CAREER POINT INTERNATIONAL JOURNAL OF RESEARCH
Career Point International Journal of Research (CPIJR)
©2022 CPIJR | Volume 1 | Issue 5 | ISSN : 2583-1895
Jan-Mar-2026 | DOI: https://doi.org/10.5281/ze 19870960nodo.19903799

Saline Soils: Distribution, Impact on Crop Production, and Management Strategies – A Review

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Abstract

Soil salinity is one of the most severe forms of land degradation limiting agricultural productivity, particularly in arid and semi-arid regions where irrigation is essential for crop production. The accumulation of soluble salts in the root zone adversely affects soil physical, chemical, and biological properties, resulting in poor soil structure, nutrient imbalance, reduced microbial activity, and ultimately significant yield losses in many important crops. According to the Food and Agriculture Organization, soil salinization is an expanding global challenge that poses a serious threat to food security, especially in irrigated agricultural systems. This review presents a comprehensive overview of the definition and classification of saline soils, their origin and distribution, and their effects on soil properties and crop growth. It also discusses methods for assessment and mapping of saline soils, and critically examines integrated management and reclamation strategies, including physical, chemical, biological, and agronomic approaches. Special emphasis is given to sustainable and site-specific practices such as drainage and leaching, chemical amendments, organic matter management, use of salt-tolerant crops, and improved irrigation strategies. The role of research, policy support, and future technological interventions is also highlighted. Overall, the review underscores that effective management of saline soils requires a holistic and coordinated approach to restore soil health, enhance crop productivity, and ensure long-term agricultural sustainability under changing climatic conditions.

Keywords: Saline soils, salt stress, soil degradation, crop productivity, reclamation, sustainable agriculture

1. Introduction

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Soil salinity is widely recognized as one of the most serious constraints to agricultural production across the world, particularly in arid and semi-arid regions where evapotranspiration exceeds precipitation and irrigation is essential for crop cultivation. The accumulation of soluble salts in the root zone adversely affects soil health and crop performance by creating unfavorable physical, chemical, and biological conditions for plant growth. A substantial proportion of the world's irrigated agricultural lands are affected by salinity to varying degrees, resulting in significant yield reductions in many economically important crops such as rice, wheat, cotton, and vegetables. The problem is not only agronomic but also socio-economic, as salinity directly threatens farmers' livelihoods and regional food security.

According to the Food and Agriculture Organization, soil salinization is an expanding global challenge and represents a growing threat to food security, particularly in regions where irrigation is indispensable for sustaining crop production. In many irrigated command areas, continuous use of water without adequate drainage, coupled with high evaporation rates, leads to the gradual buildup of salts in the soil profile. Over time, this process reduces soil productivity, limits crop choice, and increases the cost and complexity of land management and reclamation. In countries like India, the problem of soil salinity and sodicity affects millions of hectares of agricultural land, especially in canal-irrigated tracts, arid and semi-arid regions, and coastal zones. These areas are particularly vulnerable due to shallow and saline groundwater tables, seawater intrusion in coastal belts, and the long-term use of marginal-quality irrigation water. The situation is further aggravated by climate change, which is expected to intensify salinity risks through rising temperatures, altered rainfall patterns, increased evapotranspiration, and more frequent extreme weather events such as droughts and storm surges. Such changes can accelerate salt accumulation in soils and expand the extent of salt-affected lands. Given the scale and complexity of the problem, a clear understanding of the nature, origin, and behavior of saline soils is essential for developing effective and sustainable management strategies. Integrated approaches that combine sound soil, water, and crop management practices are required to mitigate the adverse effects of salinity and to restore the productivity of salt-affected lands. Therefore, addressing soil salinity is not only a technical necessity but also a critical component of achieving long-term agricultural sustainability and food security in vulnerable regions.2.

Definition and Classification of Saline Soils

Saline soils are soils that contain excessive amounts of soluble salts in the root zone, primarily chlorides, sulfates, and bicarbonates of sodium, calcium, and magnesium. These soils are generally characterized by:

- Electrical conductivity (ECe) of the saturated soil extract > 4 dS m^{-1}
- pH usually < 8.5
- Exchangeable sodium percentage (ESP) < 15

Based on salt composition and soil reaction, salt-affected soils are broadly classified into:

1. Saline soils
2. Sodic (alkali) soils
3. Saline-sodic soils

This classification is important because each category requires different management and reclamation strategies.

3. Origin and Distribution of Saline Soils

Saline soils may be primary (natural) or secondary (human-induced) in origin.

3.1 Natural Causes

- Weathering of parent rocks rich in soluble salts
- Deposition of salts through marine transgressions or aeolian processes
- Capillary rise of saline groundwater in arid and semi-arid climates

3.2 Human-Induced Causes

- Excessive and inefficient irrigation without adequate drainage
- Use of saline or sodic irrigation water

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- Seepage from canals and reservoirs
- Deforestation and land-use changes affecting the water balance

Globally, large tracts of saline soils are found in Central and West Asia, Australia, parts of Africa, and South Asia. In India, major salt-affected areas occur in Rajasthan, Gujarat, Haryana, Punjab, Uttar Pradesh, and coastal regions.

4. Effects of Salinity on Soil Properties

Soil salinity exerts profound influences on the physical, chemical, and biological properties of soils, thereby degrading overall soil quality and limiting its capacity to support healthy crop growth. According to the Food and Agriculture Organization, salt accumulation in soils not only affects plant performance directly but also alters fundamental soil processes that govern water movement, nutrient availability, and biological activity. These changes are often interrelated and tend to reinforce one another, leading to a progressive decline in soil productivity if not properly managed.

4.1 Physical Properties

Salinity, particularly when associated with high levels of exchangeable sodium, has a detrimental effect on soil physical condition. One of the most common problems observed in saline and sodic soils is poor soil structure and surface crusting. In sodic and saline-sodic soils, excess sodium causes dispersion of soil clay particles, which destroys stable soil aggregates. As a result, the soil surface becomes dense and compacted, forming crusts that hinder seedling emergence and reduce gaseous exchange between the soil and the atmosphere. Another major consequence is reduced infiltration and permeability. Dispersed clay particles clog soil pores, especially the larger pores responsible for rapid water movement. This leads to slow water infiltration, poor internal drainage, and increased surface runoff. Under such conditions, irrigation water tends to stagnate on the surface, increasing the risk of water logging and further salt accumulation in the root zone. Saline and sodic soils also commonly exhibit increased bulk density and compaction problems. The breakdown of soil aggregates and collapse of pore spaces result in a denser soil mass with fewer macro pores. High bulk density restricts root penetration, reduces aeration, and limits the movement of water and nutrients within the soil profile. Together, these physical constraints create an

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unfavorable root environment and significantly reduce the soil's capacity to support healthy crop growth.

4.2 Chemical Properties

From a chemical perspective, the most immediate effect of salinity is the high concentration of soluble salts in the soil solution, which increases the osmotic potential. This makes it more difficult for plant roots to absorb water, even when the soil appears to be adequately moist, leading to a condition often described as "physiological drought." As salinity increases, plants must expend more energy to take up water, which reduces growth and productivity. Salinity also causes nutrient imbalance and reduced availability of essential plant nutrients such as nitrogen, phosphorus, potassium, calcium, and several micronutrients. High concentrations of sodium and chloride ions can interfere with the uptake of potassium and calcium due to ionic competition at root surfaces. In addition, high soil salinity can reduce the solubility or mobility of certain nutrients, leading to deficiencies even when total nutrient content in the soil is adequate. Another important chemical constraint is the potential toxicity of specific ions, particularly sodium (Na^+), chloride (Cl^-), and boron (B^{3+}). When these ions accumulate in excessive amounts in the soil and plant tissues, they can disrupt metabolic processes, damage cellular structures, and impair enzyme activity. Ion toxicity often manifests as leaf burn, chlorosis, premature leaf drop, and overall decline in plant vigor, especially in salt-sensitive crops.

4.3 Biological Properties

Soil salinity also has a strong negative impact on the biological health of soils. High salt concentrations create an unfavorable environment for many soil microorganisms, leading to reduced microbial activity and biomass. Since soil microbes play a crucial role in nutrient cycling, organic matter decomposition, and the formation of stable soil aggregates, their decline further कमजोरens soil fertility and structure. The rate of organic matter decomposition is generally slower in saline soils because microbial populations responsible for breaking down organic residues are suppressed by osmotic stress and ion toxicity. This results in slower nutrient release and reduced availability of nitrogen, phosphorus, and sulfur to plants, further compounding fertility problems.

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5. Effects of Salinity on Crop Growth and Yield

Salinity affects plants through three major mechanisms:

1. Osmotic stress: High salt concentration in soil solution makes water uptake difficult for roots, leading to physiological drought.
2. Ion toxicity: Excess accumulation of Na^+ and Cl^- in plant tissues damages cellular structures and metabolic processes.
3. Nutrient imbalance: High salt levels interfere with the uptake of essential nutrients such as K^+, Ca^{2+}, and NO_3^-.

Visible symptoms of salt stress include poor germination, stunted growth, leaf chlorosis, leaf burn, premature senescence, and reduced yield. Crops vary widely in their salt tolerance; for example, barley and cotton are relatively tolerant, whereas rice, beans, and most vegetables are sensitive.

6. Assessment and Mapping of Saline Soils

Saline soils are commonly assessed using:

- Electrical conductivity (ECe) of soil extract
- Soil pH and exchangeable sodium percentage (ESP)
- Sodium adsorption ratio (SAR) of soil or irrigation water

Modern approaches include remote sensing and GIS techniques for large-scale mapping and monitoring of salt-affected areas, which help in planning reclamation and management strategies more effectively.

7. Management and Reclamation of Saline Soils

Effective management and reclamation of saline soils require an integrated and site-specific approach that combines physical, chemical, biological, and agronomic measures. The objective is not only to remove or reduce excess salts from the root zone, but also to restore and maintain favorable soil physical conditions, improve nutrient availability, and ensure sustainable crop productivity. International agencies such as the Food and Agriculture Organization emphasize that long-term success in managing salt-affected soils depends on

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the coordinated management of soil, water, and crops rather than reliance on a single technique. Similarly, in India, research and extension efforts led by institutions like the Indian Council of Agricultural Research have demonstrated that integrated reclamation strategies are more effective and economically viable than isolated interventions.

7.1 Physical Methods

Physical methods form the foundation of saline soil management, as they directly address the movement and removal of excess salts from the soil profile. The most important requirement is the provision of adequate surface and subsurface drainage, which prevents the rise of saline groundwater and facilitates the downward movement of salts beyond the root zone. Without proper drainage, any attempt at leaching or amendment application becomes ineffective, as salts tend to re-accumulate in the upper soil layers. Leaching of soluble salts using good-quality irrigation water is another key practice. This involves applying sufficient water to dissolve and transport salts below the active root zone, thereby reducing salinity stress on crops. The efficiency of leaching depends on soil texture, structure, permeability, and the quality of irrigation water. Coarse-textured soils generally respond more quickly to leaching, whereas fine-textured and poorly structured soils require careful water management to avoid waterlogging and secondary salinization. Land leveling and proper irrigation scheduling also play a crucial role in preventing salt accumulation. Uneven fields lead to non-uniform water distribution, causing salts to accumulate in poorly irrigated or elevated patches. Proper leveling ensures uniform infiltration and leaching, while scientifically planned irrigation scheduling helps maintain an optimal soil moisture regime and minimizes the upward movement of salts through capillary rise, especially in arid and semi-arid environments.

7.2 Chemical Methods

Chemical methods are particularly important in the reclamation of sodic and saline-sodic soils, where excess exchangeable sodium adversely affects soil structure, permeability, and aeration. The most widely used chemical amendment is gypsum (calcium sulfate), which supplies soluble calcium to the soil. Calcium replaces sodium on the soil exchange complex, and the displaced sodium is subsequently leached out of the root zone with irrigation or rainwater. This process improves soil aggregation, increases infiltration rate, and enhances overall soil physical condition. In calcareous sodic soils, where native calcium carbonate is

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present but poorly soluble, sulfur or acid-forming materials (such as elemental sulfur or pyrite) may be applied. These materials generate acidity in the soil, which helps dissolve calcium carbonate and release calcium into the soil solution, thereby facilitating the replacement of exchangeable sodium. The effectiveness of such amendments depends on soil properties, microbial activity, and proper moisture management. For best results, the combined use of chemical amendments and leaching is essential. While amendments correct the chemical imbalance of the soil, leaching ensures the physical removal of soluble salts and displaced sodium from the root zone. Without adequate leaching, the benefits of chemical amendments remain limited and temporary.

7.3 Biological and Organic Approaches

Biological and organic approaches play a supportive yet critical role in improving the long-term health and resilience of saline soils. The incorporation of organic manures, compost, and green manures helps improve soil structure, enhances aggregate stability, increases water-holding capacity, and stimulates microbial activity. These improvements facilitate better root growth, increase infiltration, and indirectly promote the leaching of salts. The use of salt-tolerant grasses and halophytes is often recommended during the initial stages of reclamation, particularly in severely salt-affected areas. Such plants can survive and grow under high salinity conditions, provide ground cover, reduce surface evaporation, and contribute organic matter to the soil. Over time, this biological intervention helps stabilize the soil surface, improve soil structure, and create more favorable conditions for the introduction of moderately salt-tolerant crops. Crop residue management is another important practice, as retaining and incorporating residues enhances soil organic carbon content and buffering capacity against salinity stress. Increased organic matter improves cation exchange capacity, nutrient availability, and microbial activity, all of which contribute to better soil functioning under saline conditions.

7.4 Agronomic Practices

Agronomic management is crucial for ensuring crop productivity in saline environments and for making reclamation efforts economically sustainable. The selection of salt-tolerant crop varieties and suitable cropping systems is one of the most practical and cost-effective strategies. Different crops and even varieties within the same crop differ widely in their

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tolerance to salinity, and choosing appropriate genotypes can significantly reduce yield losses. Proper seedbed preparation and planting methods, such as the ridge and furrow system, help minimize salt injury during germination and early seedling growth, which are the most sensitive stages of crop development. Planting on ridges, for example, keeps the root zone relatively less saline compared to furrows where salts tend to accumulate due to evaporation. Balanced fertilization and micronutrient management are also essential, as salinity often leads to nutrient imbalances and reduced availability of essential elements such as nitrogen, phosphorus, potassium, zinc, and iron. Adequate and balanced nutrient supply helps crops better withstand salinity stress and improves overall growth and yield. Finally, the conjunctive use of saline and non-saline water for irrigation is an important water management strategy in areas with limited freshwater resources. By alternating or blending waters of different qualities and applying them at appropriate growth stages, it is possible to reduce salt stress on crops while conserving good-quality water and maintaining acceptable soil salinity levels.

8. Role of Research and Policy Support

In countries like India, institutions such as the Indian Council of Agricultural Research have played a significant role in developing salt-tolerant varieties, reclamation technologies, and management practices for salt-affected soils. However, large-scale adoption requires strong policy support, farmer awareness programs, and investment in drainage and irrigation infrastructure.

9. Future Perspectives

With increasing pressure on land and water resources and the impacts of climate change, the problem of soil salinity is expected to intensify in many regions. Future research should focus on:

- Breeding and biotechnology approaches for developing highly salt-tolerant crops
- Precision irrigation and soil management techniques
- Use of remote sensing and decision-support systems for early detection and management
- Promotion of climate-resilient and resource-efficient farming systems

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10. Conclusion

Soil salinity represents a major and growing challenge to sustainable agriculture, particularly in irrigated, arid, semi-arid, and coastal regions. The accumulation of soluble salts in the soil profile leads to profound deterioration of soil physical, chemical, and biological properties, which in turn restricts root growth, disrupts nutrient uptake, reduces microbial activity, and ultimately results in substantial losses in crop yield and land productivity. The adverse effects of salinity are further intensified by improper irrigation practices, inadequate drainage, use of poor-quality water, and the emerging impacts of climate change. This review highlights that saline soils originate from both natural and human-induced processes and are widely distributed across many parts of the world, including large areas of India. The impacts of salinity on soil properties and crop performance are complex and interrelated, involving osmotic stress, ion toxicity, and nutrient imbalances. Therefore, no single practice can effectively address the problem. Instead, successful management and reclamation of saline soils depend on an integrated, site-specific approach that combines physical measures such as drainage and leaching, chemical amendments like gypsum and acid-forming materials, biological and organic interventions to improve soil health, and sound agronomic practices including the use of salt-tolerant crops and efficient water and nutrient management. In India, the efforts of institutions such as the Indian Council of Agricultural Research have been instrumental in developing salt-tolerant varieties and improved reclamation technologies. However, wider adoption of these technologies requires strong policy support, investment in irrigation and drainage infrastructure, and effective extension and farmer awareness programs. Looking ahead, future strategies should focus on breeding and biotechnology for enhanced salt tolerance, precision soil and water management, and the use of remote sensing and decision-support tools for early detection and monitoring of salinity. Addressing soil salinity in a comprehensive and sustainable manner is not only essential for restoring degraded lands but also for safeguarding long-term food security and agricultural resilience in the face of increasing environmental and climatic pressures.

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