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Sustainable Reclamation of Salt-Affected Soils: Conventional Amendments, Organic Matter, and Emerging Technologies

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Abstract

Soil salinity and sodicity are critical constraints on global agricultural productivity, particularly in arid and semi-arid regions, where they affect approximately 20% of the world's arable land. This review examines the mechanisms, efficacy, and integration of diverse reclamation strategies for salt-affected soils, including chemical amendments (gypsum, sulfuric acid, calcium chloride, and langbeinite), organic matter applications (compost, manure, and biochar), leaching techniques, phytoremediation, and bioremediation. Particular emphasis is placed on the synergistic potential of combining reduced-rate gypsum with microbially enriched organic amendments, which has demonstrated superior agronomic and economic outcomes compared with single-amendment approaches. The review further evaluates emerging technologies—including electro-reclamation, nanotechnology-assisted soil management, and flue gas desulfurization gypsum—within the context of climate change adaptation and sustainable intensification. Evidence synthesized from field studies across diverse agro-ecological zones indicates that integrated organic–gypsum systems substantially improve soil physical structure, chemical fertility, and biological activity while reducing amendment costs and water requirements by 25–50%. The findings underscore that successful reclamation requires site-specific selection of amendments based on soil properties, irrigation water quality, drainage infrastructure, and economic feasibility. Future research should prioritize optimizing amendment combinations for specific soil textures and salinity levels, assessing the long-term environmental impacts of nanomaterials, and developing cost-benefit models that incorporate carbon sequestration credits to support large-scale adoption of sustainable reclamation practices.

Keywords: Soil reclamation, gypsum, organic matter, biochar, electro-reclamation, saline-sodic soils, integrated amendment systems

Introduction

Salt-affected soils exhibit elevated concentrations of dissolved mineral salts that adversely affect crop productivity (Rengasamy, 2006; Wong et al., 2010). Soil amelioration for saline and alkaline conditions has been extensively studied over many decades (Reeve et al., 1955; Hussain et al., 2001). Consequently, fundamental principles governing the reclamation and improvement of saline-alkali soils are now well established. Soil salinity represents one of the most critical constraints on global agricultural productivity, particularly in arid and semi-arid regions characterized by water scarcity and high temperatures. Improving crop growth and yield in low-fertility, non-saline soils is relatively straightforward and primarily economically constrained. It is well established that elevated salt concentrations in the root zone impair nutrient uptake, induce ion toxicity, and consequently reduce plant growth and yield (Munns, 2002; Parida et al., 2005). Therefore, ameliorating the saline root-zone environment is essential for mitigating salinity stress (Raviv et al., 1998). Heavy-textured salt-affected soils are particularly unfavorable for plant growth. High sodicity—characterized by elevated exchangeable sodium—promotes clay swelling and dispersion, leading to soil structural degradation, reduced hydraulic conductivity, and sodium toxicity (Yousaf et al., 1987). Salt-affected soils occur on every continent, covering approximately 10% of global drylands, with the highest prevalence in arid and semi-arid regions (Szabolcs, 1989). Primary salinization has affected approximately 1000 million hectares through natural salt accumulation in soils and water, whereas secondary salinization, driven by human activities and rising groundwater tables, has impacted about 76 million hectares (Metternicht & Zinck, 2003; Amini et al., 2016). Salinity affects approximately 20% of the world's arable land, including about 10% classified as saline-sodic, while sodicity alone impacts approximately 340 million hectares(Amini et al., 2016). According to the FAO Global Map of Salt-Affected Soils (2021), more than 833 million hectares of subsoil (30–100 cm) are salt-affected globally, representing 8.7% of the planet's land area, with the highest prevalence in arid and semi-arid regions. Reclaiming sodic soils is more challenging than reclaiming saline soils because exchangeable sodium persists and becomes increasingly concentrated following the leaching of soluble salts. Therefore, sodic soil reclamation requires the application of chemical amendments that supply divalent cations—primarily calcium (Ca^{2+})—to displace adsorbed sodium before leaching (Leogrande & Vitti, 2019) Given that irrigation water is among the most limiting resources for agriculture in arid and semi-arid regions, where soil productivity constraints are prevalent (Golla, 2021)Additional factors, including ionic charge and water solubility, must be considered when selecting an amendment to minimize the water required for dissolution. This review evaluates various strategies for reclaiming salt-affected soils by examining the underlying mechanisms and comparing their effectiveness in improving soil properties, particularly under climate change scenarios. However, given rising anthropogenic CO_2 emissions and growing concerns about climate change, this review emphasizes the role of organic matter in soil reclamation. Intensification of agricultural production is necessary to fulfill the requirements of a fast-growing world population; hence, the need for salt-affected soil reclamation has become urgent in recent years. The world's population is anticipated to reach 8.5 billion by 2030 and 9.7 billion by 2050 (Dorling, 2021). Meeting the food demands of this growing population will require a 50-70% increase in

agricultural production, making the rehabilitation of degraded lands essential (Godfray et al., 2010; Foley et al., 2011). Sodic soils represent a valuable agricultural resource with considerable productive potential, particularly because they are often located in alluvial plains with access to irrigation water (Bhargava, 1989). Following successful restoration, sodic soils have demonstrated the capacity to produce 5-6 tons per hectare of rice and 3-4 tons per hectare of wheat under appropriate management (Singh and Kumar, 1985; Dagar et al., 2016). The economic returns from reclaiming these soils often justify the initial investment in reclamation activities within 3-5 years (Thimmappa et al., 2017). Recent studies have emphasized that the consequences of soil salinization extend beyond reductions in crop productivity to include degradation of soil ecosystem services, increased irrigation demand, and substantial economic losses. Moreover, climate change is expected to intensify both primary and secondary salinization through rising temperatures, altered precipitation regimes, and increased pressure on freshwater resources, underscoring the urgent need for sustainable, site-specific reclamation strategies (Elmeknassi et al., 2024).

Reclamation of salt-affected soils:

Chemical reclamation

Chemical reclamation remains the most widely practiced approach for ameliorating sodic and saline-sodic soils. The fundamental principle involves the application of amendments that provide calcium ions to replace exchangeable sodium on the soil colloids, thereby improving soil structure and hydraulic conductivity (Shainberg et al., 1989). Supplementary chemicals used in the reclamation of sodic soils include soluble calcium sources (e.g., gypsum, calcium chloride, and phospho-gypsum) and acids or acid formers (e.g., elemental sulfur, sulfuric acid, sulfates of iron and aluminum, pyrites, and lime sulfur). The effectiveness of chemical amendments depends on multiple factors, including soil properties (texture, mineralogy, initial ESP, calcium carbonate content), amendment characteristics (solubility, purity, particle size), water quality and quantity available for leaching, and climatic conditions (Kumar and Sharma, 2020). To use chemical amendment technology effectively, the land should have adequate drainage infrastructure to remove excess water, and irrigation should be conducted with freshwater or water of acceptable quality. Chemical amendments used for sodic soil reclamation include soluble calcium sources (e.g., gypsum, calcium chloride, and phosphogypsum) and acids or acid-forming materials (e.g., elemental sulfur, sulfuric acid, iron and aluminum sulfates, pyrite, and lime-sulfur). Farmyard manure is also employed as a soil amendment to facilitate sodic soil reclamation . Effective chemical amendment application requires appropriate land preparation, including bunding and drainage infrastructure for excess water removal, as well as the use of good-quality irrigation water applied through an optimized strategy. Amendment selection and crop choice should be based on soil properties, environmental conditions, and appropriate fertilization practices. Three categories of chemical amendments are commonly employed in sodic soil reclamation (Table 1): (1) soluble calcium salts: $CaSO_4 \cdot 2H_2O$, $CaCl_2$, phosphogypsum, (2) acid or acid-formers: H_2SO_4, sulfur, iron sulfate, aluminum sulfate, lime-sulfur, and pyrite, and (3) calcium salts with poor solubility, such as powdered limestone (USDA, 1954; Gupta & Abrol, 1990 ; Stroehlein & Pennington, 1986).

Table 1. Chemical Amendments Used in Sodic Soil Reclamation

Amendment	Solubility	Cost	Primary Mechanism
Gypsum	Low (2.4 g/L)	Low	Ca2+ exchange, electrolyte effect
CaCl2	High (745 g/L)	High	Rapid Ca2+ availability
H2SO4	Complete	Medium	Dissolves CaCO3, releases Ca2+
Elemental S	Insoluble	Low	Microbial oxidation to H2SO4
Fe2(SO4)3	Moderate	Medium	Acid + Fe3+ flocculation

** Common chemical amendments, their properties, and mechanisms of action (adapted from Gupta and Abrol, 1990; Oster and Frenkel, 1980)

Langbeinite ($K_2SO_4 \cdot 2MgSO_4$) is a relatively novel chemical amendment—a potash mineral with a solubility approximately 130 times that of gypsum (Artiola et al., 2000). It has recently been applied to reclaim saline-sodic soils; however, limited evidence regarding its efficacy has yielded mixed results (Heluf, 1995). Artiola et al. (2000) reported that langbeinite was more effective than gypsum in displacing and leaching exchangeable sodium at application rates exceeding 6 Mg ha^{-1}, though such high rates may limit economic feasibility. Downward movement of irrigation water—dependent on adequate internal drainage—is critical for removing excess salts and exchangeable sodium mobilized into the soil solution during reclamation; in other words, enhancing hydraulic conductivity is a prerequisite for effective amendment application. During initial leaching stages, saline-sodic soils typically exhibit good permeability. However, as soluble salts are progressively removed, residual sodium promotes clay dispersion, clogging soil pores, degrading soil structure, and reducing hydraulic conductivity.(Gupta & Abrol, 1990). Following amendment application, reclamation amendments reduce surface crusting, promote clay flocculation, and facilitate the removal of exchangeable sodium (Amezketa et al., 2005). Chemical amendments require moisture—supplied by rainfall or irrigation—to initiate reactions that reduce sodium levels or leach salts from the root zone (Kumar & Sharma, 2020). Several factors must be considered when selecting a reclamation amendment, including soil properties, relative effectiveness, required application rate, target exchangeable sodium percentage (ESP), amendment availability and cost, and irrigation water quality (salt composition and concentration) (Kumar & Sharma, 2020). Gypsum is widely available and relatively inexpensive, making it the most commonly used amendment for sodic soil reclamation (Tyagi & Minhas, 1998)(Table 1), gypsum improves soil permeability through its electrolyte effect and cation exchange reactions (Loveday, 1976). It is particularly effective in non-calcareous sodic soils; however, its low solubility necessitates longer contact times and greater water volumes for complete dissolution compared to more soluble amendments (Overstreet et al., 1951). Although gypsum has long been recognized as the benchmark amendment for sodic soil reclamation, recent evidence indicates that its effectiveness can be significantly enhanced when combined with organic

amendments. Such integrated approaches improve aggregate stability, stimulate microbial activity, and provide more sustainable long-term reclamation outcomes compared with gypsum alone (Bello et al., 2021; Elmeknassi et al., 2024). Calcium chloride is another effective amendment for sodic soil reclamation. Due to its high solubility, it provides readily available calcium and is highly effective; however, it is relatively expensive and less widely available (Bhargava, 1989; Amezketa et al., 2005)(Table 1). Compared to gypsum and sulfuric acid, calcium chloride acts most rapidly and achieves the highest electrolyte concentrations, thereby maximizing water infiltration. (Miyamoto et al., 1975; Prather *et al*., 1978). Additional amendments for sodic soil reclamation include acidified cottage cheese whey.(Lehrsch et al., 1994), Cottage cheese whey has a pH of approximately 4.2 and contains Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} at concentrations of approximately 13, 5, 27, and 57 mmol L^{-1}, respectively (Robbins & Lehrsch, 1992). The application of calcium chloride as a soluble amendment facilitates rapid cation exchange and precipitation reactions. When calcium chloride reacts with sodium carbonate in the soil solution, it forms insoluble calcium carbonate and soluble sodium chloride, which can be readily leached from the profile: $Na_2CO_3 + CaCl_2 \rightarrow CaCO_3 + 2NaCl$ *(leachable)* *(1)*
Similarly, calcium chloride displaces exchangeable sodium from soil colloids through ion exchange, producing soluble sodium chloride that is removed during leaching:

$$2Na - X + CaCl_2 \rightarrow Ca - X_2 + 2NaCl \text{ (leachable) (2)}$$

Where Na-X represents a sodium-saturated exchange site on the soil colloid. These reactions explain why calcium chloride acts more rapidly than gypsum, achieving higher electrolyte concentrations and maximizing water infiltration (Miyamoto et al., 1975).
Acid-forming amendments, including iron and aluminum sulfates and pyrite, generate sulfuric acid through hydrolysis and oxidation reactions:

$$4\,FeSO_4 + O_2 + 6H_2O \rightarrow 4Fe(OH)_3 + 2H_2SO_4 \text{ (Hydrolysis) (3)}$$

$$Al_2(SO_4)_3 + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2SO_4 \text{ (4)}$$

$$4\,FeS_2 + 15\,O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 8H_2SO_4 \text{ (5)}$$

The sulfuric acid produced subsequently dissolves native calcium carbonate to release calcium for sodium displacement.

Sulfuric and Hydrochloric Acid:

Sulfuric acid, alone or in combination with indigenous soil gypsum, has been used for sodic soil reclamation.(USDA, 1954; Miyamoto et al., 1975; Shainberg et al., 1989)(Table 1). Sulfuric acid has proven particularly effective for reclaiming calcareous sodic soils and enhancing salt leaching (Miyamoto et al., 1975; Miyamoto & Stroehlein, 1986; Overstreet et al., 1951). However, sulfuric acid presents two significant drawbacks: high cost and hazardous handling requirements. Industrial by-products, including sulfuric acid and gypsum, have recently been utilized for soil reclamation, surface crusting prevention, and erosion control. (Amezketa et al., 2005). When applied to calcareous soils, sulfur and sulfuric acid increase soil calcium availability by dissolving native calcium carbonate(Niazi et al., 2001; Amezketa et al., 2005; Sadiq et al., 2007; Vance et al., 2008). The primary reactions are:

$$H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4.2H_2O + CO_2 \text{ (6)}$$

When sodium carbonate is present, sulfuric acid converts it to less harmful sodium sulfate:

$$Na_2CO_3 + H_2SO_4 \rightarrow Na_2SO_4 + H_2O + CO_2 \text{ (7)}$$

The gypsum formed then participates in cation exchange, replacing adsorbed sodium:

$$2Na - X + CaSO_4 \rightarrow Ca - X_2 + Na_2SO_4 \text{ (leachable) (8)}$$

Alternatively, in non-calcareous soils, sulfuric acid can directly protonate exchange sites:

$$2Na - X + H_2SO_4 \rightarrow 2H - X + Na_2SO_4 \text{ (9)}$$

Elemental sulfur is commercially available in pelletized form, typically containing 90% S and bentonite clay, and its use has increased substantially. It is typically broadcast in autumn using standard reclamation equipment at relatively low cost, making it suitable for reclamation in dryland areas (Day et al., 2019), Elemental sulfur is insoluble in water and therefore does not directly supply calcium for sodium displacement. Instead, it must be microbially oxidized to sulfuric acid, which then reacts with calcium carbonate to form gypsum. The stepwise reactions are:

$$2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4 \text{ (microbial action) (10)}$$

$$SO_3 + H_2O \rightarrow H_2SO_4 \text{ (11)}$$

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + CO_2 + H_2O \text{ (12)}$$

$$CaSO_4.2H_2O\,(S) \rightleftharpoons Ca^{2+} + SO_4^{2-} + 2H_2O\,(dissolution\ reaction) \text{ (13)}$$

HCl and HNO_3 were more effective than H_2SO_4 in reducing electrical conductivity (EC) and increasing hydraulic conductivity (HC), whereas H_2SO_4 was superior to HCl and HNO_3 in reducing soil exchangeable sodium percentage (ESP)(Manukyan, 1976)(Figure 2). In reclaiming calcareous saline-sodic clay loam soils, mineral acids (H_2SO_4, HCl, HNO_3) were more effective than gypsum in reducing EC, pH, and ESP (Ghafoor, 1981)A field experiment on saline-sodic soil using rice evaluated four treatments: hydrochloric acid alone, hydrochloric acid plus gypsum, gypsum alone (applied at the gypsum requirement rate), and an untreated control. Hydrochloric acid application produced the highest grain and straw yields, followed by combined hydrochloric acid plus gypsum, and then gypsum alone. Furthermore, hydrochloric acid exhibited the greatest ameliorative effect on soil pH, EC_e, and SAR reduction compared to all other treatments(Yasin et al., 1998). Hydrochloric acid (HCl) has

demonstrated superior performance in reducing electrical conductivity and increasing hydraulic conductivity compared to sulfuric acid (Manukyan, 1976). In calcareous soils, HCl reacts with calcium carbonate to produce calcium chloride:

$$2HCl + CaCO_3 \rightarrow CaCl_2 + H_2O + CO_2 \quad (14)$$

The calcium chloride produced provides calcium for cation exchange:

$$2H - X + CaCO_3 \rightarrow Ca - X_2 + CO_2 + H_2O \ (15)$$

$$2Na - X + CaCl_2 \rightarrow Ca - X_2 + 2NaCl\ (leachable) (16)$$

Direct proton exchange also occurs:

$$Na - X + HCl \rightarrow HX + NaCl\ (leachable) \ (17)$$

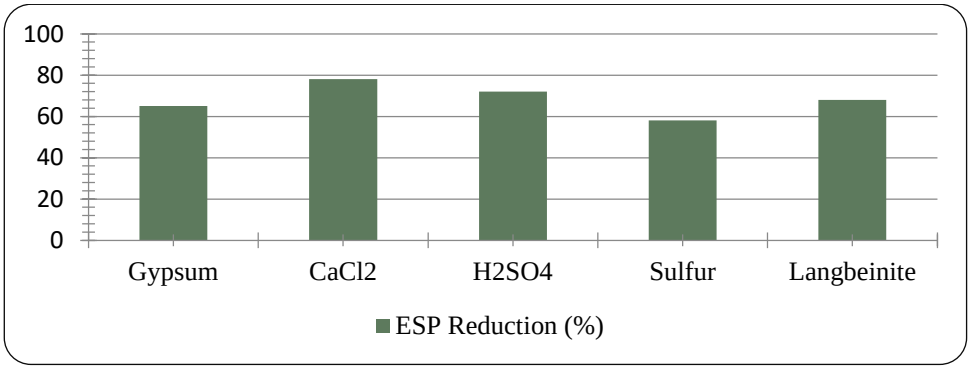


Figure 2.Comparative effectiveness of different chemical amendments in reducing Exchangeable Sodium Percentage (ESP) in sodic soils under controlled conditions. Data compiled from multiple field studies (Miyamoto et al., 1975; Prather et al., 1978; Amezketa et al., 2005).

Gypsum

Low electrolyte concentrations exacerbate the physical degradation of sodic soils. This condition arises when rainfall or high-quality irrigation water (low electrolyte concentration) is applied, resulting in significant reductions in hydraulic conductivity. Under these conditions, gypsum enhances permeability through two mechanisms: increasing soil solution electrolyte concentration and reducing the proportion of sodium on the soil cation exchange capacity (CEC) (Makoi & Verplancke, 2010). The effects of gypsum on saline-sodic soil reclamation have been extensively investigated (Armstrong & Tanton, 1992; Ilyas et al., 1997; Ghafoor et al., 2001; Lebron et al., 2002; Gharaibeh et al., 2009, 2010)(Table 1). These studies collectively demonstrate that gypsum application is effective for reclaiming sodic soils.

Gypsum effectiveness depends on: (i) particle fineness, (ii) incorporation depth and method, and (iii) drainage system efficiency (Abdel-Fattah et al., 2015). Regarding gypsum as a preventive measure against sodicity, studies have demonstrated that prophylactic gypsum application enables the successful use of lower-quality irrigation water without inducing soil degradation (Ali & Kahlown, 2001). Historically, sodic soil reclamation involved applying Ca^{2+} as gypsum equivalent to the exchangeable Na^{+} content, followed by leaching with water to remove displaced sodium (USDA, 1954)This approach historically recommended large gypsum applications, often exceeding 60 t ha^{-1}, with reclamation periods extending to a decade or more. Successful reclamation has been achieved with gypsum rates ranging from 10 to 100 t ha^{-1}, with applications below 60 t ha^{-1} generally proving more efficient (Rasmussen et al., 1972; Sharma et al., 1974; Prather et al., 1978; Oster & Frenkel, 1980; Hanay et al., 2004). Sharma et al. (1974) successfully reclaimed sodic soil, reducing profile exchangeable Na^{+} from 6.09 to 1.64 cmolc kg^{-1} following application of 62 t ha^{-1} gypsum combined with intensive tillage. Rasmussen et al. (1972) achieved comparable success with gypsum applications of 18 and 36 t ha^{-1} on soils with an initial average profile ESP of 34%. Exceptionally high rates, such as 100 t ha^{-1}, have been required only in severe cases. (Prather et al., 1978). The gypsum requirement (GR) for reclamation in ton/ ha^{-1}' can be calculated from the following equation (1) (Oster & Jayawardane, 1998):

$$GR = (0.0086) * F * D * CEC * (ESP_i - ESP_f) \ldots (18)$$

For a 30 cm soil depth, gypsum requirements (GR) to reduce initial ESP from 39.55 to 10% can be estimated as follows(Abdel-Fattah, 2012):

$$GR = \frac{(ESP_i - ESP_F)}{100} * CEC * 1.72 \ldots\ldots (19)$$

Importantly, many sodic soils contain substantial quantities of calcium carbonate ($CaCO_3$) within the profile, which can facilitate the reclamation process (Qadir et al. 2005), and therefore lower amounts of gypsum will be required for reclamation than predicted by the gypsum requirement equations. Oster et al. (1999) indicated that cropping calcareous sodic soils during irrigation can achieve satisfactory reclamation, thereby reducing the area requiring gypsum application. Furthermore, some sodic soils contain native gypsum and can be reclaimed through leaching and deep tillage without additional amendment application. Oster and Frenkel (1980) demonstrated that ESP reduction is largely confined to the depth of gypsum incorporation, attributable to the greater selectivity of exchange sites for calcium relative to sodium (Robin et al., 2015). Moreover, advances in sodic soil reclamation through integrated gypsum application, tillage operations, and improved cropping systems have enhanced gypsum use efficiency (Oster et al., 1999).

Most sodic soil reclamation efforts have historically emphasized exchangeable Na^+ removal from the soil profile, while potentially underestimating the importance of the electrolyte effect in preventing clay dispersion and maintaining hydraulic conductivity. The relative importance of these two mechanisms determines the gypsum requirement for effective reclamation (Shainberg et al., 1989). If the electrolyte effect is sufficiently pronounced, gypsum can be surface-applied, with the required amount determined by the volume of high-quality water applied and the gypsum dissolution rate. Dargan et al. (1976) and Mondal (1976) reported substantially higher berseem and rice yields when farmyard manure was combined with gypsum compared to gypsum alone. Additionally, gypsum solubility increased from 30.96 to 39.12 meq L^{-1} within one month following manure application.

Many non-sodic soils readily develop surface crusts that reduce water infiltration, thereby increasing runoff and erosion. In Georgia, Miller and Baharuddin (1986) found strong correlations among soil dispersibility indices, infiltration rates, and soil loss. Both clay dispersion and infiltration rates exhibited significant correlations with pH (Roth & Pavan, 1991). Subsequently, Miller (1987) confirmed that cumulative and steady-state infiltration rates of dispersive soils could be substantially improved by surface application of by-product gypsum (e.g., phosphogypsum) following tillage and before the first rainfall event. This beneficial effect persisted for up to four subsequent rainfall events. Microbially enriched gypsum represents an innovative approach that combines reduced gypsum application rates with microbially enriched organic amendments to enhance reclamation efficiency. Singh et al. (2023) conducted a field experiment in India evaluating the integration of mineral gypsum at 25% of the gypsum requirement (GR) with enriched municipal solid waste compost applied at 10 t ha^{-1}. This integrated approach achieved rice yields of 5.55 t ha^{-1} and wheat yields of 3.83 t ha^{-1}, outperforming gypsum alone applied at 50% GR and the untreated control. The underlying mechanism involves the production of organic acids (citric and oxalic acids) by salt-tolerant microbial consortia during compost decomposition, which dissolve native calcium carbonate ($CaCO_3$) present in calcareous sodic soils, thereby increasing calcium availability for ion exchange with adsorbed sodium. Concurrently, the reduced gypsum application provides supplemental calcium while the microbial polysaccharides and compost organic matter improve soil physical structure, aggregate stability, and hydraulic conductivity. The benefit-cost ratio (B/C) was highest for the integrated treatment, demonstrating economic viability alongside agronomic benefits. This strategy reduces gypsum requirements by 50–75% while simultaneously enhancing soil biological health through increased microbial biomass carbon, dehydrogenase activity, and phosphatase and urease enzyme activities (Singh et al., 2023).

Organic matter

In arid and semi-arid regions, soil organic matter is considered a critical determinant of soil fertility, crop productivity, and land protection against contamination, degradation, erosion, and desertification (Senesi et al., 2007; Araújo et al., 2008). Organic fertilizers, amendments, and crop residue management can be employed to reclaim saline and/or sodic soils and develop sustainable agro-ecosystems, Furthermore, combining diverse organic inputs can contribute substantially to soil organic matter conservation, carbon sequestration, and climate change mitigation (Mahmoodabadi & Heydarpour, 2014; Joseph et al., 2009; Kwapinski et al., 2010). The role of organic amendments in sodic soil reclamation is primarily attributed to organic acid production during decomposition, particularly under partial or complete anaerobic conditions (Singh et al., 1981). Saline soils, typically well-structured and highly permeable, can be reclaimed through a relatively straightforward process involving the leaching of excess salts. Nevertheless, organic amendments can increase cation exchange capacity (CEC) and ion adsorption, thereby reducing soluble salt concentrations in the soil solution, albeit with associated benefits and limitations. Economic analyses of integrated reclamation in India demonstrate that combined gypsum and organic amendment strategies achieve cost-benefit ratios of 1.2–3.2, with internal rates of return exceeding 15%, thereby justifying initial investment within 3–5 years (Thimmappa et al., 2017). Organic matter is widely recognized as a major contributor to soil CEC, influencing the magnitude and sign of net surface charge on soil particles and enhancing salt retention capacity (Oorts et al., 2003; Leogrande & Vitti, 2019). Contemporary research demonstrates that organic amendments provide benefits beyond improvements in soil structure and water-holding capacity. They enhance carbon and nitrogen cycling, increase microbial diversity, and contribute to ecosystem multifunctionality, thereby improving the resilience of saline and saline-sodic soils under environmental stress conditions (Yadav et al., 2024; Elmeknassi et al., 2024).

The effect of organic matter on soil physical properties

Growing concern over climate change, driven by increasing anthropogenic CO_2 emissions, has accelerated research on biochar production and soil application (Woolf et al., 2010).Beyond its role as a carbon source, organic matter improves soil properties and enhances plant productivity (Rondon et al., 2007; Asai et al., 2009; Thies & Rillig, 2009; Atkinson et al., 2010; Solaiman et al., 2010; Jones et al., 2012). Readily decomposable, low-molecular-weight organic compounds exert strong but short-term effects on soil physical properties, whereas more recalcitrant components such as lignin and cellulose produce weaker but more persistent effects. Enhanced biological activity, particularly during initial organic matter decomposition, along with the release of microbial binding agents such as exopolysaccharides, significantly contributes to soil aggregate stability (Abiven et al., 2009). Improved soil structural stability enhances porosity, hydraulic conductivity, and water-holding capacity(Chenu et al., 2000; Tejada & Gonzalez, 2003; Camberato et al., 2006; Eyras et al., 2008; Albaladejo Montoro et al., 2009; Leogrande & Vitti, 2019), and water holding capacity (Stehouwer & Macneal, 2003; Leogrande & Vitti, 2019; Khalil, 2002). Alterations in aggregate distribution and pore size distribution account for reductions in bulk density and improvements in other soil physical properties (Leogrande & Vitti, 2019).

Shi et al. (2016) found that organic manure application improved soil physical properties by optimizing the balance between macropores (inter-aggregate) and micropores (intra-aggregate). This optimization enhanced soil water retention capacity and permeability. Figure 3 synthesizes the effects of various organic amendments on key soil physical properties across multiple field studies.

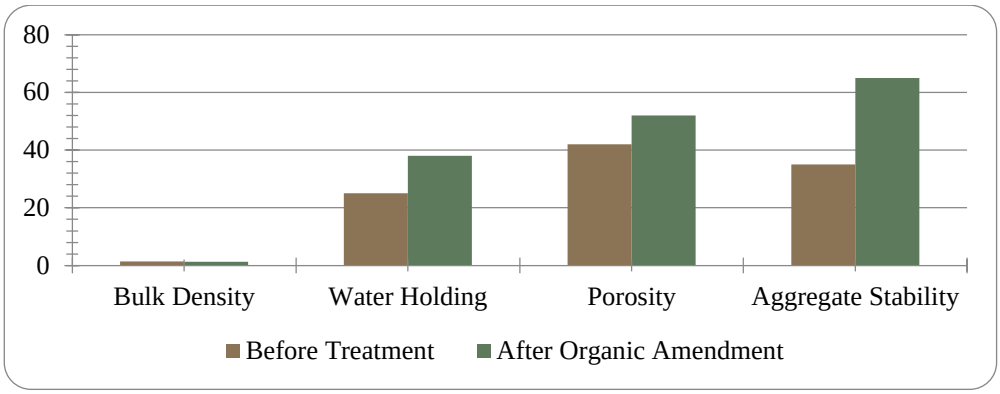


Figure 3: Impact of Organic Matter Amendments on Soil Physical Properties

Optimal soil structure and a balanced micro- to macropore ratio facilitate water movement into and through the soil, thereby enhancing salt leaching and reducing erosion (Swift, 2001; Grigg et al., 2006)This enables the soil to resist detachment by surface runoff and raindrop impact (Leogrande & Vitti, 2019). Termorshuizen et al. (2004) reported that, among various amendments used to replenish soil organic matter, compost represents one of the most stable sources, in contrast, animal manure and other fresh wastes consist primarily of readily decomposable organic matter, producing only short-lived effects. As noted by Pascual et al. (1999), the consistent application of stable organic matter sources such as compost results in a net increase in soil organic matter over time. Tejada et al. (2006) conducted a five-year field experiment under dryland conditions to evaluate the effectiveness of cotton gin waste compost and poultry manure in a saline clay loam soil (EC 9.1 dS m^{-1}). Organic amendments were applied annually at rates of 5 and 10 t ha^{-1}. Compared with the control, amended soils exhibited significantly lower bulk density and higher structural stability. In a leaching column experiment on saline-sodic soil, Chaganti et al. (2015) found that biosolids co-compost application at 75 t ha^{-1} improved soil physical properties (Figure 3).

The effect of organic matter on soil chemical properties

Reclaiming salt-affected soils and maintaining their fertility requires organic matter inputs that undergo microbial decomposition. This process increases humus content and releases acidic compounds that reduce pH and dissolve calcium carbonate in calcareous soils (Westerman & Bicudo, 2005). Xiao-gang et al., (2007) Concluded that the effect of soil salinity on organic matter disintegration varied with water availability and water interaction, salinity levels, specific ion species, and disintegration phases. Organic amendments were shown to be particularly effective in decreasing ESP and EC in the soil (Tejada et al., 2006; Wang et al., 2014; Chaganti et al., 2015). Adding up a large dose of organic matter to saline-sodic soils (120 ton. ha^{-1} of a 1:1 combination of sewage sludge and fly ash) and then leaching with freshwater resulted in a substantial reduction (more than 80%) of ESP values, especially in the topsoil layer. However, a modest dose (40 ton.ha^{-1}) resulted in ECe values significantly lower than the 4 dS.$m^{-1,}$ which is the salinity index in the soil (Ors et al., 2015)(Figure 3).

Leaching columns were used by Ranjbar & Jalali, (2011), and Jalali & Ranjbar, (2009) To examine the effects of different organic amendments (approximately 100 ton. ha^{-1} same in all the treatments) in sandy loam soil (SAR 0, 10, and 40), the findings revealed that adding organic amendments to soils boosted their CEC and increased adsorption of Ca^{++}, Mg^{++}, and K+ at the expense of Na^{+}. Furthermore, organic matter additions may be more successful than chemical additions in the approach of reclaiming sodic soil, which is widely found in arid and semi-arid areas and characterized by poor physical qualities and restricted macronutrient availability (Fa-Hu & Keren, 2009; Yazdanpanah et al., 2011; Leogrande & Vitti, 2019). In the leaching columns experiment, the efficacy of manure in the reclamation of clay saline-sodic soils was tested by Abdel-Fattah, (2012)Organic amendments reduced soil EC, pH, and ESP substantially, especially with rice compost. The findings of these studies show that organic matter derived from several types of organic waste, fresh materials, and manure can have a positive impact on the physical and chemical characteristics of soils with high salt levels.

The effect of organic matter on soil biological properties

Soil microbial structure and biochemical activities—both essential for maintaining soil quality—are adversely affected under salinization conditions, particularly in arid environments (Rietz & Haynes, 2003; Sardinha et al., 2003; Gennari et al., 2007; Yuan et al., 2007; Leogrande & Vitti, 2019). To maintain osmotic equilibrium between the cytoplasm and the surrounding medium and prevent sodium ion influx, microorganisms expend substantial resources at elevated salt concentrations (Leogrande & Vitti, 2019). Conversely, an increase in total soil organic carbon (TOC) promotes microbial biomass, as carbon serves as an energy source for microbial activity (Garcia et al., 2000; Chaoui et al., 2003). Lakhdar et al. (2010) investigated the effects of applying 40 and 80 t ha^{-1} of municipal solid waste (MSW) compost and sewage sludge on microbial biomass and selected enzymatic activities in a saline silt loam soil (ECe 7.5 dS m^{-1}). The results demonstrated that both amendments significantly increased carbon and nitrogen contents, particularly at higher application rates. Compared with untreated soil, the treatments

enhanced measured enzyme activity levels, attributable to the substantial increase in carbon quantity. Specifically, Meena et al. (2016) found that incorporating 16 and 14 t ha^{-1} of MSW compost and rice straw compost into saline soil (ECe 7.2 dS m^{-1}) significantly increased dehydrogenase, phosphatase, and urease activities relative to the control. Salinity substantially influences soil microbial community structure, which consists primarily of fungi and bacteria. Bacterial communities exhibit greater resilience to damage in saline environments than fungi; consequently, salt-affected soils harbour larger bacterial populations (Leogrande & Vitti, 2019). In soils with increasing salinity, the biomass C/N ratio was found to decrease, indicating bacterial dominance in microbial biomass under saline conditions (Yuan et al., 2007). Unlike fungi and actinomycetes, bacteria can thrive in low-nutrient environments under severe environmental conditions. As observed by Visser et al. (1983), high organic matter concentrations combined with low salinity may, however, permit fungal dominance in microbial biomass. Sardinha et al. (2003) examined fungal sensitivity to salt stress by measuring soil ergosterol concentrations and the ergosterol-to-microbial biomass C ratio; this compound may serve as an excellent marker of fungal presence, as it occurs exclusively in fungi and certain green microalgae. Compelling evidence indicates that salinity/sodicity problems substantially impede microbial activity, leading to degraded soil quality and fertility (Leogrande & Vitti, 2019).

The effect of biochar on saline-sodic soil properties

Biochar, a carbon-rich product of biomass pyrolysis under limited oxygen conditions, has emerged as a promising organic amendment for reclaiming salt-affected soils while simultaneously contributing to carbon sequestration and climate change mitigation (Woolf et al., 2010; Amini et al., 2016)(Figure 3). Unlike readily decomposable organic materials, biochar exhibits high recalcitrance in soil, providing long-term improvements to soil physical, chemical, and biological properties. The physical effects of biochar application on saline-sodic soils include increased total porosity and hydraulic conductivity, reduced bulk density, enhanced water-holding capacity, and improved aggregate stability (Vasanth, 2026)(Figure 3). These improvements facilitate salt leaching and reduce surface runoff and erosion. At the chemical level, biochar substantially increases cation exchange capacity (CEC) through surface functional groups (carboxyl, hydroxyl, and phenolic), thereby enhancing adsorption of calcium, magnesium, and potassium at the expense of sodium. Application rates of 2% by soil weight have been shown to reduce the electrical conductivity of the saturation extract (ECe) to below 4 dS m^{-1} and decrease exchangeable sodium percentage (ESP) through enhanced sodium adsorption on biochar surfaces (Vasanth, 2026). Biochar also improves nutrient balance by slowly releasing nitrogen, phosphorus, and potassium while reducing nutrient leaching losses. Biochar has emerged as one of the most promising amendments for saline and sodic soils due to its ability to increase cation exchange capacity, reduce sodium toxicity, and enhance soil carbon sequestration. Nevertheless, additional long-term field studies are needed to evaluate its persistence, scalability, and economic feasibility under diverse agroecological conditions (Vasanth et al., 2026; Elmeknassi et al., 2024). Biologically, biochar provides protected microhabitats for soil microorganisms, shielding them from osmotic stress induced by elevated salt concentrations. The porous structure of biochar increases microbial biomass and diversity, enhances dehydrogenase, phosphatase, and urease activities, and promotes the establishment of beneficial microbial communities including plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi (Vasanth, 2026). However, biochar efficacy depends critically on feedstock source: crop residues yield higher CEC and ash content; wood-derived biochar offers greater stability and porosity; manure-based biochar provides higher nutrient content. Crop residues yield higher CEC and ash content; wood-derived biochar offers greater stability and porosity; manure-based biochar provides higher nutrient content (Joseph et al., 2009). Recommended application rates range from 1% to 5% by soil weight, with cost considerations remaining a current limitation that is expected to decline as pyrolysis technology advances. Figure 3 illustrates the aggregate effects of various organic amendments—including biochar, compost, and manure—on key soil physical properties in saline-sodic soils (Tejada et al., 2006; Chaganti et al., 2015; Shi et al., 2016).

Leaching:

Unless removed through drainage water or crop harvest, salts introduced to the soil via irrigation water persist in the soil profile. To prevent salt accumulation, salts must be regularly removed by applying water in excess of consumptive use, as the quantity of salt removed by crops is negligible and contributes minimally to the total salt load requiring removal (Schwab, 1966). Excess water applied to the root zone will eliminate salts, provided the soil possesses adequate internal drainage. This concept is quantified by the term "leaching requirement," which refers to the fraction of total water applied that must percolate below the root zone to maintain soil salinity below a threshold determined by crop tolerance (Richards, 1954; USDA, 1954). According to Suarez (2001), the most common technique for mitigating salinity in irrigated areas is to supply additional water for leaching; however, the drainage system must be sufficient to remove the excess water. Leaching with freshwater, subsurface drainage, inter-irrigation mulching, and fallow-season irrigation management constitute effective and well-established technical solutions for addressing waterlogging and soil salinity problems (Smedema & Ochs, 1998; Gupta, 2002; Arora & Sharma, 2017). Although subsurface drainage is effective, barriers such as high initial costs, operational difficulties, lack of community participation, and drainage effluent disposal issues limit its widespread adoption (Singh, 2009).In India, approximately 110,000 ha of waterlogged saline soils have been successfully reclaimed using subsurface drainage technology (Table 2). Application of this technology in saline soils tripled farmers' incomes, resulting in yield increases of 45%, 111%, and 215% for paddy, wheat, and cotton, respectively (Kumar & Sharma, 2020). Detailed yield data before and after drainage implementation are provided in Table 2. Furthermore, subsurface drainage technology generated 128 employment opportunities per hectare per year for the community (Kumar & Sharma, 2020). Subsurface drainage projects require community commitment and responsibility, which must be supported by appropriate institutional mechanisms (Ritzema et al., 2008). However, in the majority of salinity-affected

regions, community engagement appears weak, as evidenced by the absence or ineffectiveness of water-user associations for irrigation and drainage projects. This constraint hinders the expansion of reclamation technology in salt-affected areas (Kumar & Sharma, 2020) (Table 2). AL-Mansori (2018) investigated the impact of continuous and intermittent ponding depths on leaching processes under various hydraulic heads. The following conclusions may be drawn from the findings:

The electrical conductivity of effluent from soil samples decreases with time, becoming progressively more gradual until the leaching process is completed. Continuous leaching requires a large volume of water over a short period, whereas intermittent leaching requires a smaller volume over a longer duration. All parameters decreased more rapidly with time under continuous leaching than under intermittent leaching. When leaching saline soil, continuous leaching is preferable if time is a critical factor, whereas intermittent leaching may be more cost-effective when water is scarce. Subsurface drainage is essential for removing excess salts and maintaining water table depth in irrigated areas. In India, around 110,000 hectares of waterlogged saline soils have successfully been restored using subsurface drainage technology (Kumar and Sharma, 2020). Farmers' income increased threefold as a result of the application of subsurface drainage technology in salty soils, with paddy, wheat, and cotton yields increasing by 45%, 111%, and 215%, respectively (Ritzema et al., 2008; Kumar and Sharma, 2020).

Table 2: Impact of Subsurface Drainage Technology on Crop Yields in India

Crop	Before Drainage (t/ha)	After Drainage (t/ha)	Yield Increase
Paddy	3.5	5.1	+45%
Wheat	2.2	4.6	+111%
Cotton	1.2	3.8	+215%

Subsurface drainage projects require community attitude and responsibility, which must be backed up by proper institutional mechanisms (Ritzema et al., 2008). However, in the majority of salinity-affected areas, community engagement appears to be weak, as shown by the lack of or ineffective water-user associations for irrigation and drainage projects. This stifles the expansion of reclamation technology in salt-affected areas (Kumar and Sharma, 2020).

Phytoremediation of salt-affected soil

Phytoremediation, or vegetative bioremediation, was first adopted as a strategic approach in 1937 when Bermuda grass was used to improve sodic soil properties (Amini et al., 2016). Since then, numerous studies have investigated the potential of crops and crop-based interventions for reclaiming salt-affected soils (Qadir et al., 1996; Qadir et al., 2001; Qadir & Schubert, 2002; Ahmad et al., 2006; Ammari et al., 2008; Gharaibeh et al., 2011). Phytoremediation is the process of removing excess salts from the soil through the cultivation of various plant species. Salt-tolerant plants, shrubs, and grasses represent cost-effective and environmentally sustainable options for rehabilitating salt-affected soils (Mishra et al., 2003; Qadir et al., 2007).

Phytoaccumulation, or phytoextraction, refers to the process by which plants absorb excess salts from the soil via their roots and sequester them in their biomass. This reduces the quantity of soluble and exchangeable sodium in the soil and improves the physical, chemical, and biological properties of the soil, as well as overall soil productivity (Bhojvaid & Timmer, 1998; Kaur et al., 2000; Mishra et al., 2003; Nosetto et al., 2007; Qadir et al., 2007). Additionally, tree plantations provide fuelwood and fodder, contribute to climate change mitigation through carbon sequestration, and render degraded lands economically viable (Dagar, 2005; Kumar & Sharma, 2020), as trees and grasses/crops can store carbon in aboveground and belowground biomass (Dagar & Swarup, 2003). Although several grass species have been identified as suitable for sodic soils, none have achieved field-scale adoption because their leaves absorb and accumulate salt and other toxic substances, rendering them unsuitable for fodder. Nevertheless, efforts are underway to identify and promote grass varieties capable of retaining a high proportion of salt in their root systems, thereby keeping the shoots palatable to livestock. However, according to Biswas & Biswas (2014), most field crops are less tolerant of alkaline conditions than grasses. Phytoremediation in salt-affected soils occurs through multiple mechanisms (Qadir et al., 2007), including the following:

The root system accelerates calcite dissolution, leading to elevated calcium concentrations in the soil solution. Many sodic and saline-sodic soils contain an essentially adequate supply of calcium at various depths within the profile, typically in the form of calcite ($CaCO_3$). Calcite is not sufficiently available to effect sodium displacement from the cation exchange complex until it is solubilised by plant activity (Qadir et al., 2005). The roots of certain plant species release protons, which enhance salt uptake by plants and subsequent removal from the field during harvest (Amini et al., 2016).

Bioremediation

The bioremediation strategy, which employs plant–microbe interactions to restore the productivity of salt-affected soils, is gaining increasing recognition worldwide (Arora et al., 2014). Microorganisms can rapidly adapt to environmental changes and thus play a critical role in the maintenance and long-term sustainability of any ecosystem. Microorganisms possess diverse characteristics, including salinity stress tolerance, genetic distinctiveness, and the synthesis of compatible solutes. Provided these attributes are effectively harnessed, microorganisms can significantly contribute to mitigating salt impacts on agricultural plants (Shrivastava & Kumar, 2015). The bacterial community composition in saline-alkaline soils of the Ararat Plain, Armenia, indicates dominance of Firmicutes populations, including halophilic bacilli genera such as Halobacillus, Piscibacillus, and Virgibacillus, which play key roles in biogeochemical cycles under extreme saline conditions (Panosyan et al., 2018). Microorganisms in the plant rhizosphere can promote growth and yield through various mechanisms under salt stress conditions (Dimkpa et al., 2009). Under conditions of nitrogen availability, certain rhizobacteria may directly enhance plant growth and development through the production of plant hormones, iron (sequestered by bacteria), and soluble phosphate (Hayat et al., 2010), while others may indirectly benefit plants by inducing structural modifications in cell walls that protect against soil-borne diseases, primarily caused by pathogenic fungi (Lugtenberg & Kamilova, 2009), or by eliciting cell wall structural modifications (Arora & Sharma, 2017).

Halophilic bacteria can remove sodium ions from the soil while simultaneously enhancing plant metabolic and enzymatic activities. In a field experiment, Arora et al. (2016) applied halophilic microorganisms to saline and sodic soils. Bio-inoculation of wheat seedlings with halophilic bacteria increased grain and straw yields in sodic soil by 18.1% and 24.2%, respectively, and enhanced microbial diversity, which improved soil properties as pH decreased from 9.4 to 8.6. Farmers are increasingly adopting a low-cost microbial bio-formulation known as CSR-BIO (Damodaran et al., 2013). This bio-formulation functions as a soil conditioner and nutrient mobiliser, increasing the yield of high-value crops such as banana, vegetables, and gladiolus by 22–43% in both sodic and normal soils (Amini et al., 2016).

Emerging reclamation technologies

Growing climate change, increasing water scarcity, and the need for sustainable agricultural intensification have stimulated the development of innovative approaches for managing salt-affected soils. While conventional reclamation practices, such as gypsum application and leaching, remain the cornerstone of saline-sodic soil management, emerging technologies seek to accelerate reclamation, improve resource-use efficiency, and enhance crop resilience under saline conditions. These approaches include electro-reclamation, nanotechnology-assisted soil and crop management, and the beneficial reuse of industrial by-products such as flue gas desulfurization (FGD) gypsum .Emerging technologies are increasingly being integrated with digital agriculture tools, including remote sensing, geographic information systems (GIS), and data-driven decision support systems. These approaches facilitate site-specific management and improve monitoring of salinity dynamics under changing climatic conditions (Corwin, 2020), offering new opportunities for precision reclamation of salt-affected soils (Elmeknassi et al., 2024). The integration of organic and inorganic amendments within a circular economy framework has gained significant attention, emphasizing waste valorization as a sustainable strategy for managing saline-sodic soils (Elmeknassi et al., 2024).

Electro-reclamation

Electro-reclamation is an emerging physicochemical technique that uses low-voltage direct current to enhance the movement of soluble ions within saline-sodic soils, particularly those with heavy clay textures and low hydraulic conductivity (Sahakyan et al., 2026). The applied electric field promotes electromigration of sodium (Na^+) toward the cathode, where it can be removed or precipitated, while calcium (Ca^{2+}) migrates toward the anode, facilitating the replacement of exchangeable sodium on soil colloids. The addition of mineral electrolyte solutions can further improve ion mobility and increase reclamation efficiency. Field studies in the Ararat Valley demonstrated that electro-reclamation combined with mineral electrolyte solutions achieved higher sodium removal than conventional chemical amendments (Ghazaryan et al., 2023). The technology is particularly advantageous for fine-textured soils where conventional leaching is slow and inefficient. Furthermore, integration with solar photovoltaic systems offers opportunities to reduce operational costs in remote arid regions. However, widespread adoption remains constrained by relatively high installation costs, electrode maintenance requirements, and the need for specialized infrastructure.

Nanotechnology applications

Nanotechnology has emerged as a promising tool for improving the management of salt-affected soils by enhancing both soil amendment efficiency and plant tolerance to salinity stress (Vasanth, 2026; Singh et al., 2025). Recent bibliometric analyses indicate exponential growth in this field, with over 500 peer-reviewed publications indexed between 2021 and 2024, led by China, India, Egypt, Pakistan, and Iran as the primary contributors (Singh et al., 2025). Nanomaterials improve saline soil management through several mechanisms, including stimulation of antioxidant defense systems, reduction of sodium uptake, improvement of plant water relations, and acceleration of soil amendment reactions. Among the most widely studied materials, zinc oxide nanoparticles (ZnO NPs) enhance wheat productivity in sodic soils by regulating antioxidant enzyme activity and improving osmotic adjustment. Magnesium oxide nanoparticles (MgO NPs) improve photosynthetic performance, increase water-use efficiency, and reduce sodium accumulation in plant tissues under saline conditions. Silicon dioxide nanoparticles (SiO_2 NPs) strengthen plant antioxidant systems, including superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX), thereby mitigating oxidative damage caused by salt stress. In addition, nano-gypsum particles possess substantially greater specific surface area than conventional gypsum, resulting in faster dissolution, enhanced calcium release, and more efficient cation exchange, which may reduce amendment application rates by 30–50% compared with conventional gypsum (Singh et al., 2025). Despite these promising results, uncertainties regarding the long-term environmental fate of nanoparticles, production costs, and the lack of standardized field application protocols continue to limit their large-scale adoption.

Flue gas desulfurization gypsum (FGD)

Flue gas desulfurization (FGD) gypsum, a by-product generated during sulfur dioxide removal from coal-fired power plants, represents an environmentally sustainable alternative to natural gypsum within a circular economy framework (Vasanth, 2026). Typically containing more than 95% calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), FGD gypsum generally exhibits finer particle size and lower concentrations of impurities than many naturally mined gypsum sources. Field applications have demonstrated that FGD gypsum effectively reduces sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) in sodic soils while providing a cost-effective source of soluble calcium, with reported costs 40–60% lower than those of conventional mined gypsum. Its use simultaneously diverts industrial waste from disposal and supports sustainable soil reclamation practices. Nevertheless, routine quality assessment is essential before field application to ensure compliance with national environmental regulations regarding mercury and other trace heavy metals. In addition, the availability of FGD gypsum depends largely on regional industrial infrastructure and the continued operation of coal-fired power plants. Overall, these emerging technologies complement rather than replace conventional reclamation practices. Their successful implementation will depend on economic feasibility, long-term environmental sustainability, and adaptation to local soil, water, and climatic conditions. Future research should focus

on integrating these innovative approaches with established reclamation strategies to improve the efficiency and sustainability of salt-affected soil management under increasing climate and water resource constraints.

Integrated organic–gypsum reclamation systems

The combined application of organic amendments and gypsum has emerged as one of the most effective integrated strategies for reclaiming saline-sodic soils because it simultaneously addresses the chemical, physical, and biological constraints associated with soil degradation. Unlike single-amendment approaches, integrated systems exploit the complementary functions of gypsum and organic materials, resulting in faster sodium displacement, improved soil structure, enhanced water infiltration, and greater long-term soil fertility. Such integrated management strategies, combining chemical amendments with organic materials and optimized irrigation practices, provide the most sustainable approach to sodic soil reclamation under diverse agroecological conditions (Qadir & Oster, 2007). Increasing evidence suggests that integrated reclamation strategies combining chemical and organic amendments consistently outperform single-treatment approaches. By simultaneously addressing chemical, physical, and biological limitations, these systems improve soil health and provide more sustainable reclamation outcomes over time (Bello et al., 2021; Singh et al., 2023; Elmeknassi et al., 2024). Organic amendments enhance gypsum effectiveness through several interacting mechanisms. During decomposition, organic materials release organic acids that increase the dissolution of native calcium carbonate, thereby supplying additional calcium for cation exchange. At the same time, they stimulate microbial activity, promote aggregate formation, improve soil porosity, and increase hydraulic conductivity, all of which facilitate the leaching of displaced sodium. Gypsum complements these processes by providing a readily available source of soluble calcium that rapidly replaces exchangeable sodium on soil colloids while maintaining electrolyte concentrations sufficient to prevent clay dispersion. Evidence from different agroecological regions consistently supports the superiority of this integrated approach. In the high valley of Cochabamba, Bolivia, Andrade Foronda and Colinet (2022) reported that combining gypsum with cattle or poultry manure reduced exchangeable sodium percentage (ESP) to below 5% and electrical conductivity of the saturated soil extract (ECe) to below 1.6 dS m^{-1}, outperforming gypsum applied alone. The improved soil aggregation and hydraulic properties promoted more effective sodium leaching while enhancing overall soil quality. Similar results were obtained in tropical saline-sodic soils of northeastern Brazil, where Gonçalo Filho et al. (2019) evaluated gypsum (6.1 t ha^{-1}) applied with cattle manure at rates of 40 and 80 t ha^{-1}. The combination of gypsum with 40 t ha^{-1} of cattle manure produced the greatest reduction in sodium adsorption ratio (SAR), whereas high manure application without gypsum also improved soil quality but was generally less effective than the combined treatment. These findings indicate that moderate rates of organic amendments integrated with gypsum can optimize reclamation efficiency while reducing amendment costs. Beyond improving reclamation effectiveness, integrated organic–gypsum systems offer several long-term agronomic and environmental benefits. Studies have reported reductions in gypsum requirements of approximately 25–50%, shorter reclamation periods, improved nutrient cycling, enhanced microbial diversity, greater soil organic carbon sequestration, and increased resilience of reclaimed soils to subsequent salinization. Nevertheless, successful implementation depends on the availability and quality of organic materials, appropriate application rates, labor requirements for amendment incorporation, and careful nutrient management to avoid excessive nutrient loading. These synergistic effects arise because organic acids released during compost decomposition dissolve native calcium carbonate, thereby supplying additional calcium for cation exchange while microbial polysaccharides improve aggregate stability and hydraulic conductivity (Hanay et al., 2004). Overall, integrated organic–gypsum reclamation represents a sustainable management strategy that combines the rapid chemical action of gypsum with the long-term improvements in soil physical and biological properties provided by organic amendments. Future research should focus on optimizing amendment combinations for different soil textures, salinity and sodicity levels, irrigation water qualities, and climatic conditions, while incorporating comprehensive economic and environmental assessments to support large-scale adoption. The relative performance of these bioremediation approaches compared with other reclamation strategies is illustrated in Figure 4, which provides a comparative assessment of effectiveness, cost, time requirements, and sustainability across all methods reviewed (Qadir et al., 2007; Leogrande and Vitti, 2019; Kumar and Sharma, 2020).

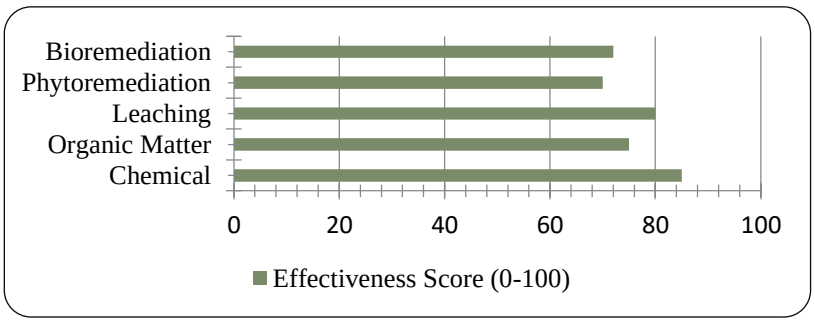


Figure 4: Comparison of Soil Reclamation Methods (Effectiveness Score 0-100)

Conclusion

The reclamation of salt-affected soils remains an imperative for global food security, particularly as agricultural intensification pressures mount against a backdrop of climate change, water scarcity, and land degradation. This review has demonstrated that while conventional chemical amendments—particularly gypsum—continue to form the cornerstone of sodic soil reclamation, their efficacy can be substantially enhanced through strategic integration with organic amendments and emerging technologies. Several

key conclusions emerge from the synthesized evidence: First, the synergistic combination of reduced-rate gypsum with microbially enriched organic amendments represents one of the most promising advances in sustainable reclamation. By exploiting the complementary mechanisms of rapid chemical exchange provided by gypsum and the long-term physical, chemical, and biological improvements conferred by organic matter, integrated systems achieve superior outcomes while reducing input costs and environmental footprints. Field evidence from India, Bolivia, and Brazil consistently demonstrates that such combinations reduce exchangeable sodium percentage (ESP) to below critical thresholds, improve hydraulic conductivity, and sustain higher crop yields compared to single-amendment strategies. Second, biochar has emerged as a particularly valuable organic amendment for saline-sodic soils due to its recalcitrance, high cation exchange capacity, and ability to provide protected microhabitats for beneficial soil microorganisms. Application rates of 1–5% by soil weight have been shown to reduce electrical conductivity (ECe) to below 4 dS m^{-1} while enhancing aggregate stability and nutrient retention. However, feedstock selection remains critical, as crop residue-derived biochar offers higher CEC, whereas wood-derived biochar provides greater structural stability. Third, emerging technologies—including electro-reclamation, nanotechnology applications, and flue gas desulfurization (FGD) gypsum—offer innovative pathways to address limitations of conventional approaches. Electro-reclamation demonstrates particular promise for heavy-textured soils with low hydraulic conductivity, achieving 40% water savings while accelerating sodium removal. Nanomaterials such as ZnO, MgO, and SiO_2 nanoparticles enhance plant tolerance mechanisms, though their long-term environmental fate requires further investigation. FGD gypsum presents an economically attractive and environmentally sustainable alternative to mined gypsum within circular economy frameworks, provided rigorous heavy metal screening is conducted before field application. Fourth, the selection of reclamation strategies must remain site-specific, integrating considerations of soil texture, initial salinity and sodicity levels, irrigation water quality and availability, drainage infrastructure, organic resource accessibility, and economic constraints. No universal solution exists; rather, successful reclamation depends on tailoring amendment types, rates, and application methods to local conditions while ensuring adequate leaching and drainage to remove displaced sodium from the root zone. Finally, future research priorities should focus on: (i) developing optimized amendment ratios for specific soil–water–crop systems through multi-location field trials; (ii) establishing long-term monitoring protocols to assess the environmental persistence and ecological impacts of nanomaterials in agricultural soils; (iii) constructing comprehensive economic models that incorporate carbon sequestration credits and ecosystem service valuations to justify investment in sustainable reclamation; and (iv) strengthening institutional mechanisms and community engagement to ensure the successful adoption and maintenance of subsurface drainage and integrated reclamation technologies in resource-limited settings. In conclusion, the transition from single-amendment, chemically dominated reclamation toward integrated, biologically enhanced, and technologically supported systems represents the most viable pathway for restoring the productivity of salt-affected soils at scale. By combining the immediate efficacy of chemical amendments with the enduring benefits of organic matter and the precision of emerging technologies, agricultural systems can achieve both short-term yield recovery and long-term resilience against recurrent salinization, thereby contributing to sustainable food production and climate change mitigation objectives.

List of symbols

AL(OH)3; Aluminum hydroxide
Al2(So3)3; Aluminum sulfate
C; Carbon
Ca++; Calcium
CaCl2; Calcium chloride
CaCO3; Calcium Carbonate
CaSO4, Calcium sulfate (gypsum)
CaSO4.2H2O; Calcium sulfate dihydrate
Cl; Chloride
CO2; Carbon dioxide
CO3-; Carbonate
Fe (OH)3; Iron hydroxide
Fe; Iron
Fe2 (So4)3; Iron sulfate
FeS2; Iron sulfide
FeSo4; ferrous sulfate
H2SO4; Sulfuric Acid
HCL; Hydrochloric acid
HCO3; Bicarbonates
K+; Potassium
K2So4.2Mg SO4; hydrated double sulfate of magnesium and potassium(langbeinite).
Mg++; Magnesium
N; nitrogen
Na+; Sodium
Na2SO4; Sodium sulfate
NaCl; Sodium chloride
NO3; Nitrate
P; Phosphorus
S; Sulfur
SO4; Sulphate

List of acronyms

CEC; Cation Exchange Capacity(cmolc/kg-1)
D: soil depth (m) to be reclaimed
dS m^{-1}; deciSiemens per meter
ECe; Electrical Conductivity
ESP: Exchangeable Sodium Percentage
ESP_t ; The final exchangeable Na+ percentage,
ESP_0 ; The initial exchangeable Na+ percentage,
F is Ca++, Na+ exchange efficiency factor (1 – 1.3) depending on ESP,
HC: hydraulic conductivity
t ha^{-1}; megagrams per hectare
Mha: The area in million hectares
MSW: The municipal solid waste
p; soil bulk density (g/cm3)
pH: Negative logarithm of the hydrogen ion activity in a solution X: Clay platelet structure
SAR: Sodium Adsorption Ratio
TOC: total soil organic carbon
USDA: The United States Department of Agriculture

References

Abdel-Fattah, M. K. (2012). Role of gypsum and compost in reclaiming saline-sodic soils. J. Agric. Vet. Sci, 1(3), 30–38.

Abdel-Fattah, M. K., Fouda, S., & Schmidhalter, U. (2015). Effects of gypsum particle size on reclaiming saline-sodic soils in Egypt. Communications in Soil Science and Plant Analysis, 46(9), 1112–1122.

Abiven, S., Menasseri, S., & Chenu, C. (2009). The effects of organic inputs over time on soil aggregate stability–A literature analysis. Soil Biology and Biochemistry, 41(1), 1–12.

Ahmad, S., Ghafoor, A., Qadir, M., & Aziz, M. A. (2006). Amelioration of a calcareous saline-sodic soil by gypsum application and different crop rotations. Int. J. Agric. Biol, 8, 142–146.

Albaladejo Montoro, J., García Izquierdo, C., Ruiz Navarro, A., García-Franco, N., & González Barberá, G. (2009). Effects of organic composts on soil properties: Comparative evaluation of source-separated and non source-separated composts. CSIC Digital Repository. https://digital.csic.es/handle/10261/18469

Ali, T., & Kahlown, M. A. (2001). Role of gypsum in amelioration of saline-sodic and sodic soil. Int. J. Agri. Biol, 3, 88–98.

Al-Mansori, N. J. (2018). Study the effect of intermittent and continuous ponding depths by using different heads to leach water. Journal of University of Babylon for Engineering Sciences, 26(5), 105–114.

Amezketa, E., Aragüés, R., & Gazol, R. (2005). Efficiency of sulfuric acid, mined gypsum, and two gypsum by-products in soil crusting prevention and sodic soil reclamation. Agronomy Journal, 97(3), 983–989.

Amini, S., Ghadiri, H., Chen, C., & Marschner, P. (2016). Salt-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

Ammari, T. G., Tahboub, A. B., Saoub, H. M., Hattar, B. I., & Al-Zu'bi, Y. A. (2008). Salt removal efficiency as influenced by phyto-amelioration of salt-affected soils. Journal of Food, Agriculture & Environment.

Andrade Foronda, D., & Colinet, G. (2022). Combined application of organic amendments and gypsum to reclaim saline–alkali soil. Agriculture, 12(7), 1049.

Armstrong, A. S. B., & Tanton, T. W. (1992). Gypsum applications to aggregated saline—sodic clay topsoils. Journal of Soil Science, 43(2), 249–260.

Arora, S., & Sharma, V. (2017). Reclamation and management of salt-affected soils for safeguarding agricultural productivity. Journal of Safe Agriculture, 1(1), 1–10.

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.

Arora, S., Vanza, M. J., Mehta, R., Bhuva, C., & Patel, P. N. (2014). Halophilic microbes for bio-remediation of salt affected soils. African Journal of Microbiology Research, 8(33), 3070–3078.

Artiola, J. F., Gebrekidan, H., & Carty, D. J. (2000). Use of langbeinite to reclaim sodic and saline sodic soils. Communications in Soil Science and Plant Analysis, 31(17–18), 2829–2842.

Asai, H., Samson, B. K., Stephan, H. M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., & Horie, T. (2009). Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. Field Crops Research, 111(1–2), 81–84.

Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. Plant and Soil, 337(1), 1–18.

Bello, S. K., Alayafi, A. H., Al-Solaimani, S. G., & Abo-Elyousr, K. A. (2021). Mitigating soil salinity stress with gypsum and bio-organic amendments: A review. Agronomy, 11(9), 1735.

Bhargava, G. P. (1989). Salt-affected soils of India: A source book. Oxford & IBH Publishing.

Bhojvaid, P. P., & Timmer, V. R. (1998). Soil dynamics in an age sequence of Prosopis juliflora planted for sodic soil restoration in India. Forest Ecology and Management, 106(2–3), 181–193.

Biswas, A., & Biswas, A. (2014). Comprehensive approaches in rehabilitating salt affected soils: A review on Indian perspective. Open Transactions on Geosciences, 1(1), 13–24.

Camberato, J. J., Gagnon, B., Angers, D. A., Chantigny, M. H., & Pan, W. L. (2006). Pulp and paper mill by-products as soil amendments and plant nutrient sources. Canadian Journal of Soil Science, 86(4), 641–653.

Chaganti, V. N., Crohn, D. M., & Šimůnek, J. (2015). Leaching and reclamation of a biochar and compost amended saline–sodic soil with moderate SAR reclaimed water. Agricultural Water Management, 158, 255–265.

Chaoui, H. I., Zibilske, L. M., & Ohno, T. (2003). Effects of earthworm casts and compost on soil microbial activity and plant nutrient availability. Soil Biology and Biochemistry, 35(2), 295–302.

Chenu, C., Le Bissonnais, Y., & Arrouays, D. (2000). Organic matter influence on clay wettability and soil aggregate stability. Soil Science Society of America Journal, 64(4), 1479–1486.

Corwin, D. L. (2020). Climate change impacts on soil salinity in agricultural areas. European Journal of Soil Science, 72(2), 842–862.

Dagar, J. C. (2005). Salinity research in India: An overview. Bulletin of the National Institute of Ecology, 15, 69–80.

Dagar, J. C., & Swarup, A. (2003). Potential of afforestation and agroforestry in carbon sequestration for mitigating climate changes. In Agroforestry: Potentials and Opportunities (pp. 43–65). Agrobios.

Damodaran, T., Rai, R. B., Jha, S. K., Sharma, D. K., Mishra, V. K., Dhama, K., Singh, A. K., & Sah, V. (2013). Impact of social factors in adoption of CSR BIO-A cost effective, eco-friendly bio-growth enhancer for sustainable crop production. South Asian Journal of Experimental Biology, 3(4), 158–165.

Dargan, K. S., Gaul, B. L., & Abrol, I. P. (1976). Effect of gypsum, farmyard manure and method of sowing on the yield of sugarcane growth in a highly sodic soil [India]. Indian Journal of Agronomy.

Day, S. J., Norton, J. B., Strom, C. F., Kelleners, T. J., & Aboukila, E. F. (2019). Gypsum, langbeinite, sulfur, and compost for reclamation of drastically disturbed calcareous saline–sodic soils. International Journal of Environmental Science and Technology, 16(1), 295–304.

Dimkpa, C., Weinand, T., & Asch, F. (2009). Plant–rhizobacteria interactions alleviate abiotic stress conditions. Plant, Cell & Environment, 32(12), 1682–1694.

Dorling, D. (2021). World population prospects at the UN: Our numbers are not our problem? In The struggle for social sustainability (pp. 129–154). Policy Press.

Elmeknassi, M., Elghali, A., de Carvalho, H. W. P., Laamrani, A., & Benzaazoua, M. (2024). A review of organic and inorganic amendments to treat saline-sodic soils: Emphasis on waste valorization for a circular economy approach. Science of The Total Environment, 921, 171087. https://doi.org/10.1016/j.scitotenv.2024.171087

Eyras, M. C., Defosse, G. E., & Dellatorre, F. (2008). Seaweed compost as an amendment for horticultural soils in Patagonia, Argentina. Compost Science & Utilization, 16(2), 119–124.

Fa-Hu, L. I., & Keren, R. (2009). Calcareous sodic soil reclamation as affected by corn stalk application and incubation: A laboratory study. Pedosphere, 19(4), 465–475.

FAO. (2021). Global map of salt-affected soils (GSASmap). Food and Agriculture Organization of the United Nations. https://www.fao.org/global-soil-partnership.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., & Zaks, D. P. (2011). Solutions for a cultivated planet. Nature, 478(7369), 337–342. https://doi.org/10.1038/nature10452

Garcia, C., Hernandez, T., Pascual, J. A., Moreno, J. L., & Ros, M. (2000). Microbial activity in soils of SE Spain exposed to degradation and desertification processes. Strategies for their rehabilitation. In Research and Perspectives of Soil Enzymology in Spain (pp. 93–143).

Gennari, M., Abbate, C., Porta, V. La, Baglieri, A., & Cignetti, A. (2007). Microbial response to Na2SO4 additions in a volcanic soil. Arid Land Research and Management, 21(3), 211–227.

Ghafoor, A. (1981). Comparison of H_2SO_4, HCl, HNO_3, and gypsum for reclaiming calcareous saline-sodic soil and for plant growth. Irrigation, Drainage and Flood Control Research Council of Pakistan, 11, 69–75.

Ghafoor, A., Gill, M. A., Hassan, A., Murtaza, G., & Qadir, M. (2001). Gypsum: An economical amendment for amelioration of saline-sodic waters and soils and for improving crop yields. Int. J. Agric. Biol, 3(3), 266–275.

Gharaibeh, M. A., Eltaif, N. I., & Albalasmeh, A. A. (2011). Reclamation of highly calcareous saline sodic soil using Atriplex halimus and by-product gypsum. International Journal of Phytoremediation, 13(9), 873–883.

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.

Gharaibeh, M. A., Eltaif, N. I., & Shunnar, O. F. (2009). Leaching and reclamation of calcareous saline-sodic soil by moderately saline and moderate-SAR water using gypsum and calcium chloride. Journal of Plant Nutrition and Soil Science, 172(5), 713–719.

Ghazaryan, K. A., Harutyunyan, A. S., Khachatryan, H. E., Singh, A., Minkina, T. M., Rajput, V. D., & Movsesyan, H. S. (2023). Study of tolerance and phytodesalination potential of wheat, oat, emmer, and barley for sustainable saline agriculture. Applied Ecology & Environmental Research, 21(5), 4853–4882.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. Science, 327(5967), 812–818.

Golla, B. (2021). Agricultural production system in arid and semi-arid regions. Journal of Agricultural Sciences and Food Technology, 7(2), 234–244.

Gonçalo Filho, F., da Silva Dias, N., Suddarth, S. R. P., Ferreira, J. F., Anderson, R. G., dos Santos Fernandes, C., ... & Cosme, C. R. (2019). Reclaiming tropical saline-sodic soils with gypsum and cow manure. Water, 12(1), 57.

Grigg, A. H., Sheridan, G. J., Pearce, A. B., & Mulligan, D. R. (2006). The effect of organic mulch amendments on the physical and chemical properties and revegetation success of a saline-sodic minespoil from central Queensland, Australia. Soil Research, 44(2), 97–105.

Groenewegen, H. (1961). Composition of the soluble and exchangeable ions of the salty soils of the Mirrool Irrigation Area (New South Wales). Journal of Soil Science, 12(1), 129–141.

Gupta, R. K., & Abrol, I. P. (1990). Salt-affected soils: Their reclamation and management for crop production. In Advances in soil science (pp. 223–288). Springer.

Gupta, S. K. (2002). A century of subsurface drainage research in India. Irrigation and Drainage Systems, 16(1), 69–84.

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.

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.

Hayat, R., Ali, S., Amara, U., Khalid, R., & Ahmed, I. (2010). Soil beneficial bacteria and their role in plant growth promotion: A review. Annals of Microbiology, 60(4), 579–598.

Heluf, G. (1995). Evaluation of the potential use of langbeinite (K2SO4·2MgSO4) as a reclaiming material for sodic and saline sodic soils [Doctoral dissertation, The University of Arizona].

Hussain, N., Hassan, G., Arshadullah, M., & Mujeeb, F. (2001). Evaluation of amendments for the improvement of physical properties of sodic soil. International Journal of Agriculture and Biology, 3(3), 319–322.

Ilyas, M., Qureshi, R. H., & Qadir, M. A. (1997). Chemical changes in a saline-sodic soil after gypsum application and cropping. Soil Technology, 10(3), 247–260.

Jalali, M., & Ranjbar, F. (2009). Effects of sodic water on soil sodicity and nutrient leaching in poultry and sheep manure amended soils. Geoderma, 153(1–2), 194–204.

Jones, D. L., Rousk, J., Edwards-Jones, G., DeLuca, T. H., & Murphy, D. V. (2012). Biochar-mediated changes in soil quality and plant growth in a three year field trial. Soil Biology and Biochemistry, 45, 113–124.

Joseph, S., Peacocke, C., Lehmann, J., & Munroe, P. (2009). Developing a biochar classification and test methods. In J. Lehmann & S. Joseph (Eds.), Biochar for environmental management: Science and technology (pp. 107–126). Earthscan.

Kaur, B., Gupta, S. R., & Singh, G. (2000). Soil carbon, microbial activity and nitrogen availability in agroforestry systems on moderately alkaline soils in northern India. Applied Soil Ecology, 15(3), 283–294.

Khalil, M. Y. (2002). Biochemical studies on Rosmarinus officinalis L. plant tolerance to salinity under compost levels. Annals of Agricultural Science, Ain-Shams University, 47(3), 1195–1210.

Kumar, P., & Sharma, P. K. (2020). Soil salinity and food security in India. Frontiers in Sustainable Food Systems, 4, 174.

Kwapinski, W., Byrne, C. M. P., Kryachko, E., Wolfram, P., Adley, C., Leahy, J. J., Novotny, E. H., & Hayes, M. H. B. (2010). Biochar from biomass and waste. Waste and Biomass Valorization, 1(2), 177–189.

Lakhdar, A., Scelza, R., Scotti, R., Rao, M. A., Jedidi, N., Gianfreda, L., & Abdelly, C. (2010). The effect of compost and sewage sludge on soil biologic activities in salt affected soil. Revista de La Ciencia Del Suelo y Nutrición Vegetal, 10(1), 40–47.

Lebron, I., Suarez, D. L., & Yoshida, T. (2002). Gypsum effect on the aggregate size and geometry of three sodic soils under reclamation. Soil Science Society of America Journal, 66(1), 92–98.

Lehrsch, G. A., Robbins, C. W., & Hansen, C. L. (1994). Cottage cheese (acid) whey effects on sodic soil aggregate stability. Arid Soil Research and Rehabilitation, 8(1), 19–31.

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.

Loveday, J. (1976). Relative significance of electrolyte and cation exchange effects when gypsum is applied to a sodic clay soil. Australian Journal of Soil Research, 14(3), 361–371.

Lugtenberg, B., & Kamilova, F. (2009). Plant-growth-promoting rhizobacteria. Annual Review of Microbiology, 63, 541–556.

Mahmoodabadi, M., & Heydarpour, E. (2014). Sequestration of organic carbon influenced by the application of straw residue and farmyard manure in two different soils. International Agrophysics, 28(2), 207–213.

Makoi, J. H. J. R., & Verplancke, H. (2010). Effect of gypsum placement on the physical chemical properties of a saline sandy loam soil. Australian Journal of Crop Science, 4(7), 556–563.

Manukyan, R. R. (1976). Improvement of a sodic Solonchak Solonetz on the Ararat plain with mineral acids and copperas (based on laboratory experiments). Soviet Soil Science, 8(4), 395–403.

Meena, M. D., Joshi, P. K., Narjary, B., Sheoran, P., Jat, H. S., Chinchmalatpure, A. R., Yadav, R. K., & Sharma, D. K. (2016). Effects of municipal solid waste compost, rice-straw compost and mineral fertilisers on biological and chemical properties of a saline soil and yields in a mustard–pearl millet cropping system. Soil Research, 54(8), 958–969.

Metternicht, G. I., & Zinck, J. A. (2003). Remote sensing of soil salinity: Potentials and constraints. Remote Sensing of Environment, 85(1), 1–20.

Miller, W. P. (1987). Infiltration and soil loss of three gypsum-amended Ultisols under simulated rainfall. Soil Science Society of America Journal, 51(5), 1314–1320.

Miller, W. P., & Baharuddin, M. K. (1986). Relationship of soil dispersibility to infiltration and erosion of southeastern soils. Soil Science, 142(4), 235–240.

Mishra, A., Sharma, S. D., & Khan, G. H. (2003). Improvement in physical and chemical properties of sodic soil by 3, 6 and 9 years old plantation of Eucalyptus tereticornis: Biorejuvenation of sodic soil. Forest Ecology and Management, 184(1–3), 115–124.

Miyamoto, S., & Stroehlein, J. L. (1986). Sulfuric acid effects on water infiltration and chemical properties of alkaline soils and water. Transactions of the ASAE, 29(5), 1288–1296.

Miyamoto, S., Ryan, J., & Stroehlein, J. L. (1975). Sulfuric acid for the treatment of ammoniated irrigation water: I. Reducing ammonia volatilization. Soil Science Society of America Journal, 39(3), 544–548.

Mondal, R. C. (1976). Effect of farmyard manure on the solubility of calcium sulphate under alkaline condition. Journal of the Indian Society of Soil Science, 24(1), 91–92.

Munns, R. (2002). Salinity, growth and phytohormones. In A. Läuchli & U. Lüttge (Eds.), Salinity: Environment–plants–molecules (pp. 271–290). Springer.

Niazi, B. H., Ahmed, M., Hussain, N., & Salim, M. (2001). Comparison of sand, gypsum and sulphuric acid to reclaim a dense saline sodic soil. International Journal of Agriculture and Biology, 3(3), 316–318.

Nosetto, M. D., Jobbágy, E. G., Tóth, T., & Di Bella, C. M. (2007). The effects of tree establishment on water and salt dynamics in naturally salt-affected grasslands. Oecologia, 152(4), 695–705.

Oorts, K., Vanlauwe, B., & Merckx, R. (2003). Cation exchange capacities of soil organic matter fractions in a Ferric Lixisol with different organic matter inputs. Agriculture, Ecosystems & Environment, 100(2–3), 161–171.

Ors, S., Sahin, U., & Khadra, R. (2015). Reclamation of saline sodic soils with the use of mixed fly ash and sewage sludge. Arid Land Research and Management, 29(1), 41–54.

Oster, J. D., & Frenkel, H. (1980). The chemistry of the reclamation of sodic soils with gypsum and lime. Soil Science Society of America Journal, 44(1), 41–45.

Oster, J. D., Shainberg, I., & Abrol, I. P. (1999). Reclamation of salt-affected soils. In Agricultural drainage (Agronomy Monograph No. 38, pp. 659–691). American Society of Agronomy.

Oster, J., & Jayawardane, N. S. (1998). Agricultural management of sodic soils. FAO.

Overstreet, R., Martin, J. C., & King, H. M. (1951). Gypsum, sulfur, and sulfuric acid for reclaiming an alkali soil of the Fresno series. Hilgardia, 21(5), 113–127.

Panosyan, H., Hakobyan, A., Birkeland, N. K., & Trchounian, A. (2018). Bacilli community of saline–alkaline soils from the Ararat Plain (Armenia) assessed by molecular and culture-based methods. Systematic and Applied Microbiology, 41(3), 232–240.

Pascual, J. A., García, C., & Hernandez, T. (1999). Lasting microbiological and biochemical effects of the addition of municipal solid waste to an arid soil. Biology and Fertility of Soils, 30(1), 1–6.

Prather, R. J., Goertzen, J. O., Rhoades, J. D., & Frenkel, H. (1978). Efficient amendment use in sodic soil reclamation. Soil Science Society of America Journal, 42(5), 782–786.

Qadir, M., & Oster, J. D. (2007). Crop and irrigation management strategies for saline-sodic soils. Science of the Total Environment, 323(1–3), 1–19. https://doi.org/10.1016/j.scitotenv.2004.10.006

Qadir, M., & Schubert, S. (2002). Degradation processes and nutrient constraints in sodic soils. Land Degradation & Development, 13(4), 275–294.

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., Oster, J. D., Schubert, S., Noble, A. D., & Sahrawat, K. L. (2007). Phytoremediation of sodic and saline-sodic soils. Advances in Agronomy, 96, 197–247.
Qadir, M., Qureshi, R. H., & Ahmad, N. (1996). Reclamation of a saline-sodic soil by gypsum and Leptochloa fusca. Geoderma, 74(3–4), 207–217.
Qadir, M., Schubert, S., Ghafoor, A., & Murtaza, G. (2001). Amelioration strategies for sodic soils: A review. Land Degradation & Development, 12(4), 357–386.
Ranjbar, F., & Jalali, M. (2011). Effects of plant residues and calcite amendments on soil sodicity. Journal of Plant Nutrition and Soil Science, 174(6), 874–883.
Rasmussen, W. W., Moore, D. P., & Alban, L. A. (1972). Improvement of a solonetzic (slick spot) soil by deep plowing, subsoiling and amendments. Soil Science Society of America Proceedings, 36(1), 137–142.
Raviv, M., Krasnovsky, A., Medina, S., & Reuveni, R. (1998). Assessment of various control strategies for recirculation of greenhouse effluents under semi-arid conditions. The Journal of Horticultural Science and Biotechnology, 73(4), 485–491.
Reeve, R. C., Pillsbury, A. F., & Wilcox, L. V. (1955). Reclamation of a saline and high boron soil in the Coachella Valley of California. Hilgardia, 24(4), 69–91.
Rengasamy, P. (2006). World salinization with emphasis on Australia. Journal of Experimental Botany, 57(5), 1017–1023.
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.
Ritzema, H. P., Satyanarayana, T. V., Raman, S., & Boonstra, J. (2008). Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: Lessons learned in farmers' fields. Agricultural Water Management, 95(3), 179–189.
Robbins, C. W., & Lehrsch, G. A. (1992). Effects of acidic cottage cheese whey on chemical and physical properties of a sodic soil. Arid Soil Research and Rehabilitation, 6(2), 127–134.
Robin, V., Tertre, E., Beaufort, D., Regnault, O., Sardini, P., & Descostes, M. (2015). Ion exchange reactions of major inorganic cations (H+, Na+, Ca2+, Mg2+ and K+) on beidellite: Experimental results and new thermodynamic database. Toward a better prediction of contaminant mobility in natural environments. Applied Geochemistry, 59, 74–84.
Rondon, M. A., Lehmann, J., Ramírez, J., & Hurtado, M. (2007). Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions. Biology and Fertility of Soils, 43(6), 699–708.
Roth, C. H., & Pavan, M. A. (1991). Effects of lime and gypsum on clay dispersion and infiltration in samples of a Brazilian Oxisol. Geoderma, 48(3–4), 351–361.
Sadiq, M., Hassan, G., Mehdi, S. M., Hussain, N., & Jamil, M. (2007). Amelioration of saline-sodic soils with tillage implements and sulfuric acid application. Pedosphere, 17(2), 182–190.
Sahakyan, S., Yedoyan, T., Khachatryan, E., Hakobyan, M., & Gevorgyan, A. (2026). Reclamation of saline-sodic heavy-textured soils using a novel electro-reclamation method. Journal of the Saudi Society of Agricultural Sciences, 25(3), 35.
Sardinha, M., Müller, T., Schmeisky, H., & Joergensen, R. G. (2003). Microbial performance in soils along a salinity gradient under acidic conditions. Applied Soil Ecology, 23(3), 237–244.
Schwab, G. O. (1966). Soil and water conservation engineering. Wiley.
Senesi, N., Plaza, C., Brunetti, G., & Polo, A. (2007). A comparative survey of recent results on humic-like fractions in organic amendments and effects on native soil humic substances. Soil Biology and Biochemistry, 39(6), 1244–1262.
Shainberg, I., Sumner, M. E., Miller, W. P., Farina, M. P. W., Pavan, M. A., & Fey, M. V. (1989). Use of gypsum on soils: A review. Advances in Soil Science, 1–111.
Sharma, A. K., Fehrenbacher, J. B., & Jones Jr, B. A. (1974). Effect of gypsum, soil disturbance and tile spacing on the amelioration of Huey silt loam, a natric soil in Illinois. Soil Science Society of America Journal, 38(4), 628–632.
Shi, Y., Zhao, X., Gao, X., Zhang, S., & Wu, P. (2016). The effects of long-term fertiliser applications on soil organic carbon and hydraulic properties of a loess soil in China. Land Degradation & Development, 27(1), 60–67.
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.
Singh, A., Rajput, V. D., Singh, R. K., Elshikh, M. S., El-Ramady, H., Prokisch, J., ... & Ghazaryan, K. (2025). Emerging frontiers in nanotechnology for salinity stress management: A global bibliometric analysis. Diyala Agricultural Sciences Journal, 17(2), 46–69.
Singh, G. (2009). Salinity-related desertification and management strategies: Indian experience. Land Degradation & Development, 20(4), 367–385.
Singh, K. N., & Kumar, B. M. (1985). Interactive effects of soil moisture, fertilizers and salinity in crop production. Agricultura, 8–22.
Singh, R. P., Saxena, S. K., & Khan, A. M. (1981). Effect of salinity, alkalinity, phosphate and organic matter on the movement of nematicides in soil. Nematologia Mediterranea, 9(1), 33–42.
Singh, Y. P., Arora, S., Mishra, V. K., & Singh, A. K. (2023). Rationalizing mineral gypsum use through microbially enriched municipal solid waste compost for amelioration and regaining productivity potential of degraded alkali soils. Scientific Reports, 13, 11816. https://doi.org/10.1038/s41598-023-37823-5
Smedema, L. K., & Ochs, W. J. (1998). Needs and prospects for improved drainage in developing countries. Irrigation and Drainage Systems, 12(4), 359–369.
Solaiman, Z. M., Blackwell, P., Abbott, L. K., & Storer, P. (2010). Direct and residual effect of biochar application on mycorrhizal root colonisation, growth and nutrition of wheat. Soil Research, 48(7), 546–554.
Stehouwer, R. C., & Macneal, K. (2003). Use of yard trimmings compost for restoration of saline soil incineration ash. Compost Science & Utilization, 11(1), 51–60.
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. (2001). Sodic soil reclamation: Modelling and field study. Soil Research, 39(6), 1225–1246.
Swift, R. S. (2001). Sequestration of carbon by soil. Soil Science, 166(11), 858–871.
Szabolcs, I. (1989). Salt-affected soils. CRC Press.

Tejada, M., & Gonzalez, J. L. (2003). Effects of the application of a compost originating from crushed cotton gin residues on wheat yield under dryland conditions. European Journal of Agronomy, 19(2), 357–368. https://doi.org/10.1016/S1161-0301(02)00089-8

Tejada, M., Garcia, C., Gonzalez, J. L., & Hernandez, M. T. (2006). Use of organic amendment as a strategy for saline soil remediation: Influence on the physical, chemical and biological properties of soil. Soil Biology and Biochemistry, 38(6), 1413–1421.

Termorshuizen, A. J., Moolenaar, S. W., Veeken, A. H. M., & Blok, W. J. (2004). The value of compost. Reviews in Environmental Science and Bio/Technology, 3(4), 343–347.

Thies, J. E., & Rillig, M. C. (2009). Characteristics of biochar: Biological properties. In J. Lehmann & S. Joseph (Eds.), Biochar for environmental management: Science and technology (pp. 85–105).

Thimmappa, K., Singh, Y. P., & Raju, R. (2017). Reclamation of sodic soils in India: An economic impact assessment. In S. Arora, Y. P. Singh, & R. K. Singh (Eds.), Bioremediation of salt affected soils: An Indian perspective (pp. 257–274). Springer.

Tyagi, N. K., & Minhas, P. S. (1998). Agricultural salinity management in India. CSSRI.

US Salinity Laboratory Staff. (1954). Diagnosis and improvement of saline and alkali soils (USDA Agricultural Handbook No. 60). U.S. Department of Agriculture.

Vance, G. F., King, L. A., & Ganjegunte, G. K. (2008). Soil and plant responses from land application of saline–sodic waters: Implications of management. Journal of Environmental Quality, 37(S5), S-139–S-153.

Vasanth, P., & Kannappan, M. (2026). Saline and sodic soil reclamation: Recent advances and agronomic implications. JOSTA: Journal of Sustainable Technology in Agriculture, 2(1). https://doi.org/10.65287/josta.202601.A408

Visser, S., Griffiths, C. L., & Parkinson, D. (1983). Effects of surface mining on the microbiology of a prairie site in Alberta, Canada. Canadian Journal of Soil Science, 63(2), 177–189.

Wang, L., Sun, X., Li, S., Zhang, T., Zhang, W., & Zhai, P. (2014). Application of organic amendments to a coastal saline soil in North China: Effects on soil physical and chemical properties and tree growth. PloS One, 9(2), e89185. https://doi.org/10.1371/journal.pone.0089185

Westerman, P. W., & Bicudo, J. R. (2005). Management considerations for organic waste use in agriculture. Bioresource Technology, 96(2), 215–221.

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.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. Nature Communications, 1(1), 56. https://doi.org/10.1038/ncomms1053

Xiao-gang, L., Li, F., Zed, R., & Zheng-yan, Z. (2007). Soil management changes organic carbon pools in alpine pastureland soils. Soil and Tillage Research, 93(1), 186–196.

Yadav, B. K., Meena, H. M., & Meena, R. L. (2024). Remediation of antagonistic saline effect on crops using organic amendments: A review. Journal of Soil Salinity and Water Quality, 16(2), 166–179.

Yasin, M., Zada, R., & Niazi, B. H. (1998). Conjunctive use of hydrochloric acid and gypsum in reclamation of a saline sodic soil. Pakistan Journal of Soil Science.

Yazdanpanah, N., Pazira, E., Neshat, A., Naghavi, H., Moezi, A., & Mahmoodabadi, M. (2011). Effect of some amendments on leachate properties of a calcareous saline-sodic soil. International Agrophysics, 25(3), 307–310.

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.

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.