, can improve establishment under saline conditions. Mulching reduces evaporation and upward salt movement. Hydropriming, halopriming, osmopriming, hormonal priming and biopriming can improve germination and early seedling performance under salinity.

5. Nutrient Management and Biostimulants

Balanced nutrition is essential because salinity frequently causes nutrient imbalance. Adequate K^+ and Ca^{2+} support ionic balance and membrane stability, while Zn, Fe and Mn may require supplementation under alkaline conditions. Silicon, proline, glycine betaine, trehalose, salicylic acid and seaweed extracts have potential as stress-mitigating inputs, although their effectiveness depends on crop, dose and stress intensity.

6. Biological Approaches and Alternate Land Use

PGPR and arbuscular mycorrhizal fungi (AMF) can improve nutrient acquisition, water relations and plant performance under saline conditions, whereas conventional reclamation is economically difficult, halophytes and agroforestry systems provide alternative options for productive use of salt-affected land.



Figure 1. Salinity-affected soil and integrated agronomic approaches for enhancing crop resilience and productivity

Table 1: Integrated framework

Salt-affected condition	Priority management	Complementary practices
Saline soil	Drainage + leaching	Irrigation management, tolerant crops, organic amendments
Sodic/alkaline soil	Gypsum/Ca amendment + leaching	Organic matter, drainage, tolerant cultivars
Saline-sodic soil	Correct sodicity + salt removal	Drainage, leaching, amendments and tolerant crops

CONCLUSION

Salinity and alkalinity require coordinated management of soil, water, crops, nutrients and biological resources. Combining drainage

and leaching with appropriate amendments, irrigation practices, tolerant cultivars, seed priming, balanced nutrition and microbial interventions can improve crop establishment, productivity and the sustainable use of salt-affected soils.

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