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Salinity and Sodicity in Soils: Impacts, Mechanisms, and Sustainable Management

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Abstract
Land is a finite and non-renewable resource that underpins global agricultural production. However, population growth, climate change, land-use change, and environmental pollution have accelerated land degradation, with soil salinization emerging as one of the most serious threats to sustainable agriculture. Salt-affected soils, comprising saline, saline-sodic, and sodic categories, are estimated to cover 831–1,128 million hectares worldwide and cause annual economic losses exceeding US$27.3 billion. Elevated electrical conductivity (ECe), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), and high pH in sodic soils adversely affect soil structure, nutrient availability, microbial activity, and crop productivity. This review synthesizes current knowledge on salt-affected soils by examining their classification, diagnostic criteria, and impacts on soil physical, chemical, and biological properties. It also discusses the physiological and molecular mechanisms through which salinity impairs plant growth, from osmotic stress to ion toxicity and metabolic disruption. In addition, the review evaluates integrated reclamation strategies, including leaching, calcium-based amendments, organic matter incorporation, and the cultivation of salt-tolerant crops, while highlighting emerging technologies such as nanotechnology and remote sensing for salinity monitoring and management. As salinity is projected to affect nearly half of the world's arable land by 2050, sustainable management and continued research are essential to protect soil resources, ensure agricultural productivity, and strengthen global food security.
Keywords: Soil salinization, sodicity, salt-affected soils, soil reclamation, crop salt tolerance, sustainable land management**.**

Introduction

The world's growing population faces the challenge of shrinking arable land. Agricultural productivity is being hampered by increasing environmental constraints worldwide, particularly salinity, which has a large impact and wide distribution. Salinity stress, resulting from excessive accumulation of soluble salts in the soil—primarily NaCl—is an unavoidable consequence of high ion concentrations that limits crop cultivation (Reynolds et al., 2005; Zilli et al., 2008; Sobhanian et al., 2010). Consequently, greater emphasis should be placed on bringing marginally productive and currently non-arable land into production. Every year, increased soil salinity causes large sections of formerly arable land to be withdrawn from crop production, and 75 countries have been identified as having large tracts of salt-affected land globally (Amini et al., 2016). Global estimates of salt-affected land vary depending on methodology and data sources. According to Martinez-Beltran (2005), Leogrande and Vitti (2019), and Osman (2018), global salt-affected land is estimated at 831–952 million hectares. More recent global mapping efforts using machine learning and remote sensing have provided high-resolution assessments of soil salinity and sodicity dynamics (Hassani et al., 2020; Sahbeni et al., 2023). Mandal et al. (2018) indicate an increasing trend, with total affected areas reaching 1,128 Mha, while annual global economic losses from soil salinization exceed US$27.3 billion (Kumar & Sharma, 2020). According to FAO (2024), approximately 1.381 billion hectares (10.7% of the world's land area) are affected by salt-affected soils, including about 10% of both irrigated and rainfed croplands, while an additional one billion hectares are at risk of salinization due to climate change and unsustainable land and water management practices. By 2050, approximately half of all arable land could be affected by salinity (Kumar & Sharma, 2020). Salt-affected soils are usually found in arid and semiarid climates, and many salt-affected wastelands have formerly been productive areas (Bajwa et al., 1991; Qadir et al., 2000; Mirza et al., 2005; Arora et al., 2016). Recent advances in remote sensing and machine learning have enabled more precise spatio-temporal monitoring of soil salinization dynamics at regional and global scales (Wang et al., 2020; Zhang et al., 2023; Zhao et al., 2025). According to FAO (2008), more than 6% of the world's land is affected by salinity, as shown in Figure 1 (Leogrande & Vitti, 2019). Although much soil salinity and sodicity is natural, a significant portion of cultivated agricultural land has recently become saline and/or sodic (Munns, 2005). In addition, environmental changes could exacerbate the issue, as global warming is driving temperature increases and precipitation fluctuations, leading to

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higher evapotranspiration demand and reduced salinity leaching, thereby promoting salinity accumulation in the root zone (Kang et al., 2009; Leogrande & Vitti, 2019). Perri et al. (2022) demonstrated that aridity and seasonality have contrasting effects on global salinization patterns, highlighting the complex interplay between climate and soil processes.

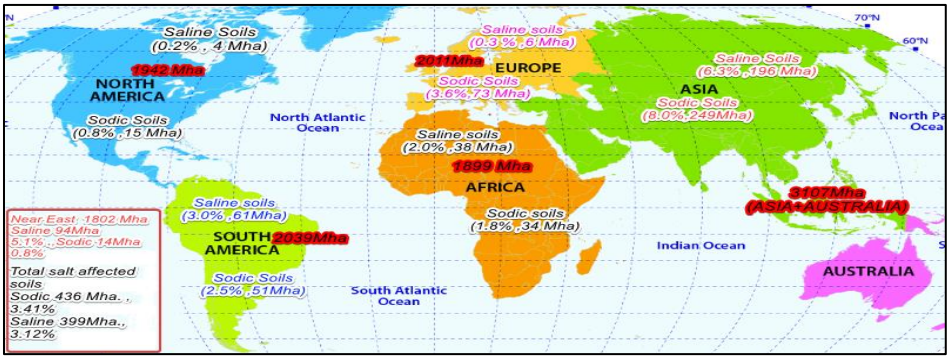


Figure 1. Area of saline and sodic soils worldwide in million hectares (Mha)

Natural causes of salinity in arid and semi-arid regions include low rainfall, high evaporation rates, and the presence of saline parent material. However, anthropogenic activities can cause salinity through various factors, including poor irrigation systems, accumulation of salinity from irrigation water, insufficient leaching and drainage (Tanji, 1990), deforestation, and replacement of native trees with shallow-rooted field crops (Szabolcs, 1994; Qadir et al., 2000; Manchanda & Garg, 2008). Heavy metal accumulation from industrial wastes and chemical fertilizers may also contribute to soil degradation in affected areas, though its direct linkage to salinity requires further clarification. Irrigated agriculture is essential for food production in arid and semi-arid locations; however, because of the hot and dry temperatures in these areas, irrigation water must not contain soluble salts in quantities that are damaging to plants or soil quality (Golla, 2021). High salinity affects approximately 20% of total cultivated land and 33% of irrigated agricultural land worldwide (Shrivastava & Kumar, 2015). Salinity is determined by the concentration of dissolved mineral salts in water and soils, where cations such as Na^+, Ca^{2+}, Mg^{2+}, and K^+, and anions such as Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, and NO_3^-, are the most common ions found in dissolved mineral salinity. Furthermore, saline irrigation and drainage waters, saline and sodic soils, saline groundwater, seawater intrusion, brine from natural salinity deposits or geologic formations, and brines from oil and gas fields and mining all contribute to soil salinity (Qadir et al., 2000; Manchanda & Garg, 2008; Rengasamy, 2010). Heavy-textured, salt-affected soils are often unsuitable for plant growth due to inherent salinity and sodicity problems. High amounts of total soluble salts primarily cause a marked reduction in the water potential of soil solution, limiting the water available to plants and thus increasing plant stress. Furthermore, high salinity concentrations, particularly of toxic ions (i.e., chloride, sodium, and boron), interfere with normal plant metabolism (Abrol et al., 1988). On the other hand, high sodicity (high exchangeable sodium) causes physical deterioration of soil structure because of clay swelling and dispersion, and high toxicity potential to plants by sodium. Clay dispersion and degradation of soil structure cause a reduction in hydraulic conductivity (Quirk & Schofield, 1955; Frenkel et al., 1978; Yousaf et al., 1987). For all these reasons, reclamation and management of these soils are critical worldwide. Although numerous studies have investigated individual aspects of salt-affected soils, including their classification, physicochemical properties, plant responses, and reclamation approaches, recent advances remain scattered across different disciplines. In addition, emerging challenges associated with climate change, soil biological degradation, and sustainable land management require an updated synthesis that integrates classical concepts with recent findings. Therefore, this review critically examines the causes, classification, and impacts of salinity and sodicity on soil physical, chemical, and biological properties, as well as plant performance, while identifying current knowledge gaps and future research priorities for sustainable management of salt-affected soils.

Definition and classification of salinity-affected soils

The total salt concentration and sodium status of the soil are the primary criteria used to distinguish saline, sodic, and saline-sodic soils. Soil salinity is commonly quantified by the electrical conductivity of the saturated soil paste extract (ECe), whereas soil sodicity is assessed using the exchangeable sodium percentage (ESP) and/or the sodium adsorption ratio (SAR). The SAR expresses the relative concentration of sodium ions (Na^+) to the combined concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions in the soil solution and is widely used to evaluate the potential sodicity hazard (Van Hoorn & Van Alphen, 1994; Rengasamy, 2010). However, the importance of anions

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in the soil solution during the process of soil degradation has also been recognized (Rengasamy & Olsson, 1993). The most prevalent soluble salts are sodium chloride and sulfates, as well as calcium and magnesium sulfates; nitrates might be available in considerable amounts only occasionally. Sodium and chloride are by far the most prevalent ions, especially in highly saline soils, although magnesium and calcium are typically present in adequate amounts to meet the nutritional requirements of plants. Many saline soils contain appreciable amounts of gypsum ($CaSO_4 \cdot 2H_2O$) in the soil profile (Abrol et al., 1988). Soils with naturally high salinity contents resulting from processes such as rock weathering are classified as primarily salinized (Rengasamy, 2006). Human actions such as irrigation with saline water without proper salinity leaching induce secondary salinization, affecting approximately 76.6 Mha (Oldeman, 1991; Mashali, 1995; Shahid et al., 2018). Shallow groundwater tables, along with poor drainage and high evaporation rates, create secondary salinization (Smedema & Shiati, 2002; Brinck & Frost, 2009). Excessive use of chemical fertilizers, overgrazing, and deforestation are all factors that contribute to soil salinity (Bernstein, 1975; Lakhdar et al., 2009). Salinization can be broadly categorized into:

1.Primary salinity results from geological origin and soil formation processes, often occurring around the margins of natural depressions where water accumulates and weathers saline rocks. Through capillary action, water containing dissolved salts rises to the soil surface, and salts are deposited following water evaporation (Qureshi & Barrett Lennard, 1998).

2.Secondary salinity, resulting from irrigation practices and management, is commonly associated with: (A) rising water tables and accelerated salinity redistribution within the soil profile; (B) insufficient leaching of salts following replacement of deep-rooted perennial vegetation with shallow-rooted annual crops (Rao et al., 2012), recognized as a major cause of dryland salinity. Continuous irrigation of crops and pastures increases groundwater recharge, thereby raising groundwater levels, which ultimately transport and accumulate subsurface salinity at the surface (Ruprecht & Schofield, 1991). According to Sisodiya and Vaghani (2016), saline-alkali soils develop due to one or more of the following factors:

*In arid regions where evaporation exceeds precipitation, soluble salts concentrate near the soil surface.

*Groundwater in arid regions often contains high concentrations of soluble salts. Its excessive use for irrigation degrades productive soils (Kumar & Sharma, 2020). The rate of deterioration depends on irrigation water salinity, salt composition, and soil type. Sodium salinity is more detrimental than calcium and magnesium salinity. Continued irrigation with such water leads to land productivity decline, particularly when farmers do not monitor well water quality, although salinity may also be introduced directly from the chemical weathering of rocks.

*Increased irrigation water use and seepage from canals and reservoirs raise groundwater levels, enabling salinity accumulation at the surface through capillary rise and evaporation. When underlying groundwater is saline, salinity accumulation occurs more rapidly.

*Poor drainage prevents salts from leaching below the root zone, leading to surface accumulation, and many saline soils in arid environments result from inadequate drainage.

*Coastal soil salinization results from salt deposition by seawater intrusion or tidal inundation, while irrigation water with high soluble salt concentrations, particularly sodium salinity, causes soil salinity. Salt-affected soils are generally classified into three main categories: saline soils, sodic soils, and saline-sodic soils (Paz et al., 2023b). Saline soils are characterized by high concentrations of soluble salts, predominantly sodium chloride (NaCl) and sodium sulfate (Na_2SO_4), whereas sodic soils contain excessive amounts of exchangeable sodium and are typically associated with high soil pH, clay dispersion, poor soil structure, and reduced water infiltration (Hanay et al., 2004; Rengasamy, 2010). Saline-sodic soils exhibit both high soluble salt concentrations and elevated exchangeable sodium levels, thereby combining the characteristics of saline and sodic soils. Salinity and sodicity are among the major desertification processes affecting irrigated lands worldwide because of their widespread occurrence and severe impacts on the productive capacity of agricultural lands, forests, and rangelands (Dregne et al., 1991). Early global assessments highlighted the magnitude of land degradation, estimating that salinization accounted for nearly one-third of the world's loss of arable land caused by major degradation processes (Buringh,1978). The increasing trend in salinity-affected areas underscores the continued relevance of Buringh's warning about land degradation (Hassani et al., 2020; Perri et al., 2022).

Salt-affected soils are commonly classified using four key indicators: the electrical conductivity of the saturated soil paste extract (ECe), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), and soil pH. Electrical conductivity (ECe), which reflects the ability of the soil solution to conduct electrical current, is expressed in decisiemens per meter ($dS\ m^{-1}$). Together, these parameters are widely used to evaluate the degree of soil salinity and sodicity (Richards, 1954; Bohn et al., 2001; Rengasamy, 2010). The classification thresholds established by

Richards (1954)—particularly the ECe > 4 dS m^{-1} criterion for saline soils—remain foundational, though recent studies have refined these thresholds for specific crops and soil types (Paz et al., 2023a; Omar et al., 2024). The electrical conductivity of soil paste extracts gives a measure of the total dissolved salt content, while ESP is another determinant for salt-affected soil, as it gives a measure of the sodium status of the soil; the risk of sodium in a solution generally increases as the salinity concentration increases (Bresler et al., 2012). Surface soil is equilibrated with the applied water each time water is applied, so the ESP of surface soil can be predicted with reasonable accuracy from the sodium adsorption ratio (SAR) of the applied water (Sposito, 1989; Bresler et al., 2012). Determining the exchangeable sodium percentage is laborious, time-consuming, and error-prone. During the washing stage of CEC measurements, incomplete removal of the index salt solution might result in high CEC readings and, as a result, poor ESP estimations (Abrol et al., 1988). Similarly, hydrolysis of exchangeable cations during the removal of the index salt solution by the soil minerals and the dissolution of calcium carbonate or gypsum in the index or replacing solutions can all lead to low values of cation exchange capacity and, therefore, too high ESP estimates. The problem of CEC and ESP determination was also encountered in high-pH soils containing zeolite minerals (Gupta & Gupta, 1984). To overcome some of these difficulties, several workers prefer to obtain an estimate of the exchangeable sodium percentage from the analysis of the saturated soil extract. Richards (1954) proposed that the sodium adsorption ratio (SAR) of the soil solution can adequately define the soil sodicity problem and could be quantitatively related to the exchangeable sodium percentage of the soils. Although ECe > 4 dS m^{-1} and ESP > 15 are the two primary criteria for classifying salt-affected soils, from a practical standpoint, ECe values as low as 2 dS m^{-1} may reduce growth in salinity-sensitive crops and cause problems with their germination (Stroehlein & Pennington, 1986). For soils with high fine clay content and low soluble salt concentrations, an ESP of 6 has been proposed as the threshold for soil structural degradation (Northcote & Srene, 1972). Salinity and sodicity have a combined effect on soil characteristics and plant growth (Rengasamy, 2002; USDA, 1954; Bohn et al., 2001; Sposito, 1989).

Salinity–affected soils

Saline soils

High concentrations of sodium sulfates, chlorides, and carbonates, along with calcium and magnesium carbonates, result in excessive soluble salt levels in these soils (ECe > 4 dS m^{-1}, pH ordinarily less than 8.5). When water containing soluble salts is used for irrigation, the salts reach the surface, where the water evaporates, and the salts are left behind. Water-soluble salts include NaCl and Na_2SO_4. Saline soils significantly affect uncultivated lands that remain fallow for extended periods, and downward salt migration in these soils occurs through percolation. Saline soils are relatively easy to reclaim through intensive irrigation, provided adequate drainage exists (Ali & Kahlown, 2001). Recent reviews have emphasized the growing importance of sustainable organic amendments in soil reclamation strategies (Elmeknassi et al., 2024; Luo et al., 2025). The physical properties and water permeability in saline soils are comparable to those of their normal counterparts (Sharma & Singh, 2016).

In the field, affected soils can be diagnosed by the following visual characteristics (Sisodiya & Vaghani, 2016):

-During the dry season, upward soil moisture movement results in a white, fluffy salinity crust on the soil surface.

-Water permeability is higher than in sodic soils.

-Seedling germination is reduced, leaf spots appear, and in severely affected areas, crop failure occurs.

In many arid and semiarid regions of the world, soil salinization is one of the principal causes of declining agricultural productivity. Traditionally, salt-affected soils have been classified according to the electrical conductivity of the saturated soil paste extract (ECe) and the exchangeable sodium percentage (ESP) (El-Morsy et al., 1991; Horneck et al., 2007) (Figure 2). According to the classical USDA classification, soils with an ECe greater than 4 dS m^{-1} are considered saline (USDA, 1954). However, recent studies emphasize that the salinity threshold at which crop yield begins to decline varies considerably among plant species and is strongly influenced by climate, soil properties, and soil-water conditions (Corwin, 2021). The USDA classification system remains the global standard, with recent studies in East African irrigation schemes confirming that 68.7% of analyzed soils fall within the non-saline category (ECe 0–2 dS m^{-1}), while 13.8% are extremely saline (ECe > 16 dS m^{-1}), validating the practical utility of these thresholds (Omar et al., 2024). As ion concentration in the soil solution increases, so does electrical conductivity; above 4 dS m^{-1}, yields of sensitive crops may decline. Saline soils are soils that are harmed by soluble salts only, consisting mainly of Na^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-}, and secondarily of K^+, HCO_3^-, CO_3^{2-}, and BO_3^{3-} (Sposito, 1989). Extensive information is available on managing saline soils under irrigation in regions where annual rainfall is insufficient to meet crop evapotranspiration demands, and consequently, salinity accumulates to levels or in forms detrimental to plant growth (Bohn et al., 1985).

Water-soluble salts are present in all soils, but when concentrations become harmful to seed germination and plant growth, the soils are classified as saline. Saline soils are the easiest of the salt-affected soils to reclaim if good quality water is available and the site is well-drained (Ezeaku & Ene, 2015). In addition to general osmotic effects, many plants are sensitive to specific ions in irrigation water or soil solution (specific-ion effect), and a third mechanism for potential salinity injury to plants involves nutritional imbalances. However, plants growing on such soils may appear stunted, with thickened leaves and dark green coloration, and significant growth reduction can occur without noticeable changes in plant appearance (Bohn et al., 2001). It is also widely recognized that some salts are more toxic than others and that certain plants can tolerate high salinity concentrations while others are sensitive to low concentrations; however, this tolerance varies with the stage of plant growth, as plants are most sensitive to salinity during germination and early seedling stages, becoming more tolerant as they mature (Munns, 2005).

Sodic soils

Saline soils are defined as those with an electrical conductivity of the saturation extract exceeding 4 dS m^{-1} (USDA 1954), whereas sodic soils have an exchangeable sodium percentage of greater than 15 based on the American definition (USDA, 1954) and have SAR > 13 with pH usually between 8.5 and 10 (Northcote & Srene, 1972). Sodic soils contain substantial sodium (Na^+) at cation exchange sites, and sodium carbonate concentrations are typically elevated. The adsorption of excessive sodium onto the negatively charged surfaces of clay particles substantially weakens interparticle cohesive forces, resulting in the breakdown of soil structure. Upon wetting, sodium-saturated clay particles disperse into fine particles that migrate and clog soil pores. During subsequent drying, these dispersed particles consolidate into dense, compact layers, reducing soil porosity, limiting water infiltration, and decreasing hydraulic conductivity (Qadir & Schubert, 2002; Zewd & Siban, 2021).

Sodic soils are difficult and costly to reclaim due to their reduced permeability and high sodium content. However, recent studies have shown that bio-organic ameliorants can significantly enhance the fertility of calcareous and saline-sodic soils by improving organic matter decomposition and enzyme activities (Hafez et al., 2022a, 2022b). Poor soil structure adversely affects seed germination, tillage operations, and root growth, and wind and water are more likely to affect sodic soils and lead to soil erosion (Sisodiya & Vaghani, 2016). The following signs can be observed in the field:

-During summer, the surface is covered with white salts, which turns dark black when wet; consequently, these soils are often called "black alkali soils."

-The soil becomes sticky when cultivated under slightly moist conditions.

-As the soil dries, shallow surface cracks develop, and the soil becomes extremely hard and compacted, making clods excessively hard and difficult to achieve a suitable seedbed.

- Due to low hydraulic conductivity, water infiltrates slowly and remains turbid on the surface for extended periods.

- Sporobolus grasses may thrive temporarily but often die during peak summer.

Swelling and dispersion result from interactions between clay fraction constituents and pore solution composition (Sumner, 1993). In clays, diffuse electrical double layers consist of clay lattice charges and compensating counterions (Shainberg & Letey, 1984). However, interactions at this scale that increase the thickness of the diffuse double layer also increase interparticle repulsive forces, leading to greater swelling pressures and enhanced clay dispersion (Sumner, 1993). The structural differences between sodium- and calcium-saturated montmorillonite platelets are well established. In sodium montmorillonite, individual platelets tend to remain dispersed in solution (Shainberg & Letey, 1984), whereas in calcium montmorillonite, platelets aggregate into "tactoids" or "quasi-crystals" (Blackmore & Miller, 1961; Aylmore & Quirk, 1960). Each quasicrystal consists of four to nine platelets arranged in parallel, and this stacking increases pore volume in calcium-saturated clays (Shainberg & Letey, 1984). Our understanding of sodium behavior in response to soil chemistry changes derives primarily from laboratory studies. The effects of electrolyte concentration and soil sodicity on clay swelling and hydraulic properties have been investigated by several researchers (Aylmore & Quirk, 1960; Gardner et al., 1959; McNeal & Coleman, 1966; Quirk & Schofield, 1955). The primary requirement for reclaiming salt-affected soils is sufficient water percolation through the root zone to reduce salinity concentrations to acceptable levels, and soluble divalent ions (generally calcium and magnesium) must be present during the reclamation of sodic soils (Shainberg et al., 1981).

Saline –Sodic soils

Saline-sodic soils contain both soluble salts and exchangeable sodium (i.e., ECe > 4 dS m^{-1}), with pH typically not exceeding 8.5. These soils cover an estimated 560 × 10^6 hectares worldwide (Tanji, 1990; Manzoor Qadir et al., 2005). Given their extensive area, effective, low-cost, and environmentally sustainable management strategies are required to enhance crop production and expand the diversity of crop species that can be cultivated on these soils

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(USDA, 1954). Saline-sodic soils suffer from both the detrimental effects of salinity on plant growth and the adverse effects of sodicity on soil structure. High levels of soluble and exchangeable sodium cause swelling and dispersion, resulting in poor structure and restricting water infiltration and permeability (Gharaibeh et al., 2010). In addition to structural degradation, high salinity and sodicity adversely affect chemical and biological properties (Ganjegunte et al., 2008). Crops under saline-sodic conditions suffer not only from high salinity but also from reduced nutrient availability due to alkalinity (Sisodiya & Vaghani, 2016). When sodic soils are also saline, high ion concentrations between clay platelets compress the diffuse double layer, helping to stabilize soil structure; however, when leached with low-salinity water, soil stability decreases, and clay dispersion occurs (Shainberg et al., 1981). Saline-sodic soils remain permeable if soil solution salinity concentrations are maintained sufficiently high to promote flocculation (El-Morsy et al., 1991).

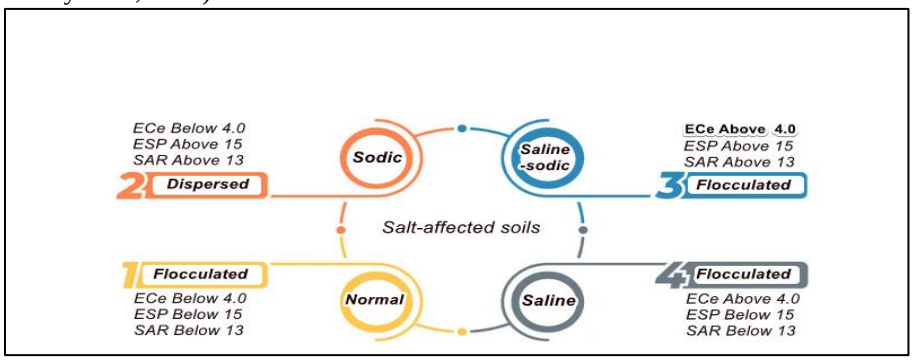


Figure 2. Classification of salinity-affected soils used by the Natural Resources Conservation Service (NRCS).

Table 1 highlights that successful reclamation of salt-affected soils requires soil-specific management based on the dominant constraint. Saline soils can often be reclaimed by leaching, whereas sodic soils require calcium-based amendments before leaching. Saline-sodic soils demand integrated management to reduce both soluble salts and exchangeable sodium while preventing clay dispersion. Accurate diagnosis is therefore essential for selecting effective reclamation strategies and avoiding further soil degradation.

Table 1. Comparative characteristics of saline, sodic, and saline-sodic soils. Synthesized from Richards (1954), Abrol et al. (1988), and USDA-NRCS criteria.

Property	Saline	Sodic	Saline-Sodic
Main stress	Osmotic	Structural	Combined
Soil structure	Usually stable	Dispersed	Partially dispersed
Infiltration	Moderate–High	Very low	Low
Hydraulic conductivity	Near normal	Severely reduced	Reduced
Dominant ions	NaCl, Na_2SO_4	Exchangeable Na^+	Both
Plant limitation	Water uptake	Root penetration	Water + roots
Relative reclamation difficulty	Low	High	Very high

Although saline, sodic, and saline-sodic soils are commonly classified using ECe, ESP, SAR, and pH thresholds, their management requirements differ substantially because the dominant constraints are not identical. Saline soils are primarily limited by osmotic stress, whereas sodic soils are mainly affected by structural degradation and reduced permeability. Saline-sodic soils present a combined challenge in which both osmotic and structural constraints must be addressed simultaneously, making their reclamation more complex than that of saline soils alone.

Salinity effect

Effects of salinity level on soil physical properties

Excessive salinity levels have a deleterious impact on soil microbial activity, as well as chemical and physical properties, resulting in a decline in soil productivity (Parvaiz & Satyawati, 2008). As a result of salinity toxicity and negative osmotic potential, vegetation growth declines, which affects the amount of carbon (C) added to these soils as well as their physical and chemical properties (Wong et al., 2009) , and consequently, throughout a long period of soil salinization, (C) storage diminishes significantly (Wong et al., 2010). Soil salinity affects physical properties by inducing fine particles to aggregate. (Warrence et al., 2002) , a process called flocculation that enhances soil aeration, root penetration, and root development. Remote sensing-based indices have been increasingly used for

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quantitative estimation of saline-soil amelioration and monitoring in arid lands **(**Aboelsoud et al., 2022**)**. However, while increased soil solution salinity improves aggregation and stability, high levels can be detrimental or lethal to plants; therefore, increasing salinity to maintain soil structure while ignoring plant health consequences is not feasible (Warrence et al., 2002). The effects on infiltration rates and hydraulic conductivity are the primary concerns regarding the relationship between irrigation water salinity and soil physical properties, a relationship that has been studied for over five decades (McNeal, 1968). McNeal's original model for predicting hydraulic conductivity in mixed-salinity solutions has been significantly improved through incorporation of electrostatic double-layer theory and clay mineralogy effects. Modern studies using packed soil columns with controlled SAR and EC solutions have demonstrated strong hysteresis effects, with Ks decreasing by up to 75% as SAR increased from 0 to 30, showing limited recovery upon reduction (Yacine et al., 2025; Ezlit et al., 2013). Clay swelling and soil dispersion are the key physical processes associated with excessive sodium concentrations. The relationship between electrolyte concentration, SAR, and soil hydraulic conductivity, first described by Quirk & Schofield (1955), has been extensively validated and refined through modern experimental approaches. Recent studies using tropical soils confirmed that Ksat decreases with increasing SAR at all EC levels, revealing Na^+-dispersing behavior consistent with the original theory (Yacine et al., 2025). Furthermore, threshold electrolyte concentration (TEC) analysis has been updated with new reduction percentages for practical irrigation management (Ezlit et al., 2013; Quirk, 2001). When excessive sodium ions occupy spaces between clay particles, interparticle binding forces are disrupted, and separated clay particles expand, causing swelling and dispersion (Warrence et al., 2002). Repeated wetting and drying cycles promote the consolidation of dispersed clay particles into a dense, nearly cement-like mass with poor structural stability (Figure 3). This sodium-induced clay dispersion and subsequent structural degradation reduce soil infiltration, decrease hydraulic conductivity, and promote surface crusting, thereby restricting water movement and impairing soil productivity (Qadir & Schubert, 2002; Zewd & Siban, 2021). Calcium and magnesium ions are smaller and bind more closely to clay particles and do not cause dispersion. Furthermore, calcium and magnesium compete with sodium for adsorption sites on clay particles; they tend to maintain soil flocculation, and their concentrations can help minimize sodium-induced dispersion (Agassi et al., 1981). In the same line, higher calcium and magnesium concentrations limit the quantity of sodium bound to soil particles (Hanson et al., 1999). However, soil physical condition (dispersion or flocculation) is also influenced by factors beyond those considered in the NRCS classification system, such as soil organic matter content, texture, and irrigation water EC (Horneck et al., 2007).

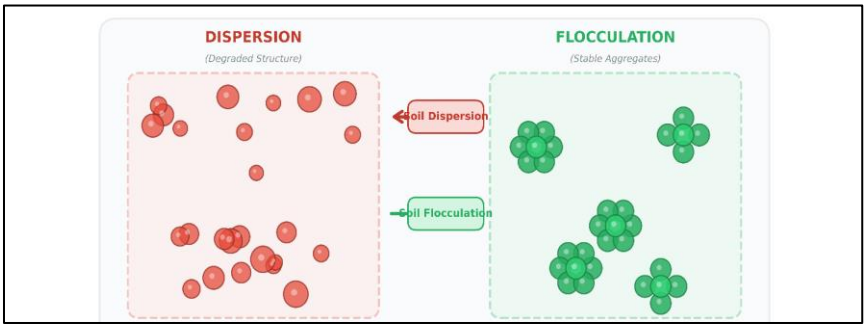


Figure 3. Soil Particles in a Dispersed and Flocculated Condition

Surface crusting is an indicator of salt-affected soils, and this phenomenon results from two main factors: (1) physical dispersion caused by raindrop or irrigation water impact, and (2) chemical dispersion due to the salinity and sodicity of applied water. Dispersed clay particles seal macropores in surface soil through two mechanisms. First, water and root movement through the soil is impeded, and second, upon drying, they form a cement-like surface layer. The hardened surface layer, or surface crust, restricts water infiltration and plant emergence (Zewd & Siban, 2021). However, soils with high clay content and smectite minerals were found to be less susceptible to decreases in hydraulic conductivity at a given level of sodicity than soils with moderate clay content and mixed mineralogy (Shaw et al., 1994). High SAR values reduce aggregate stability and dry cohesive strength, promote deflocculation, and increase soil dispersion (Aly & Letey, 1990). In addition, SAR significantly affects steady-state infiltration rates and hydraulic conductivity (El-Morsy et al., 1991; Hamid & Mustafa, 1975). On the other hand, calcium prevents clay dispersion and aggregate disruption by replacing Na^+ and Mg^{2+} on clay surfaces and within aggregates, thereby improving aggregate stability (Zhang & Norton, 2002). Previous studies have shown that Mg^{2+} can be detrimental when its concentration exceeds that of calcium (Yuan et al., 2007; Horneck et al., 2007).

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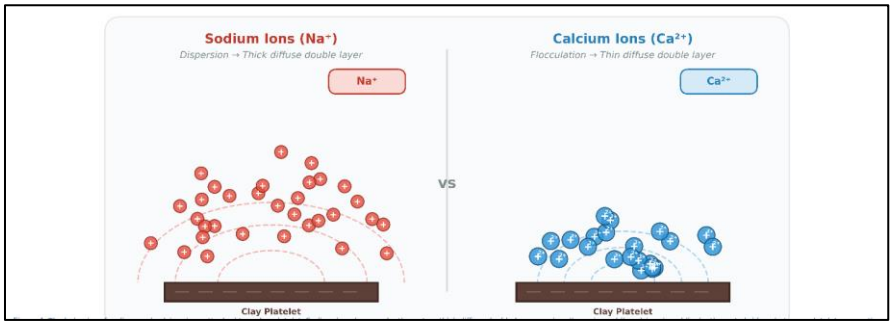


Figure 4. The behavior of sodium and calcium ions attached to a clay platelet.

Under various salinity-sodicity combinations, the balance between salinity-induced flocculation and sodicity-induced dispersion determines whether soil remains aggregated or becomes dispersed. When low-salinity irrigation water or rainfall infiltrates soil, it seeps into micropores between clay particles, leading to clay swelling and dispersion; however, irrigation with water of higher salinity than that of the soil tends to maintain particle cohesion and preserve soil structure (Szabolcs, 1999; Warrence et al., 2002). Porosity is defined as the ratio of void or pore volume to total soil volume, expressed as a fraction or percentage. Total pore space, pore size distribution, and drainage characteristics all influence water and air availability to plant roots and soil organisms; however, sodium-induced dispersion hardens the soil and reduces water infiltration, leading to increased runoff and, consequently, soil erosion (Zewd & Siban, 2021). Suarez et al. (1984) showed that soil solution pH also affects hydraulic conductivity, and it has been suggested that the increase in hydraulic conductivity with decreasing pH results from increased bonding between negatively charged clay edges and positively charged iron and magnesium oxides, which reduces clay dispersion. Overall, the physical degradation of salt-affected soils is governed by a delicate balance between salinity-driven flocculation and sodicity-driven dispersion. While moderate salinity can enhance soil aggregation, excessive sodium leads to clay swelling, dispersion, and structural collapse. These processes collectively reduce infiltration, hydraulic conductivity, and aeration, ultimately limiting root penetration and plant establishment. Effective management of soil physical properties therefore requires simultaneous control of both salinity concentration and sodium saturation, alongside maintenance of adequate calcium levels to preserve soil structure.

Effects of salinity level on the soil chemical properties

In saline and sodic soils, ECe, ESP, SAR, and pH tend to be high (Figure 2); however, deficiencies of nitrogen (N), phosphorus (P), and potassium (K) are common in saline soils, and their high pH reduces the availability of micronutrients such as Fe, Al, Zn, Mn, and Cu (Pessarakli & Szabolcs, 1999; Lakhdar et al., 2009). Long-term spatiotemporal studies in China's West Songnen Plain have documented significant variations in soil salinization patterns over decades (Yu et al., 2023). In addition, reduced plant growth due to salinity toxicity, increased osmotic stress, and impaired soil structure result in reduced carbon inputs and further deterioration of physical and chemical properties in salt-affected soils (Wong et al., 2009; Hussain et al., 2019). Surface crusting and sealing cause significant erosive organic matter losses; thus, organic matter content is low in these soils due to both reduced inputs and high losses (Qadir et al., 1997; Nelson et al., 1998). Chander et al. (1994) reported that total nitrogen and organic carbon decreased with increasing soil sodicity under irrigation with sodium-rich water, and according to Adu and Oades (1978), increased aggregate dispersion in sodic soils exposes occluded organic matter to rapid microbial decomposition. Gandhi and Paliwal (1976) found that increasing salinity reduced nitrogen mineralization while increasing gaseous NH_3 losses. Pathak and Rao (1998) found that increased salinity and sodicity in arid soils treated with organic amendments decreased carbon and nitrogen mineralization; however, Nelson et al. (1996) found that increasing sodicity enhanced organic matter solubilization and carbon decomposition in salt-affected soils, whereas salinity reduced carbon mineralization. Frankenberger and Bingham (1982) found that increasing salinity reduced the activity of soil enzymes involved in carbon, nitrogen, phosphorus, and sulfur cycling, and high ion concentrations, particularly Na^+ and Cl^-, impair plant water uptake and affect cell function and growth (Muneer & Oades, 1989). In summary, salt-affected soils exhibit marked chemical deterioration characterized by elevated ECe, ESP, SAR, and pH, alongside deficiencies in essential macronutrients and micronutrients. The interplay between high pH and ion toxicity reduces nutrient availability and disrupts biogeochemical cycling, while diminished organic matter further depletes soil fertility. These chemical constraints are intrinsically linked to physical and biological degradation, creating a self-reinforcing cycle of soil quality decline that demands integrated chemical and physical remediation strategies.

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Effects of salinity level on the soil biological properties

While the effects of salinity and sodicity on soil chemical and physical properties and plant growth are well documented, their impacts on soil microbial processes remain relatively understudied. Indeed, several recent comprehensive reviews on the effects of salinity and sodicity on soil properties do not address their impacts on soil microbial and biochemical activity (Sumner, 1995; Keren, 2000; Rietz & Haynes, 2003). Soil microbial and biochemical processes, which are essential for maintaining soil biological functions, are adversely affected by changes in soil chemistry (Rietz & Haynes, 2003). Microbial growth and activity are adversely affected by increasing soil salinity, as high salinity concentrations in soils cause osmotic stress and dehydration of microbial cells (Oren, 1999; Wichern et al., 2006). Furthermore, in addition to salinity stress, high sodium levels, calcium deficiency, toxic concentrations of other ions such as carbonate, bicarbonate, and chloride, and organic matter depletion all contribute to declining microbial populations and activity in saline soils (Zahran, 1997; Nelson et al., 1996). Garcia et al. (1994) investigated the effects of salinity on microbial community composition in soils collected from arid regions of southeast Spain and found that increasing salinity negatively affected soil microbial communities. Furthermore, enzyme activities and carbon and nitrogen mineralization rates decreased at high salinity levels, while the nitrification rate increased by up to 83% with increasing salinity to 20 dS m^{-1}, which enhanced ammonia losses through volatilization (Rietz & Haynes, 2003). Wichern et al. (2006) suggested that fungal communities are more sensitive to salinity increases than bacterial populations. Rietz and Haynes (2003) also reported that soil microbial and biochemical activities were adversely affected by irrigation-induced salinity and sodicity, and they evaluated various biochemical enzyme activities, reporting that enzyme activities decreased directly with increasing ECe, ESP, and SAR. Several other studies have also reported that salinity and sodicity significantly reduce soil microbial biomass and associated enzyme activities (Tripathi et al., 2006, 2007). Rietz and Haynes (2003) and Wong et al. (2008) showed that with increasing salinity and sodicity, the metabolic quotient (respiration per unit biomass) increases, indicating greater stress on the microbial community. It has been shown that salinity above a critical level reduces enzyme activity (Garcia & Hernandez, 1996; Liang et al., 2005; Ghollarata & Raiesi, 2007) and soil microbial biomass. Similarly, Yuan et al. (2007) observed that increasing salinity induces shifts in soil microbial communities, with slower metabolic rates. Microbial and biochemical activities profoundly influence soil ecology, and these activities also play a central role in enhancing soil structure by increasing and improving the formation and stabilization of soil aggregates (Six et al., 2004). Collectively, these findings demonstrate that salinity and sodicity exert profound negative effects on soil biological properties by suppressing microbial biomass, reducing enzyme activities, and altering community composition. The resulting decline in microbial-mediated nutrient cycling and aggregate stabilization further exacerbates both chemical and physical degradation. Restoring soil biological function is therefore a critical, yet often overlooked, component of any comprehensive reclamation strategy for salt-affected soils.

Effects of salinity level on the plant

Salinity influences crops through four main mechanisms: osmotic effect, specific ion effect, ion imbalance, and oxidative stress (Flowers, 2004). However, salinity appears to exert two independent effects on plant growth: water relations and ionic relations (Hussain et al., 2019). The two-phase model of salinity stress, first conceptualized by Bernstein (1975)—distinguishing osmotic stress from specific ion toxicity—has been confirmed through modern molecular studies. Recent proteomic analyses have identified key genes (e.g., HKT transporters) responsible for Na^+ exclusion and K^+/Na^+ homeostasis, providing mechanistic evidence for the ionic stress phase described decades earlier (Munns, 2005; Hauser & Horie, 2010). Initially, plants face water stress, which causes decreased leaf development, and secondly, under long-term salinity stress, plants experience ionic stress from Na^+ and Cl^- accumulation (Amirjani, 2011). In arid and semiarid regions, salinity stress is likely the most important abiotic factor limiting plant development and the activity of soil microorganisms (Ghollarata & Raiesi, 2007). Excessive salinity may reduce crop yield by limiting root water uptake due to decreased osmotic potential, nutritional imbalance, and ion toxicity (Munns, 2005). Compared to plants grown in soils with similar moisture levels irrigated with fresh water, plants may ingest more water from the soil receiving freshwater. The presence of salinity in the water causes plants to use more energy collecting water from the soil, diverting some of the energy that a plant would otherwise use to survive and grow (Warrence et al., 2002). In essence, excess soil water salinity reduces plant-available water and induces plant stress (Sisodiya & Vaghani, 2016). In general, excessive root-zone salinity causes poor and uneven crop stands, irregular growth, and reduced yield and quality (James et al., 2011). According to Munns (2005), within minutes of exposure to salinity, the first phase of growth reduction begins. Osmotic stress, alterations in osmotic potential outside the root surface, and associated osmotic effects cause this growth reduction.

After days, weeks, or months, a slower effect (specific ion effect) occurs, leading to salt accumulation in leaves, particularly older leaves, and eventual salt toxicity. The plant's salt toxicity can result in leaf death and a reduction in total photosynthetic leaf area. As a result, the availability of photosynthate to the plant decreases, affecting the overall carbon balance required for plant growth and development (Munns, 2005). When sufficient salinity accumulates in the root zone, plant development is inhibited (Warrence et al., 2002). The uptake of sodium and chloride ions from soil into plant cells causes ionic imbalance, and excessive uptake of these ions by plants creates numerous physiological problems in tissues such as roots, leaves, grains, fruits, or fibers (James et al., 2011; Netondo et al., 2004). Excess sodium ions in plant tissues damage cell membranes and organelles, leading to cell death (Siringam et al., 2011), and the primary detrimental effect of salinity is the accumulation of sodium and chloride ions in plant tissues (Nishimura et al., 2011; Hussain et al., 2019). Increased Na^+ uptake in sodic soils limits K^+ absorption because potassium ions compete with high sodium concentrations (Jung et al., 2009), which impairs enzyme activities involved in metabolic processes such as photosynthesis and protein synthesis, adversely affecting plant growth (Hauser & Horie, 2010; Kumar & Sharma, 2020). Furthermore, plant nitrogen uptake is reduced under high-salinity conditions (Abdelgadir et al., 2005). In field crops such as rice, salinity has an antagonistic effect on P, K, Zn, Fe, Ca, and Mn uptake, while exerting a synergistic effect on N and Mg (Bano & Fatima, 2009; García et al., 2010). In addition to osmotic effects, individual ions in salt-affected soils can be hazardous to plants through additional mechanisms, and regardless of saline and/or sodic soil conditions, high concentrations of sodium, chloride, boron, and/or carbonates can reduce crop yield. Halophytes have shown promising potential for phytoremediation of salt-affected soils, particularly in degraded ecosystems such as the bed of Urmia Lake in Iran (Ghorbanpour et al., 2022; Hu et al., 2024). According to several studies, sodium limits plant growth primarily through generalized salinity effects (i.e., any salinity reduces plant water availability), rather than through a specific toxicity mechanism (Horneck et al., 2007). The potential for specific ion toxicities can be diagnosed by testing soil using the saturated paste method or by testing irrigation water (Horneck et al., 2007). In addition, direct sensitivity to ESP or soluble sodium is more pronounced at low salinity levels; for plants that are extremely sensitive to sodium, less than 5% exchangeable sodium may lead to toxic accumulation in leaf tissue (Bohn et al., 1985). High ESP values limit plant growth by decreasing calcium uptake; thus, plant damage may result more from calcium deficiency than from direct sodicity effects (Thorne & Peterson, 1954). The Ca^{2+} deficiency hypothesis proposed by Thorne and Peterson has gained substantial support from modern research on specific ion transporters. Studies have shown that high Na^+ concentrations compete with Ca^{2+} for uptake channels, disrupting cell signalling and membrane integrity. Recent nanotechnology approaches using nano-$ZnSO_4$ have demonstrated improved plant performance on saline-sodic soils by enhancing nutrient acquisition and mitigating Ca^{2+} deficiency (Ahmed et al., 2023; Gao et al., 2024). Recent research has explored the potential of nanotechnology, including nano zinc sulphate and zinc oxide nanoparticles, in mitigating salinity stress and improving plant performance on saline-sodic soils (Ahmed et al., 2023; Gao et al., 2024). Seedling emergence is drastically affected by higher ESP values due to increased crust strength (Chaudhri & Das, 1978), and high ESP values generally result in plant root degradation (Sposito, 1989). Taken together, the evidence indicates that salinity impairs plant growth through a dual-phase mechanism involving initial osmotic stress followed by progressive ion toxicity and nutritional imbalance. These effects reduce photosynthetic capacity, disrupt cellular metabolism, and ultimately diminish crop yield and quality. The severity of plant response depends on salinity concentration, ion composition, plant species, and growth stage, underscoring the need for context-specific management strategies that integrate salinity-tolerant cultivars, proper irrigation practices, and soil amendments to sustain agricultural productivity in salt-affected regions.

Gaps in policy and social dimensions

The human and institutional dimensions of soil salinity management have received far less attention than the biophysical aspects. Land tenure insecurity, lack of farmer knowledge, inadequate extension services, and weak policy frameworks often undermine technical interventions. Future research should investigate how governance structures, incentive mechanisms, and participatory approaches can enhance the adoption of sustainable salinity management practices. Furthermore, the gendered impacts of soil degradation—particularly how salinization affects women farmers who often have limited access to resources and decision-making power—remain virtually unstudied in the salinity literature. Addressing the global challenge of salt-affected soils requires a paradigm shift from disciplinary, reductionist research toward interdisciplinary, systems-level approaches that integrate soil science, plant biology, microbiology, hydrology, climatology, economics, and social science. Future research priorities should emphasize: (i) long-term field experiments across diverse agro-ecological zones; (ii) multi-scale modeling that couples hydrological and biogeochemical processes; (iii) farmer-centered innovation systems; and (iv) policy-

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relevant outcomes that can translate scientific knowledge into tangible improvements in land productivity and rural livelihoods.

Conclusion

This review has examined the classification, causes, and multifaceted impacts of salinity and sodicity on soil physical, chemical, and biological properties, as well as on plant performance. Salt-affected soils are broadly classified into three categories: saline soils, characterized by high soluble salt concentrations (ECe > 4 dS m^{-1}, ESP < 15, pH < 8.5); sodic soils, defined by elevated exchangeable sodium (ESP > 15, SAR > 13, pH 8.5–10, ECe < 4 dS m^{-1}); and saline-sodic soils, which exhibit both high soluble salts and high exchangeable sodium (ECe > 4 dS m^{-1}, ESP > 15, pH typically < 8.5). These classifications, originally established by Richards (1954) and the USDA, remain foundational, though recent research has refined thresholds for specific crops and soil types. The physical degradation of salt-affected soils is driven primarily by the interplay between salinity-induced flocculation and sodicity-induced dispersion. Excessive sodium causes clay swelling, reduced hydraulic conductivity, surface crusting, and poor aeration, while adequate calcium levels help maintain soil structure. Chemically, these soils exhibit elevated ECe, ESP, SAR, and pH, alongside deficiencies in nitrogen, phosphorus, potassium, and micronutrients. Reduced organic matter and suppressed enzyme activities further diminish soil fertility. Biologically, salinity and sodicity reduce microbial biomass, alter community composition, and decrease enzyme-mediated nutrient cycling, with fungal communities often more sensitive than bacterial populations. These biological impairments, in turn, weaken aggregate stabilization and exacerbate physical and chemical degradation.

For plants, salinity imposes a two-phase stress: an immediate osmotic phase that limits water uptake and leaf expansion, followed by a slower ionic phase characterized by Na^+ and Cl^- accumulation, nutritional imbalance, and cellular damage. Modern molecular studies have confirmed classical models, identifying key transporters such as HKT genes responsible for Na^+ exclusion and K^+/Na^+ homeostasis. Crop yield losses result from reduced photosynthetic area, impaired metabolic enzyme function, and disrupted nutrient acquisition, with sensitivity varying by species, cultivar, and growth stage. Reclamation and sustainable management of salt-affected soils require integrated approaches that address physical, chemical, biological, and plant-related constraints simultaneously. Strategies include leaching with good-quality water, application of calcium-based amendments such as gypsum, use of organic matter to restore biological activity, cultivation of salinity-tolerant crops and halophytes, and adoption of precision irrigation and drainage systems. Emerging technologies, including nanotechnology and remote sensing, offer promising avenues for monitoring and amelioration. Future research directions should prioritize: (1) developing crop cultivars with enhanced Na^+ exclusion and tissue tolerance through marker-assisted selection and genetic engineering; (2) elucidating the role of soil microbiome engineering in restoring biological functions in degraded saline-sodic soils; (3) advancing coupled hydrological-salinity-crop models that can predict salinization dynamics under changing climate scenarios; (4) evaluating the long-term sustainability and economic viability of organic and nano-enabled amendments at the farm scale; and (5) designing inclusive policy frameworks that address land tenure, gender equity, and farmer knowledge gaps. Without sustained scientific and policy attention, the projected expansion of salt-affected areas—potentially reaching 50% of arable land by 2050—poses a severe threat to global food security and environmental sustainability.

Table A1. Symbols, acronyms, and abbreviations used in this review.

List of symbols	
Al; Aluminum	K^+; Potassium
H_3BO_3; Borate	Mg^{2+}; Magnesium
B; Boron	Mn; manganese
C; Carbon	N; nitrogen
Ca^{2+}; Calcium	Na^+; Sodium
$CaCO_3$; Calcium Carbonate	Na_2SO_4; Sodium sulfate
$CaSO_4$; Calcium sulfate	NaCl; Sodium chloride
Cl–; Chloride	NO_3^-; Nitrate
CO_2; Carbon dioxide	P; Phosphorus
CO_3^{2-} ; Carbonate	S; Sulfur
Cu; Copper	$SO4^{2-}$; Sulfate
Fe; Iron	Zn; Zinc
HCO_3^-; Bicarbonates	

List of acronyms
CEC; Cation Exchange Capacity ($cmol_c/kg^{-1}$)
ECe; Electrical Conductivity
ESP: Exchangeable Sodium Percentage
SAR: Sodium Adsorption Ratio
dS m^{-1}; Millimhos per centimeter
USDA: United States Department of Agriculture
Mha: Area in million hectares
FAO: Food and Agriculture Organization
NRCS: Natural Resources Conservation Service (USA)
pH: Negative logarithm of the hydrogen ion activity in a solution

References

Abdelgadir, E. M., Oka, M., & Fujiyama, H. (2005). Nitrogen nutrition of rice plants under salinity. Biologia Plantarum, 49(1), 99–104.
Aboelsoud, H. M., AbdelRahman, M. A. E., Kheir, A. M. S., Eid, M. S. M., Ammar, K. A., Khalifa, T. H., & Scopa, A. (2022). Quantitative estimation of saline-soil amelioration using remote-sensing indices in arid land for better management. Land, 11(7), 1041.
Abrol, I. P., Yadav, J. S. P., & Massoud, F. I. (1988). Salinity-affected soils and their management (Issue 39). Food & Agriculture Org.
Adu, J. K., & Oades, J. M. (1978). Physical factors influencing decomposition of organic materials in soil aggregates. Soil Biology and Biochemistry, 10(2), 109–115.
Agassi, M., Shainberg, I., & Morin, J. (1981). Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. Soil Science Society of America Journal, 45(5), 848–851.
Ahmed, R., Zia-ur Rehman, M., Sabir, M., Usman, M., Rizwan, M., Ahmad, Z., & Bamagoos, A. A. (2023). Differential response of nano zinc sulphate with other conventional sources of Zn in mitigating salinity stress in rice grown on saline-sodic soil. Chemosphere, 327, 138479.
Aly, S. M., & Letey, J. (1990). Physical properties of sodium-treated soil as affected by two polymers. Soil Science Society of America Journal, 54(2), 501–504.
Amini, S., Ghadiri, H., Chen, C., & Marschner, P. (2016). Salinity-affected soils, reclamation, carbon dynamics, and biochar: a review. Journal of Soils and Sediments, 16(3), 939–953. https://doi.org/10.1007/s11368-015-1293-1
Amirjani, M. R. (2011). Effect of salinity stress on growth, sugar content, pigments and enzyme activity of rice. International Journal of Botany, 7(1), 73–81.
Arora, S., Singh, Y. P., Vanza, M., & Sahni, D. (2016). Bio-remediation of saline and sodic soils through halophilic bacteria to enhance agricultural production. Journal of Soil and Water Conservation, 15(4), 302–305.
Aylmore, L. A. G., & Quirk, J. P. (1960). Domain or turbostratic structure of clays. Nature, 187(4742), 1046–1048.
Bajwa, M. I., Zia, M. S., & Naim, P. A. (1991). Research findings in arid lands of Pakistan: A summary. Pakistan Agric. Res. Council, Islamabad, Pakistan.
Bano, A., & Fatima, M. (2009). Salinity tolerance in Zea mays (L.) following inoculation with Rhizobium and Pseudomonas. Biology and Fertility of Soils, 45(4), 405–413.
Bernstein, L. (1975). Effects of salinity and sodicity on plant growth. Annual Review of Phytopathology, 13(1), 295–312.
Blackmore, A. V., & Miller, R. D. (1961). Tactoid size and osmotic swelling in calcium montmorillonite. Soil Science Society of America Journal, 25(3), 169–173.
Bohn, H. L., Brain, L. M., & George, A. (1985). Soil chemistry. John Wiley & Sons, New York.
Bohn, H. L., McNeal, B. L., & O'Connor, G. A. (2001). Soil chemistry. John Wiley & Sons, Inc., New York, 155–171.
Bresler, E., McNeal, B. L., & Carter, D. L. (2012). Saline and sodic soils: principles-dynamics-modeling (Vol. 10). Springer Science & Business Media.
Brinck, E., & Frost, C. (2009). Evaluation of amendments used to prevent sodification of irrigated fields. Applied Geochemistry, 24(11), 2113–2122.
Buringh, P. (1978). The Natural Environment and Food Production. In Alternatives for Growth: The Engineering and Economics of Natural Resources Development (pp. 97–146). NBER.
Chander, K., Goyal, S., & Kapoor, K. K. (1994). Effect of sodic water irrigation and farmyard manure application on soil microbial biomass and microbial activity. Applied Soil Ecology, 1(2), 139–144.
Chaudhri, K. G., & Das, D. K. (1978). Emergence of soybean, cotton and maize seedlings as influenced by crust formation in salt-affected soils. Journal of the Indian Society of Soil Science, 26(2), 106–111.
Corwin, D. L. (2021). Climate change impacts on soil salinity in agricultural areas. European Journal of Soil Science, 72(2), 842–862.
Dregne, H., Kassas, M., & Rozanov, B. (1991). A new assessment of the world status of desertification. Desertification Control Bulletin, 20(1), 7–18.
El-Morsy, E. A., Malik, M., & Letey, J. (1991). Polymer effects on the hydraulic conductivity of saline and sodic soil conditions. Soil Science, 151(6), 430–435.
Elmeknassi, M., El Moustaine, R., El Khalil, H., Elgamouz, A., & Benaissa, M. (2024). A review on the application of sustainable organic amendments for soil reclamation and plant growth. Journal of Plant Growth Regulation, 43, 1–20.
Ezeaku, P. I., Ene, J., & Shehu, J. A. (2015). Application of different reclamation methods on salt affected soils for crop production.
Ezlit, Y., McMillan, R., & Rengasamy, P. (2013). Modification of the McNeal clay swelling model improves prediction of saturated hydraulic conductivity. Geoderma, 211–212, 86–93.
FAO. (2008). Land and plant nutrition management service. Food and Agriculture Organization of the United Nations, Rome.
FAO. (2024). Global status of salt-affected soils. Food and Agriculture Organization of the United Nations, Rome.
Flowers, T. J. (2004). Improving crop salinity tolerance. Journal of Experimental Botany, 55(396), 307–319.
Frankenberger Jr, W. T., & Bingham, F. T. (1982). Influence of salinity on soil enzyme activities. Soil Science Society of America Journal, 46(6), 1173–1177.
Frenkel, H., Goertzen, J. O., & Rhoades, J. D. (1978). Effects of clay type and content, exchangeable sodium percentage, and electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Science Society of America Journal, 42(1), 32–39.
Gandhi, A. P., & Paliwal, K. V. (1976). Mineralization and gaseous losses of nitrogen from urea and ammonium sulphate in salt-affected soils. Plant and Soil, 45(1), 247–255.
Ganjegunte, G. K., King, L. A., & Vance, G. F. (2008). Cumulative soil chemistry changes from land application of saline–sodic waters. Journal of Environmental Quality, 37(S5), S-128.
Gao, Y., Li, Y., Zhang, J., Liu, W., Dang, Z., Ye, W., & Cheng, Y. (2024). New insights of salinity impacts on natural organic matter and disinfection byproducts formation during chlorination. Chemical Engineering Journal, 466, 143334.
Garcia, C., & Hernandez, T. (1996). Influence of salinity on the biological and biochemical activity of a calciorthird soil. Plant and Soil, 178(2), 255–263. https://doi.org/10.1007/bf00011591
Garcia, C., Hernandez, T., & Costa, F. (1994). Microbial activity in soils under Mediterranean environmental conditions. Soil Biology and Biochemistry, 26(9), 1185–1191.

García, M. J., Lucena, C., Romera, F. J., Alcántara, E., & Pérez-Vicente, R. (2010). Ethylene and nitric oxide involvement in the up-regulation of key genes related to iron acquisition and homeostasis in Arabidopsis. Journal of Experimental Botany, 61(14), 3885–3899.
Gardner, W. R., Mayhugh, M. S., Goertzen, J. O., & Bower, C. A. (1959). Effect of electrolyte concentration and exchangeable sodium percentage on diffusivity of water in soils. Soil Science, 88(5), 270–274.
Gharaibeh, M. A., Eltaif, N. I., & Shra'Ah, S. H. (2010). Reclamation of a calcareous saline-sodic soil using phosphoric acid and by-product gypsum. Soil Use and Management, 26(2), 141–148.
Ghassemi, F., Jakeman, A. J., & Nix, H. A. (1995). Salinisation of land and water resources: human causes, extent, management and case studies. CAB International.
Ghollarata, M., & Raiesi, F. (2007). The adverse effects of soil salinization on the growth of Trifolium alexandrinum L. and associated microbial and biochemical properties in a soil from Iran. Soil Biology and Biochemistry, 39(7), 1699–1702. https://doi.org/10.1016/j.soilbio.2007.01.024
Ghorbanpour, M., Omidvari, M., Abbaszadeh-Dahaji, P., Omidvar, R., & Kariman, K. (2022). Halophytes play important role in phytoremediation of salt-affected soils in the bed of Urmia Lake, Iran. Scientific Reports, 12(1), 12269.
Golla, B. (2021). Agricultural production system in arid and semi-arid regions. Journal of Agricultural Science and Food Technology, 7(2), 234–244.
Gupta, V. K., & Gupta, S. P. (1984). Effect of zinc sources and levels on the growth and Zn nutrition of soybean (Glycine max L.) in the presence of chloride and sulphate salinity. Plant and Soil, 81(2), 299–304.
Hafez, M., Abdallah, A. M., Mohamed, A. E., & Rashad, M. (2022a). Influence of environmental-friendly bio-organic ameliorants on abiotic stress to sustainable agriculture in arid regions. Journal of King Saud University – Science, 34, 102212.
Hafez, M., Ge, S., Tsivka, K. I., Popov, A. I., & Rashad, M. (2022b). Enhancing calcareous and saline-sodic soils fertility by increasing organic matter decomposition and enzyme activities. Communications in Soil Science and Plant Analysis, 53(15), 1942–1959.
Hamid, K. S., & Mustafa, M. A. (1975). Dispersion as an index of relative hydraulic conductivity in salt-affected soils of the Sudan. Geoderma, 14(2), 107–114.
Hanay, A., Büyüksönmez, F., Kiziloglu, F. M., & Canbolat, M. Y. (2004). Reclamation of saline-sodic soils with gypsum and MSW compost. Compost Science & Utilization, 12(2), 175–179.
Hanson, B., Grattan, S. R., & Fulton, A. (1999). Agricultural salinity and drainage. University of California Irrigation Program, University of California, Davis.
Hassani, A., Azapagic, A., & Shokri, N. (2020). Predicting long-term dynamics of soil salinity and sodicity on a global scale. Proceedings of the National Academy of Sciences USA, 117(52), 33017–33027.
Hauser, F., & Horie, T. (2010). A conserved primary salinity tolerance mechanism mediated by HKT transporters: a mechanism for sodium exclusion and maintenance of high K^+/Na^+ ratio in leaves during salinity stress. Plant, Cell & Environment, 33(4), 552–565.
Horneck, D. A., Ellsworth, J. W., Hopkins, B. G., Sullivan, D. M., & Stevens, R. G. (2007). Managing salt-affected soils for crop production.
Hu, J. P., He, Y. Y., Li, J. H., Lii, Z. L., Zhang, Y. W., Li, Y. H., & Wang, W. (2024). Planting halophytes increases the rhizosphere ecosystem multifunctionality via reducing soil salinity. Environmental Research, 261, 119707.
Hussain, S., Shaukat, M., Ashraf, M., Zhu, C., Jin, Q., & Zhang, J. (2019). Salinity stress in arid and semi-arid climates: Effects and management in field crops. Climate Change and Agriculture, 13.
James, R. A., Blake, C., Byrt, C. S., & Munns, R. (2011). Major genes for Na^+ exclusion, Nax1 and Nax2 (wheat HKT1;4 and HKT1;5), decrease Na^+ accumulation in bread wheat leaves under saline and waterlogged conditions. Journal of Experimental Botany, 62(8), 2939–2947.
Jung, J.-Y., Shin, R., & Schachtman, D. P. (2009). Ethylene mediates response and tolerance to potassium deprivation in Arabidopsis. The Plant Cell, 21(2), 607–621.
Kang, Y., Khan, S., & Ma, X. (2009). Climate change impacts on crop yield, crop water productivity and food security—A review. Progress in Natural Science, 19(12), 1665–1674.
Keren, R. (2000). Salinity. In M. E. Sumner (Ed.), Handbook of Soil Science (pp. G-3–G-25). CRC Press, Boca Raton, FL, USA.
Kumar, P., & Sharma, P. K. (2020). Soil salinity and food security in India. Frontiers in Sustainable Food Systems, 4, 174.
Lakhdar, A., Rabhi, M., Ghnaya, T., Montemurro, F., Jedidi, N., & Abdelly, C. (2009). Effectiveness of compost use in salt-affected soil. Journal of Hazardous Materials, 171(1–3), 29–37.
Leogrande, R., & Vitti, C. (2019). Use of organic amendments to reclaim saline and sodic soils: a review. Arid Land Research and Management, 33(1), 1–21.
Liang, Y., Si, J., Nikolic, M., Peng, Y., Chen, W., & Jiang, Y. (2005). Organic manure stimulates biological activity and barley growth in soil subject to secondary salinization. Soil Biology and Biochemistry, 37(6), 1185–1195.
Luo, S., Chen, Z., Zhang, X., Zhou, M., Peng, Y., Wu, J., & Kuzyakov, Y. (2025). Rehabilitation of soil salinity and sodicity using diverse amendments and plants: A critical review. Discover Environment, 3, 199.
Manchanda, G., & Garg, N. (2008). Salinity and its effects on the functional biology of legumes. Acta Physiologiae Plantarum, 30(5), 595–618.
Mandal, S., Raju, R., Kumar, A., Kumar, P., & Sharma, P. C. (2018). Current status of research, technology response and policy needs of salt-affected soils in India—a review. Journal of the Indian Society of Coastal Agricultural Research, 36, 40–53.
Martinez-Beltran, J. (2005). Overview of salinity problems in the world and FAO strategies to address the problem. Proceedings of the International Salinity Forum, Riverside, California, 2005.
Mashali, A. M. (1995). Integrated soil management for sustainable use of salt-affected soils and network activities. International Workshop on Integrated Soil Management for Sustainable Use of Salinity Affected Soils, Philippines, November 6–10, 29–38.
McNeal, B. L. (1968). Prediction of the effect of mixed-salinity solutions on soil hydraulic conductivity. Soil Science Society of America Journal, 32(2), 190–193.
McNeal, B. L., & Coleman, N. T. (1966). Effect of solution composition on soil hydraulic conductivity. Soil Science Society of America Journal, 30(3), 308–312.
Mirza, B. B., Zia, M. S., Szombathova, N., & Zaujec, A. (2005). Rehabilitation of soils through environmental friendly technologies: Role of Sesbania and farmyard manure. Agricultura Tropica et Subtropica, 38(1), 11–17.
Muneer, M., & Oades, J. M. (1989). The role of Ca-organic interactions in soil aggregate stability. III. Mechanisms and models. Soil Research, 27(2), 411–423.
Munns, R. (2005). Genes and salinity tolerance: bringing them together. New Phytologist, 167(3), 645–663.

Nelson, P. N., Baldock, J. A., & Oades, J. M. (1998). Changes in dispersible clay content, organic carbon content, and electrolyte composition following incubation of sodic soil. Soil Research, 36(6), 883–898.
Nelson, P. N., Ladd, J. N., & Oades, J. M. (1996). Decomposition of ^{14}C-labelled plant material in a salt-affected soil. Soil Biology and Biochemistry, 28(4–5), 433–441.
Netondo, G. W., Onyango, J. C., & Beck, E. (2004). Sorghum and salinity: II. Gas exchange and chlorophyll fluorescence of sorghum under salinity stress. Crop Science, 44(3), 806–811.
Nishimura, T., Cha-Um, S., Takagaki, M., Ohyama, K., & Kirdmanee, C. (2011). Survival percentage, photosynthetic abilities and growth characters of two indica rice (Oryza sativa L. spp. indica) cultivars in response to iso-osmotic stress. Spanish Journal of Agricultural Research, 9(1), 262–270.
Northcote, K. H., & Srene, J. K. M. (1972). Australian soils with saline and sodic properties.
Oldeman, L. R. (1991). World map of the status of human-induced soil degradation: An explanatory note. Global assessment of soils degradation, GLASOD.
Omar, M. D. M., Shitindi, M. J., Massawe, B. H., Pedersen, O., Meliyo, J. L., & Fue, K. G. (2024). Modeling the electrical conductivity relationship between saturated paste extract and 1:2.5 dilution in different soil textural classes. Frontiers in Soil Science, 4, 1421661.
Oren, A. (1999). Bioenergetic aspects of halophilism. Microbiology and Molecular Biology Reviews, 63(2), 334–348.
Osman, K. T. (2018). Saline and sodic soils. In Management of soil problems (pp. 255–298). Springer.
Parvaiz, A., & Satyawati, S. (2008). Salinity stress and phyto-biochemical responses of plants—a review. Plant, Soil and Environment, 54(3), 89.
Pathak, H., & Rao, D. L. N. (1998). Carbon and nitrogen mineralization from added organic matter in saline and alkali soils. Soil Biology and Biochemistry, 30(6), 695–702.
Paz, V. P. S., Ramos, T. B., & Simunek, J. (2023a). National-scale assessment of salinity-affected areas in Portugal. Journal of Environmental Management, 344, 118380.
Paz, A. M., Amezketa, E., Canfora, L., Castanheira, N., Falsone, G., Gonçalves, M. C., ... Costantini, E. A. C. (2023b). Salt-affected soils: Field-scale strategies for prevention, mitigation, and adaptation to salt accumulation.
Perri, S., Molini, A., Hedin, L. O., & Porporato, A. (2022). Contrasting effects of aridity and seasonality on global salinization. Nature Geoscience, 15, 375–381.
Pessarakli, M., & Szabolcs, M. I. (1999). Soil salinity and sodicity as particular plant/crop stress factors. In M. Pessarakli (Ed.), Handbook of Plant and Crop Stress (pp. 1–15). Marcel Dekker Inc., New York.
Qadir, M., Quillérou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R. J., ... Noble, A. D. (2014). Economics of salt-induced land degradation and restoration. Natural Resources Forum, 38(4), 282–295.
Qadir, M., Ghafoor, A., & Murtaza, G. (2000). Amelioration strategies for saline soils: a review. Land Degradation & Development, 11(6), 501–521.
Qadir, M., Noble, A. D., Oster, J. D., Schubert, S., & Ghafoor, A. (2005). Driving forces for sodium removal during phytoremediation of calcareous sodic and saline–sodic soils: a review. Soil Use and Management, 21(2), 173–180.
Qadir, M., Qureshi, R. H., & Ahmad, N. (1997). Nutrient availability in a calcareous saline-sodic soil during vegetative bioremediation. Arid Land Research and Management, 11(4), 343–352.
Qadir, M., & Schubert, S. (2002). Degradation processes and nutrient constraints in sodic soils. Land Degradation & Development, 13(4), 275–294.
Quirk, J. P., & Schofield, R. K. (1955). The effect of electrolyte concentration on soil permeability. Journal of Soil Science, 6(2), 163–178.
Quirk, J. P. (2001). The significance of the threshold and turbidity concentration in relation to sodicity and microstructure. Australian Journal of Soil Research, 39(6), 1185–1202.
Qureshi, R. H., & Barrett Lennard, E. G. (1998). Saline agriculture for irrigated land in Pakistan: a handbook.
Rao, G. G., Khandelwal, M. K., Arora, S., & Sharma, D. K. (2012). Salinity ingress in coastal Gujarat: Appraisal of control measures. Journal of Soil Salinity and Water Quality, 4(2), 102–113.
Rengasamy, P. (2002). Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: an overview. Australian Journal of Experimental Agriculture, 42(3), 351–361.
Rengasamy, P. (2006). World salinization with emphasis on Australia. Journal of Experimental Botany, 57(5), 1017–1023.
Rengasamy, P. (2010). Soil processes affecting crop production in salt-affected soils. Functional Plant Biology, 37(7), 613–620.
Rengasamy, P., & Olsson, K. A. (1993). Irrigation and sodicity. Soil Research, 31(6), 821–837.
Reynolds, M. P., Mujeeb-Kazi, A., & Sawkins, M. (2005). Prospects for utilising plant-adaptive mechanisms to improve wheat and other crops in drought-and salinity-prone environments. Annals of Applied Biology, 146(2), 239–259.
Richards, L. A. (1954). Diagnosis and improvement of saline and alkali soils (Vol. 78, Issue 2). LWW.
Rietz, D. N., & Haynes, R. J. (2003). Effects of irrigation-induced salinity and sodicity on soil microbial activity. Soil Biology and Biochemistry, 35(6), 845–854.
Ruprecht, J. K., & Schofield, N. J. (1991). Effects of partial deforestation on hydrology and salinity in high salinity storage landscapes. II. Strip, soils and parkland clearing. Journal of Hydrology, 129(1–4), 39–55.
Sahbeni, G., Ngabire, M., Musyimi, P. K., & Székely, B. (2023). Challenges and opportunities in remote sensing for soil salinization mapping and monitoring: A review. Remote Sensing, 15(10), 2540.
Shahid, S. A., Zaman, M., & Heng, L. (2018). Soil salinity: historical perspectives and a world overview of the problem. In Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques (pp. 43–53). Springer.
Shainberg, I., & Letey, J. (1984). Response of soils to sodic and saline conditions. Hilgardia, 52(2), 1–57.
Shainberg, I., Rhoades, J. D., & Prather, R. J. (1981). Effect of low electrolyte concentration on clay dispersion and hydraulic conductivity of a sodic soil. Soil Science Society of America Journal, 45(2), 273–277.
Sharma, D. K., & Singh, A. (2016). Sustainable management of salinity-affected soils: A brief review of the work done in India.
Shaw, R., Brebber, L., Ahern, C., & Weinand, M. (1994). A review of sodicity and sodic soil behavior in Queensland. Soil Research, 32(2), 143–172.
Shrivastava, P., & Kumar, R. (2015). Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi Journal of Biological Sciences, 22(2), 123–131.

Siringam, K., Juntawong, N., Cha-um, S., & Kirdmanee, C. (2011). Salinity stress induced ion accumulation, ion homeostasis, membrane injury and sugar contents in salinity-sensitive rice (Oryza sativa L. spp. indica) roots under isoosmotic conditions. African Journal of Biotechnology, 10(8), 1340–1346.
Sisodiya, S., & Vaghani, M. (2016). Reclamation of saline and sodic soil: The state of review. Department of Civil Engineering, 2455–5703.
Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil and Tillage Research, 79(1), 7–31.
Smedema, L. K., & Shiati, K. (2002). Irrigation and salinity: a perspective review of the salinity hazards of irrigation development in the arid zone. Irrigation and Drainage Systems, 16(2), 161–174.
Sobhanian, H., Razavizadeh, R., Nanjo, Y., Ehsanpour, A. A., Jazii, F. R., Motamed, N., & Komatsu, S. (2010). Proteome analysis of soybean leaves, hypocotyls and roots under salinity stress. Proteome Science, 8(1), 1–15.
Sposito, G. (1989). Soil particle surface. In The Chemistry of Soils (pp. 136–141). Oxford University Press, New York.
Stroehlein, J. L., & Pennington, D. A. (1986). Use of sulfur compounds for soil and irrigation water treatments. Sulfur in Agriculture, 27, 435–454.
Suarez, D. L., Rhoades, J. D., Lavado, R., & Grieve, C. M. (1984). Effect of pH on saturated hydraulic conductivity and soil dispersion. Soil Science Society of America Journal, 48(1), 50–55.
Sumner, M. E. (1993). Sodic soils—New perspectives. Soil Research, 31(6), 683–750.
Sumner, M. E. (1995). Sodic soils: new perspectives. In R. Naidu, M. E. Sumner, & P. Rengasamy (Eds.), Australian Sodic Soils: Distribution, Properties and Management. CSIRO, Melbourne.
Szabolcs, I. (1994). Prospects of soil salinity for the 21st century. Agrokémia és Talajtan, 43(1–2), 5–24.
Szabolcs, I. (1999). In M. Pessarakli (Ed.), Handbook of Plant and Crop Stress (p. 1).
Tanji, K. K. (1990). Nature and extent of agricultural salinity. In Agricultural Salinity Assessment and Management (pp. 71–92).
Thorne, D. W., & Peterson, H. B. (1954). Irrigated soils. The Blakiston Co. Inc., New York.
Tripathi, S., Chakraborty, A., Chakrabarti, K., & Bandyopadhyay, B. K. (2007). Enzyme activities and microbial biomass in coastal soils of India. Soil Biology and Biochemistry, 39(11), 2840–2848. https://doi.org/10.1016/j.soilbio.2007.05.027
Tripathi, S., Kumari, S., Chakraborty, A., Gupta, A., Chakrabarti, K., & Bandyapadhyay, B. K. (2006). Microbial biomass and its activities in salt-affected coastal soils. Biology and Fertility of Soils, 42(3), 273–277. https://doi.org/10.1007/s00374-005-0037-6
USDA. (1954). Diagnosis and improvement of saline and alkali soils. USDA Agricultural Handbook No. 60. U.S. Salinity Laboratory Staff.
Van Hoorn, J. W., & Van Alphen, J. G. (1994). Salinity control. In Drainage Principles and Applications (pp. 533–600).
Wang, Z., Zhang, F., Zhang, X., Chan, N. W., Kung, H., Zhou, X., & Wang, Y. (2020). Quantitative evaluation of spatial and temporal variation of soil salinization risk using GIS-based geostatistical method. Remote Sensing, 12(15), 2405.
Warrence, N. J., Bauder, J. W., & Pearson, K. E. (2002). Basics of salinity and sodicity effects on soil physical properties. Department of Land Resources and Environmental Sciences, Montana State University-Bozeman, MT, 129, 1–29.
Wichern, J., Wichern, F., & Joergensen, R. G. (2006). Impact of salinity on soil microbial communities and the decomposition of maize in acidic soils. Geoderma, 137(1–2), 100–108.
Wong, V. N. L., Dalal, R. C., & Greene, R. S. B. (2008). Salinity and sodicity effects on respiration and microbial biomass of soil. Biology and Fertility of Soils, 44(7), 943–953. https://doi.org/10.1007/s00374-008-0279-1
Wong, V. N. L., Dalal, R. C., & Greene, R. S. B. (2009). Carbon dynamics of sodic and saline soils following gypsum and organic material additions: a laboratory incubation. Applied Soil Ecology, 41(1), 29–40.
Wong, V. N. L., Greene, R. S. B., Dalal, R. C., & Murphy, B. W. (2010). Soil carbon dynamics in saline and sodic soils: a review. Soil Use and Management, 26(1), 2–11.
Yacine, L., et al. (2025). Dynamics of soil hydraulic conductivity in response to incremental changes in sodium adsorption ratio: Evidence for soil structural hysteresis. Revista Brasileira de Engenharia Agrícola e Ambiental, 29(4), e215241.
Yousaf, M., Ali, O. M., & Rhoades, J. D. (1987). Clay dispersion and hydraulic conductivity of some salt-affected arid land soils. Soil Science Society of America Journal, 51(4), 905–907.
Yu, H., et al. (2023). Spatiotemporal variations of soil salinization in China's West Songnen Plain. Land Degradation & Development, 34, 2366–2378.
Yuan, B.-C., Xu, X.-G., Li, Z.-Z., Gao, T.-P., Gao, M., Fan, X.-W., & Deng, J.-M. (2007). Microbial biomass and activity in alkalized magnesic soils under arid conditions. Soil Biology and Biochemistry, 39(12), 3004–3013.
Zahran, H. H. (1997). Diversity, adaptation and activity of the bacterial flora in saline environments. Biology and Fertility of Soils, 25(3), 211–223.
Zewd, I., & Siban, M. (2021). The effects of alkalinity on physical and chemical properties of soil. Journal of Plant Biology and Agriculture Sciences, 3(2), 1–5.
Zhang, X. C., & Norton, L. D. (2002). Effect of exchangeable Mg on saturated hydraulic conductivity, disaggregation and clay dispersion of disturbed soils. Journal of Hydrology, 260(1–4), 194–205.
Zhang, H., Fu, X., Zhang, Y., Qi, Z., Zhang, H., & Xu, Z. (2023). Mapping multi-depth soil salinity using remote sensing-enabled machine learning in the Yellow River Delta, China. Remote Sensing, 15(23), 5640.
Zhao, J., Fan, Y., Xuan, J., Shi, M., Wang, D., Wu, H., Bi, Y., & Li, Y. (2025). Monitoring of soil salinization and analysis of driving factors in the oasis zone of South Xinjiang. Land, 14, 803.
Zilli, C. G., Balestrasse, K. B., Yannarelli, G. G., Polizio, A. H., Santa-Cruz, D. M., & Tomaro, M. L. (2008). Heme oxygenase up-regulation under salinity stress protects nitrogen metabolism in nodules of soybean plants. Environmental and Experimental Botany, 64(1), 83–89.