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Research Article

Soil Salinity Management and Salt-Tolerant Cropping Systems for Coastal and Irrigated Agriculture

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Abstract

Soil salinity affects hundreds of millions of hectares of cropland and threatens food production in coastal deltas, arid irrigated schemes, and areas where groundwater is brackish or drainage is poor. Salt reduces water uptake, disrupts nutrient balance, damages soil structure, and lowers yield, often unevenly across a field. This article reviews salinity management as an integrated agronomic problem, covering the causes of salt accumulation, how crops respond to salt stress, and the practical tools available to farmers and irrigation managers: drainage and leaching, water quality management, gypsum and organic amendments, salt-tolerant varieties, halophyte rotations, precision irrigation, and landscape-level water governance. It shows that no single tool restores a saline field on its own, and that the best results come from combining drainage, leaching, soil improvement, and tolerant crops in a sequence matched to soil type, water availability, and cost. It proposes a field-scale decision framework based on measurement, diagnosis, and monitoring, and it identifies research and policy priorities for keeping saline land productive without deepening inequity in access to good water and drainage.

Keywords: soil salinity; salt tolerance; drainage; leaching; gypsum; irrigation water quality; halophytes; coastal agriculture

1. Introduction

Salt is a quiet constraint. Unlike a drought that wilts a crop or a pest that visibly eats leaves, salinity often reduces growth gradually, unevenly, and without a clear single cause that a farmer can see (Rhoads, 1992; Qadir et al., 2014). A field may have patches where seedlings emerge poorly, plants are stunted, leaves show marginal burn, and yield is low, while nearby patches appear normal. Over seasons, the patches expand, fallow periods lengthen, and land that once supported a full crop becomes marginal. Global estimates vary with definition and measurement, but saline and sodic soils affect a large share of irrigated land and a substantial area of rain-fed coastal land, and the area is expanding where irrigation expands without drainage, where sea-level rise and storm surges push salt into deltas, and where groundwater is over-pumped and becomes more saline (FAO, 2020; Qadir et al., 2014).

Salinity is therefore not only a soil chemistry problem. It is a water management, drainage, crop choice, and governance problem. Irrigation water always contains some salt. When water evaporates or is taken up by crops, salt remains. If there is no drainage or leaching to move salt below the root zone, salt accumulates. In coastal areas, seawater intrusion, tidal flooding, and saline groundwater can add salt from below and from the side. In arid areas, high evaporation and low rainfall can concentrate salt near the surface. In all cases, the agronomic question is the same: how can salt be kept below the level that damages the crop, at a cost farmers can afford, with water that is available, and without moving the salt problem to a neighbour or a downstream ecosystem?

This article reviews salinity management as agronomy. It explains how salt harms crops and soils, how to measure and diagnose salinity, and how drainage, leaching, amendments, tolerant varieties, halophytes, and precision irrigation can be combined. It gives particular attention to smallholders and coastal farmers, where water quality and drainage are often poor, and where the cost of a wrong decision, such as planting a sensitive variety on a saline patch, can be a lost season.

2. How Salt Harms Crops and Soils

Salt harms crops through osmotic stress, ion toxicity, and nutrient imbalance. Osmotic stress occurs because dissolved salts lower the water potential of the soil solution, making it harder for roots to take up water even when the soil feels moist (Munns and Tester, 2008; Flowers, 2004). Ion toxicity occurs when sodium and chloride accumulate in leaves, damaging enzymes, membranes, and photosynthetic machinery. Nutrient imbalance occurs because excess sodium competes with potassium, calcium, and magnesium uptake, and high pH in sodic soils can reduce availability of iron, zinc, and phosphorus (Rhoads, 1992; Qadir et al., 2014). Crops differ in sensitivity and in the growth stage at which they are most vulnerable. Seed germination and seedling establishment are often more sensitive than later growth, because seedlings have small roots and limited reserves. Flowering and grain filling can also be sensitive, because salt stress reduces assimilate supply and grain set.

Salt also harms soil structure. In sodic soils, excess sodium disperses clay, destroys aggregation, reduces infiltration, and creates crusts that impede emergence and root growth (Qadir et al., 2014; Rhoads, 1992). A soil that was once friable can become hard, poorly aerated, and difficult to till. This creates a feedback loop: poor structure reduces leaching, reduced leaching increases salt, and increased salt further damages structure. Breaking this loop requires both chemical and physical action, for example gypsum to replace sodium on exchange sites, organic matter to rebuild aggregation, and drainage to allow leaching (Qadir et al., 2014; Oster et al., 1999).

Measurement is the foundation of management. Electrical conductivity of a saturated soil paste extract, ECe, is the standard measure of soil salinity, while sodium adsorption ratio, SAR, and exchangeable sodium percentage, ESP, indicate sodicity risk (Rhoads, 1992; Ayers and Westcot, 1985). Irrigation water quality is assessed by electrical conductivity, SAR, and specific ions such as sodium, chloride, and boron. Low-cost field meters, soil test laboratories, and remote sensing can all help, but the key is to measure in the right places: salinity varies within a field, with depth, and over the season, so a single sample can mislead. Farmers who map saline patches, even with simple observations of emergence, crusting, and plant colour, can target interventions where they matter most.

3. Drainage, Leaching, and Water Management

Drainage is the most fundamental salinity control because without a way for salt to leave the root zone, every other intervention is temporary (Oster et al., 1999; Qadir et al., 2014). Surface drainage removes excess water and salt after heavy rain or irrigation, while subsurface drainage lowers the water table and prevents capillary rise of saline groundwater. Drainage design must consider soil texture, slope, outlet availability, and maintenance. A drain that is blocked, silted, or without a safe outlet can fail, and drainage water itself must be managed so it does not salinise downstream land or waterways.

Leaching is the deliberate application of extra water to move salt below the root zone. The leaching requirement depends on irrigation water salinity, crop tolerance, and drainage. A common rule is that more saline water requires a larger leaching fraction, but too much leaching wastes water and can leach nutrients (Ayers and Westcot, 1985). Timing matters: leaching is most effective when the soil is not already waterlogged, when drainage is functioning, and when it is done before planting or at a tolerant growth stage. In water-scarce areas, leaching must be balanced against water saving, which is why precise leaching, using just enough water to move salt below the root zone without over-irrigating, is preferable to blanket over-irrigation.

Water quality management includes blending saline and fresh water, using saline water only at tolerant stages, and using drip irrigation to keep salt at the edge of the wetted zone (Ayers and Westcot, 1985; Rhoads, 1992). Drip irrigation can allow farmers to use moderately saline water that would damage crops under flood irrigation, because it maintains a low-salinity zone near the emitter and avoids wetting leaves with salty water. However, drip systems require filtration, maintenance, and careful emitter placement, and they can concentrate salt at the wetting front if leaching is insufficient. Figure 1 summarises the pattern from the cited syntheses: drainage, leaching, tolerant varieties, and amendments together reduce salinity more than any single tool.

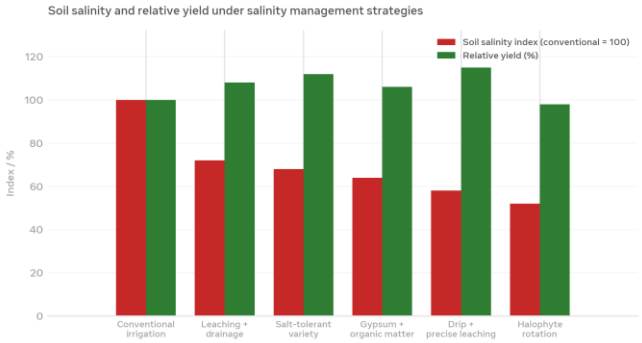

Figure 1. Soil salinity and relative yield under salinity management strategies, based on synthesis of the reviews and meta-analyses cited in the text. Values vary by soil, water quality, crop, and management.

4. Amendments, Organic Matter, and Soil Structure

Gypsum, calcium sulfate, is the most widely used chemical amendment for sodic soils. Calcium replaces sodium on exchange sites, improving aggregation and infiltration so that sodium can be leached (Qadir et al., 2014; Oster et al., 1999). Gypsum is most effective when combined with leaching and drainage; without water movement, displaced sodium remains in the profile. The required gypsum rate depends on exchangeable sodium, soil depth, and clay content, and should be based on a soil test rather than a fixed recommendation. Other amendments, including elemental sulfur, sulfuric acid, and calcium chloride, can also supply calcium or lower pH, but they have different costs, safety, and availability constraints.

Organic matter is a powerful complement to gypsum. Compost, manure, crop residues, and green manures improve aggregation, infiltration, water storage, and biological activity, and can help leaching by creating pores that move water and salt downward (Lal, 2004; Qadir et al., 2014). Organic amendments also provide nutrients and can buffer pH. In saline soils, organic matter alone will not remove salt, but it can make leaching and drainage more effective and can help seedlings establish in a hostile surface layer. Cover crops and mulches can reduce evaporation, which

reduces upward movement of salt, and can protect the soil surface from crusting.

Biochar, compost teas, and microbial inoculants are sometimes promoted for saline soils, but evidence is mixed and context-dependent. Some studies report improved growth and soil properties, while others report little effect or even negative effects if the amendment itself contains salt (Qadir et al., 2014). Farmers should treat such products as experimental: test on a small area, measure ECe and yield, and compare with a control before scaling. The most reliable soil improvement remains the combination of gypsum where sodicity is diagnosed, organic matter, and water movement.

5. Salt-Tolerant Varieties and Halophyte Rotations

Breeding for salt tolerance has produced varieties of rice, wheat, barley, sorghum, and legumes that can maintain yield under moderate salinity better than sensitive varieties (Flowers, 2004; Munns and Tester, 2008). Tolerance mechanisms include sodium exclusion from shoots, compartmentalisation of sodium in vacuoles, osmotic adjustment, and maintenance of potassium uptake. Tolerance is not a single trait, and it often trades off with yield under non-saline conditions, so a tolerant variety may yield less than a sensitive variety on good soil but more on saline soil (Flowers, 2004; Munns and Tester, 2008). Variety choice should therefore be matched to field salinity, not applied blanket-wise across a farm.

Halophytes, plants that naturally tolerate high salinity, offer another option for severely saline land where conventional crops fail. Species such as Salicornia, Atriplex, and Suaeda can produce fodder, oilseed, vegetables, or biomass on saline land, and can help remove salt and improve soil over time through phytoextraction and organic matter addition (Flowers and Colmer, 2008; Glenn et al., 1999). Halophyte rotations can be used to reclaim land in stages: grow halophytes to reduce salt and improve structure, then introduce tolerant crops, then less tolerant crops as salinity falls. Markets for halophyte products are still limited in many regions, so halophyte systems need market development as well as agronomic research.

Crop choice and rotation also matter. Barley and cotton are more salt-tolerant than maize and many legumes, while rice can tolerate moderate salinity if water management prevents salt accumulation at sensitive stages (Ayers and Westcot, 1985; Flowers, 2004). Rotating a tolerant crop with a sensitive crop can allow farmers to use saline patches productively while reserving better land for sensitive, high-value crops. Intercropping and relay cropping can also help, but they must be designed so that the tolerant crop does not shade or compete excessively with the sensitive crop.

6. Coastal Systems, Sea-Level Rise, and Governance

Coastal deltas face a distinct salinity challenge: sea-level rise, storm surges, and upstream water abstraction can push salt into rivers, canals, and groundwater, making previously fresh land saline in a single season (FAO, 2020; IPCC, 2022). In deltas such as the Mekong, Ganges-Brahmaputra, and Niger, farmers have adapted by shifting to salt-tolerant rice, shrimp-rice rotations, and halophyte systems, and by building bunds, sluices, and community drainage (FAO, 2020). These adaptations require collective action: a single farmer cannot control tidal flooding or canal salinity alone. Community sluice management, shared drainage maintenance, and early warning of saline intrusion are essential.

Governance of water and drainage is therefore central to salinity management. Water allocation rules, drainage maintenance responsibilities, and discharge standards determine whether salt is removed from a scheme or simply moved downstream. Subsidies for pumps and fertiliser that encourage over-irrigation without drainage can worsen salinity, while public investment in drainage, water measurement, and soil testing can make salinity management possible at scale (Qadir et al., 2014; FAO, 2020). Land tenure also matters: farmers who expect to lose land are less likely to invest in drainage, gypsum, or trees whose benefits accrue over years.

7. A Field-Scale Decision Framework

A practical framework for saline fields can be stated in six steps. First, measure: test soil ECe, SAR, and pH, and test irrigation water EC and SAR, at multiple points and depths. Second, diagnose: is the problem salinity, sodicity, or both, and is it caused by irrigation, drainage, seawater, or groundwater? Third, fix water movement: ensure drainage and an outlet, and plan leaching. Fourth, amend where diagnosed: apply gypsum for sodicity, add organic matter, and avoid amendments that add salt. Fifth, choose crops: plant tolerant varieties on saline patches, sensitive varieties on good land, and consider halophytes for severely saline patches. Sixth, monitor: re-test ECe after leaching and after the season, record yield by patch, and adjust the plan. Table 1 summarises salinity management bundles, while Table 2 proposes indicators for monitoring.

Table 1. Salinity management bundles and their main mechanisms.

Bundle	Core practices	Main mechanism	Likely outcome
Drainage-first bundle	Subsurface drainage, leaching, outlet	Salt removal, water table control	Lower ECe, better emergence
Amendment bundle	Gypsum, organic matter, leaching	Sodium replacement, aggregation	Better infiltration, structure
Tolerant-crop bundle	Salt-tolerant variety, tolerant rotation	Exclusion, compartmentalisation	Higher yield on saline patches
Precision water bundle	Drip, blending, staged saline use	Low-salinity root zone	Higher water productivity
Halophyte reclamation	Halophyte rotation, leaching, monitoring	Salt removal, organic matter	Gradual reclamation of severe patches

Table 2. A balanced indicator set for salinity management.

Dimension	Indicator	Practical measurement
Soil salinity	ECe, SAR, ESP	Soil and water tests
Drainage	Water table depth, drain flow	Well observations, drain checks
Yield	Yield by patch, emergence	Harvest and emergence records
Water	Water EC, leaching fraction	Meter, records
Economics	Gross margin, amendment cost	Cost, price, yield records
Equity	Access to drainage and good water	Association records, survey

8. Future Research and Policy Priorities

Future research should report salinity, yield, water use, cost, and labour together, rather than yield alone. Long-term trials are needed because salinity changes slowly and reclamation can take several seasons. Research on low-cost salinity monitoring, including field meters, mobile phone tools, and remote sensing validated against ground measurements, can help farmers target interventions (FAO, 2020; Qadir et al., 2014). Breeding should combine salt tolerance with yield, quality, and tolerance to drought and heat, because saline fields are often also hot and dry. Policy should invest in drainage, soil testing, water measurement, and community governance, and should ensure that drainage water is managed safely. Subsidies for pumps and water that encourage over-irrigation without drainage should be reviewed, and support for tolerant seed, gypsum, and halophyte markets should be expanded where diagnosis shows they are needed.

9. Conclusion

Soil salinity is manageable, but only when it is measured, diagnosed, and treated as a system. Drainage and leaching remove salt, gypsum and organic matter repair structure, tolerant varieties and halophytes allow productive use of saline land, and precision water management keeps salt below damaging levels. When these tools are combined in a sequence matched to soil, water, and cost, saline land can be kept productive and even reclaimed. When they are applied in isolation, or without drainage, the result is often wasted money and continued decline. The priority is practical: test soil and water, fix drainage, leach precisely, amend where diagnosed, plant the right crop for each patch, and monitor after each season.

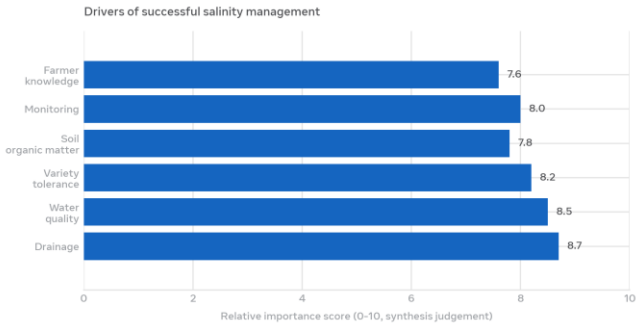

Figure 2. Drivers of successful salinity management, based on synthesis judgement from the cited evidence. Drainage and water quality are central.

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Conflict of Interest

The authors declare no conflict of interest.

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