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Sustainable Management of Sodic Soils for Crop Production: Opportunities and Challenges

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Abstract

Salt induced land degradation adversely affects the productivity of ~1000 million hectares (M ha) of agricultural land worldwide. Salt-affected soils occupy 6.73 M ha area in India of which ~56% are sodic and the remainder 44% saline. Sodic soils in large parts of Indo-Gangetic plains have naturally formed due to rapid alternate wetting and drying conducive to alkali hydrolysis, sodium saturation and high pH development. Nonetheless, the problem of human-induced secondary soil sodification has considerably increased in the last few decades largely due to irrigation mismanagement, neglect of drainage and continued irrigation with sodic groundwater. Fresh water scarcity, climate change impacts and reduced availability and quality of widely used amendment gypsum may further accentuate the problem in foreseeable future. Yet, the growing food demands and continual shrinkage of prime agricultural lands have necessitated sustainable management of degraded lands in an environmental friendly and socially acceptable manner. This article briefly reviews the progress in sodic soil reclamation and management. Considering the emerging constraints which may adversely impact restoration programmes, the future research needs are suggested.

Key words: Agroforestry, Climate change, Gypsum, Sodicty, Sodification, Sustainable agriculture, Water scarcity

Introduction

Growing realization that healthy soils play a vital role in sustaining the Earth's ecosystem services and diverse human needs has gradually led to a pronounced shift in the perception that soil should not be merely viewed as the growing medium for crops. Instead, any assessment of the real worth of soil vis-à-vis sustainable human life should also consider the 'living and dynamic nature of soil' enabling it to provide multifarious benefits to the human society (Karlen *et al.*, 1997). Despite their huge significance in producing diverse tangible goods for human use and indirect role in the provisioning of different life-supporting environmental services, soils continue to be viewed only in terms of their potential to produce food (Dominati *et al.*, 2010). The biased view that soil as an infinite and renewable resource has an unceasing potential to satisfy the human needs seems to have inculcated misperception among farming communities in many parts of the world that soil will be perpetually capable of supporting

the ever-growing food, feed, fiber and fuel requirements. This unrealistic assumption has caused immense harm by severely diminishing the ecosystem functions and services of soils. Indiscriminate attempts to augment the soil productivity through land clearings, irrigation development and heavy agro-chemical use have left indelible scars on agricultural sustainability in many parts of the world.

The linkage between anthropogenic activities and land degradation is best illustrated by the development of vast stretches of salt-affected soils (SAS) in the north-western region of India. This region, comprising of Punjab, Haryana and parts of Rajasthan and Uttar Pradesh states, has played a crucial role in the national food security since the Green Revolution (GR) days. Introduction of dwarf, fertilizer responsive and high yielding rice and wheat cultivars around mid-1960s marked the onset of rice-wheat cropping system in these states which now covers about 12 M ha in the alluvial Indo-Gangetic plains (IGP). After about two

decades in the late 1980s, the unintended side-effects of GR technologies, *inter alia*, declining soil fertility, receding watertable, stagnant crop yields, repeated pest infestations, waterlogging and salinity became noticeable. In the ensuing decades, these problems substantially increased seriously affecting the crop yields and farm incomes. The most severe impact has been noted in the south-western parts of Punjab and Haryana states where extensive pockets of waterlogged SAS have developed over the years (Sharma *et al.*, 2016). Prior to the advent of GR, farmers raised locally adapted crops for their subsistence and agriculture in north-western parts of the country was essentially a means of securing the necessities of life. Adoption of high yielding seeds provided an impetus to the commercial motives leading to a gradual transition from the subsistence farming to profit-oriented agriculture. Over time, an apparent lack of careful judgment ignoring the fact that soil as a biological entity had a threshold carrying capacity led to a host of 'second generation problems' in the post-GR period. In a nutshell, agriculture became a victim of its own success necessitating a paradigm shift in the means and way of food production (Conway and Barbier, 2013).

Considering the global extent of land degradation and the far-reaching consequences, the 68th United Nations General Assembly declared 2015 as the 'International Year of Soils' to sensitize the members of civil society and policy makers about the huge value of healthy soils. This initiative specifically aimed to gather the public support and policy attention to 'promote the investment in sustainable soil management activities to develop and maintain healthy soils for different land users and population groups' (FAO, 2015). As an offshoot to this initiative, International Union of Soil Sciences declared 2015-2024 as the 'International Decade of Soils' to give impetus to the ongoing efforts by obtaining the support of global organizations such as Consultative Group for International Agricultural Research, Food and Agriculture Organization and United Nations Environment Program to mobilize the resources and scientific knowledge for this purpose as public sensitization alone may not be

sufficient to address these concerns (IUSS, 2016). Commensurate with the global trends, Government of India recently launched an ambitious scheme to make India a 'land degradation neutral' country by 2030. This initiative, a follow up to the United Nations Conference on Sustainable Development (Rio+20) held in 2012, aims to arrest the desertification of about 81 M ha lands including salt-affected lands by stabilizing and enhancing their productivity through sustainable management of soil, water and biodiversity (Economic Times, 2014).

Available evidences show that crop intensification has dealt a serious blow to the sustainability of natural resources across the world. According to recent estimates, pervasive and intensive land use has caused deterioration of about 25% of the global soils, water and biodiversity threatening the food security and economic wellbeing of populations dependent on them (FAO, 2011). Land degradation not only substantially lowers the agro-ecosystems productivity measured in terms of crop yields but also causes drastic reduction in the economic value of land derived ecosystem goods and services including climate regulation, provisioning of fresh water and air, carbon sequestration and nutrient recycling. A recent study based on 'human appropriation of net primary productivity' dataset revealed that total monetary losses due to land degradation were \$6.3 trillion per year. This may seem to be a distorted estimate as agriculture contributes only 2.8% to the global GDP and the total losses will be hardly \$1.7 trillion of the global GDP valued at \$63 trillion in 2010. Nonetheless, when the total output including the ecosystem services are considered in place of monetary value of agricultural produce, total losses will be \$6.3 trillion per year (Sutton *et al.*, 2016).

This paper presents an account of the causes of sodicity development, sodicity-induced land degradation and management practices to deal with the problem with special reference to India. It also briefly highlights the emerging constraints and challenges in their reclamation and management. Taking into account the emerging constraints, future research needs are delineated.

Causes and Mechanisms of Soil Sodification

Salinization refers to the process of salt accumulation in the soil. If sodium salts predominate, soils tend to become alkaline in reaction and develop sodicity (Rengasamy, 2006). Saline soils with good drainage lose a substantial portion of soluble salts resulting in a high $\text{Na}^+:\text{Ca}^{2+}$ ratio after leaching or rainfall. Subsequently, sodium clays hydrolyze to form free sodium hydroxide causing deflocculation of the colloidal particles followed by clay movements to lower depths and formation of a hard clay pan. Abrol *et al.* (1988) reviewed the factors responsible for sodicity development and found that specific topographic conditions, weathering of rocks, anaerobic reduction of sulphate ions and irrigation with carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) rich groundwater induces excessive Na^+ accumulation on the soil exchange complex (SEC). Various causes of sodification may broadly be categorized into natural and anthropogenic factors.

Natural causes

Pal *et al.* (2003b) noted that several meandering rivers have created microhigh (MH) and microlow (ML) positions on an apparently smooth surface in the IGP. High intensity rainfall in a relatively short duration causes repeated flooding of ML depressions subjecting the soils therein to rapid cycles of wetting and drying favourable to the release and dissociation of alkali salts leading to Ca^{2+} displacement, Na^+ saturation and high pH (≥ 8.4). Vaidya and Pal (2002) observed that micro-topographic variations were also responsible for sub-soil sodicity in the calcareous Vertisols of Central India, albeit in a different manner. In contrast to IGP, sodicity develops in MH areas while soils on ML positions are either non-sodic or only mildly sodic. While ML positions receive high amounts of rainwater, relative dryness in MH positions proves conducive to the accumulation of pedogenic CaCO_3 (PC), rise in pH and sodicity. Srivastava *et al.* (2002) found that non-pedogenic CaCO_3 (NPC) present in Vertisols of Peninsular India representing a climosequence from moist sub-humid to dry arid is derived from the weathering of rocks. Upon dissolution, NPC

releases Ca^{2+} ions which recrystallize to form PC responsible for the increase in pH, decrease in Ca/Mg ratio and the development of subsoil sodicity. Pal *et al.* (2006) also found that formation of PC at the expense of NPC was the main cause of high soil pH and sodicity in peninsular Vertisols. They noted that despite high ESP (≤ 15), gypsum and Ca-zeolites arrested the rise in soil pH and decrease in Ca/Mg ratio with a concurrent improvement in soil hydraulic properties. The parent material from which the soils develop also influences their properties. Calcareous, shrink-swell soils of the Peninsular India exhibiting sub-soil sodicity have mainly formed from the weathering of Deccan basalt rich in plagioclase feldspars (Thakare *et al.*, 2013). Sodic soils in many semi-arid parts of IGP have also developed over the alluvium rich in plagioclase feldspars (Pal *et al.*, 2003).

Anthropogenic causes

In addition to natural factors, anthropogenic activities also contribute to soil sodification; often at an accelerated rate. Intensive irrigation with marginal quality water is the major human action responsible for sodicity development in the cultivated soils. Aquifers pumping sodic water are found in many parts of north-western India. In the absence of reliable fresh water supplies, farmers are compelled to irrigate their crops with such water putting the soils at risk of sodification. Furthermore, very high water requirements of RWCS make it more vulnerable to sodicity hazard as evident from almost 2-fold higher soil pH and ESP values compared to low water requiring rotations such as millet/maize-wheat under similar conditions (Minhas and Bajwa, 2001). Sodic water constitutes about 25 and 21% of the total groundwater in Punjab and Haryana states, respectively (Kaledhonkar *et al.*, 2012). Geographic Information System-based mapping indicated that good quality, marginally suitable and unsuitable groundwater is present in 45.7%, 46.1% and 8.2% area of Punjab state, respectively. Unsuitable groundwater zones were found in the reclaimed sodic areas of the central alluvial plain and south-western alluvial plain (Kumar *et al.*, 2014). In arid parts of Rajasthan having poor surface water resources, groundwater is not only

scarce but also moderately to highly saline/sodic in most of the areas (Joshi, 2014). In some cases, moderate improvements in water-quality after monsoon occur possibly due to groundwater recharge and the dilution effect of rainwater (Goyal *et al.*, 2010).

The problem of irrigation-induced sodification has also been reported from other countries. Intensive use of groundwater has caused steady rise in groundwater table which now lies within 1.5 m of the surface compared to 20-30 m depth prior to irrigation development causing massive waterlogging and salinization in the Indus Basin of Pakistan. Annual rate of salinity-induced land abandonment is estimated at about 40,000 ha. As about 70% of the installed tube-wells pump sodic water containing high levels of Na^+ , CO_3^{2-} and HCO_3^- , increased sodification of new areas is likely (Qureshi *et al.*, 2008). Development of strongly sodic soils unsuitable for crop production in the semi-arid, tube-well irrigated Songnen plains of northeast China is ascribed to the occurrence of shallow groundwater table and excessive evaporation losses. Watertable lay close to the surface (~ 1.5 m) in 1960s. Over time, excessive water withdrawal lowered the watertable to about 3 m but sodicity problem did not subside (Luo *et al.*, 2011). Hungary has the largest expanse of saline and sodic soils in Europe. The Great Hungarian Plain, covering $\sim 47,000$ km² of the eastern Hungary, has an extremely flat topography and poor drainage favourable to the development of shallow watertables and salt accumulation (Nosetto *et al.*, 2007).

Of late, irrigation with treated wastewater (TWW) has considerably increased in many freshwater starved regions. Compared to the fresh water of origin, TWW is often high in sodium adsorption ratio (SAR) and its continued use may adversely affect the soil properties. In Israel, regular use of even low SAR (5) TWW unexpectedly increased (>8) the exchangeable sodium percentage (ESP) in sub-surface (60-90 cm) soil (Levy *et al.*, 2014). Although adverse effects of sodicity generally become noticeable at ESP values ≥ 15 , internal swelling of clays starts even at very low ESP of 5. Prolonged use of TWW raises the soil ESP making them susceptible to clay

swelling and dispersion. Negative impacts of TWW on soil hydraulic properties could be high during the rainy season as low electrolyte rainwater increases clay dispersion (Bardhan *et al.*, 2016). Continued irrigation with recycled wastewater originating from desalinated water in the extremely arid (annual rainfall ≥ 150 mm year⁻¹) Spanish island of Lanzarote has increased soil sodicity as evident from 1.6-fold higher SAR values than control soils (Díaz *et al.*, 2013). Many South American countries such as Argentina, Chile, Bolivia and Peru face high risk of soil sodification due to irrigation with contaminated wastewater (Fernández-Cirelli *et al.*, 2009).

Characteristics and Distribution of Sodic Soils

Sodic soils are characterized by variable electrical conductivity of soil saturation paste (EC_e , mostly < 4 dS m⁻¹), high pH_s (>8.2) and high ESP (>15). Contrary to the saline soils having excessive levels of chlorides and sulphates of Na^+ , Ca^{2+} and Mg^{2+} , sodic soils contain high amounts of CO_3^{2-} and HCO_3^- salts (Sharma *et al.*, 2016). Under extreme conditions, soil pH_s may be as high as 10.5 or more. In highly sodic soils, dissolved organic matter (OM) often accumulates on the surface imparting a dark colour. Such soils are commonly referred to as black sodic soils. Upper surface of sodic soils is often very hard and virtually impenetrable to water while the sub-surface layers remain saturated with water. Upon drying, deep and 1-2 cm wide cracks develop on the surface (Abrol *et al.*, 1988).

Natural and human-induced salinization of agricultural landscapes is recognized as the major driver of land degradation globally. Based on FAO/UNESCO soil map of the world, Szabolcs (1989) reported that salt-affected soils (SAS) occupy about 831 M ha area globally. Recently, Wicke *et al.* (2011) used Harmonized World Soil Database in a Geographic Information System (ESRI ArcGIS 9.3.1) to map the global extent of salt-affectedness and estimated that salt stress diminishes the productivity of over 1100 M ha area globally of which saline, sodic and saline-sodic soils constitute roughly 60%, 26% and 14%, respectively. Although salt-affected soils (SAS) naturally occur in about 100 countries of the

world, relentless secondary salinization in many irrigated and dryland parts of the world in recent years has emerged as a serious cause for concern.

In irrigated lands, seepage from earthen canals and field channels, frequent and over irrigation, continued use of saline/sodic water, low water application to leach the salts and virtually no emphasis on land drainage contribute to rapid rise in watertable and salt accumulation (Sharma and Singh, 2015). Currently, $\sim 1/3^{\text{rd}}$ of 260 M ha of global irrigated lands suffer from salinization to varying extent. In countries like Australia, Egypt, India and Pakistan, a significant proportion (15–36%) of the irrigated lands have become salinized (Schwabe *et al.*, 2006). Salinization in drylands is a consequence of the clearing of perennial vegetation for growing the annual field crops. This alters the water balance resulting in deep drainage below the root zone, rise of watertable and excessive salt accumulation in the surface layers (Lambers, 2003). In India, about 6.73 M ha area is salt-affected; sodic and saline soils constitute $\sim 56\%$ (3.77 M ha) and 44% (2.96 M ha) of the total salt-affected area, respectively (Singh *et al.*, 2010). Sodicity is a severe obstacle to sustainable

crop production in 11 states. Uttar Pradesh has the largest area (1.35 M ha) under sodic soils constituting nearly 36% of the total. Besides Uttar Pradesh, Gujarat (14.36%), Maharashtra (11.21%), Tamil Nadu (9.41%), Haryana (4.86%) and Punjab (4.02%) have high sodicity problem and together represent about 80% of the total sodic lands in India (Table 1).

Effects of Sodicity on Soil Structure and Plant Growth

Under sodic conditions, poor soil structure, restricted water movement and nutrient toxicities are the major constraints to plant growth. Structural degradation arises due to clay dispersion, plugging of the soil pores and development of a calcareous hard layer in the sub-soil. High pH may persist throughout soil profile hampering the availability of essential plant nutrients.

Clay dispersion and structural problems

Sodicity induced deterioration in soil structure impedes water entry into the soil (infiltration rate; IR) and the subsequent percolation of water

Table 1. State-wise distribution of sodic soil in India (ha)

State	Sodic soils (ha) ¹	Remarks ²
Andhra Pradesh	196609	Sodic soils predominantly occur in Prakasam, Nellore, Guntur and Anantapur districts.
Bihar	105852	Sodic soils are a major problem in Bhojpur (71000 ha) and Patna (31000 ha) districts.
Gujarat	541430	Highly affected districts are Kachchh (468000 ha), Patan (253000 ha), Surendranagar (119000 ha) and Ahmedabad (96000 ha).
Haryana	183399	Sodicity affects about 3.7% of the total geographical area.
Karnataka	148136	Chitradurga (50000 ha), Bellary (16000 ha) and Mysore (14000 ha) districts are most severely affected.
Madhya Pradesh	139720	Sodic soils are found in Vidisha (28000 ha), Bhind (12000 ha), Morena (11000 ha), and Datia (4000 ha) districts.
Maharashtra	422670	Highest sodicity affected area is in Ahmednagar district (265000 ha) followed by Nashik (40000 ha), Aurangabad (31000 ha), Pune (26000 ha) and Solapur (20000 ha).
Punjab	151717	Sodic soils are found in all districts except Faridkot, Hoshiarpur and Nawanshahr. Sangrur (41000 ha), Firozpur (29000 ha) and Patiala (14000 ha) are highly affected.
Rajasthan	179371	Alwar, Ajmer, Chittorgarh, Dungarpur, Udaipur and Sri Ganganagar suffer from sodicity problem.
Tamil Nadu	354784	–
Uttar Pradesh	1346971	Sodicity affects about 6% of the total geographical area of state. Jaunpur (125000 ha), Mainpuri (120000 ha) and Azamgarh (100000 ha) are highly affected districts.
Total	3770659	

Source: ¹Singh *et al.* (2010); ²ICAR and NAAS (2010).

through the soil profile (permeability). Factors such as soil texture, ESP, total electrolyte concentration (TEC) in water, external mechanical forces and the rate of soil wetting determine the extents of structural deformity and infiltration problem. [Levy *et al.* \(2005\)](#) examined the effects of varying ESP (1-20), fast wetting (50 mm h^{-1}) and leaching with distilled water on hydraulic conductivity (HC) of 60 differentially textured Israeli soils and found that sodicity induced changes in HC varied with the soil texture. They also studied the effects of slow and high wetting rates (2 or 50 mm h^{-1}), different ESP and two salinity waters (distilled or marginally saline- 2 dS m^{-1}) on HC of 16 selected soils and concluded that rate of wetting had no effect on the HC beyond that of sodicity and salinity in loamy sand. In contrast, a significant interaction among wetting rate, TEC and ESP on HC was noted in loam, sandy clay and clay soils. Moderate ESP (5-10) and absence of electrolytes hastened slaking and swelling causing heavy reduction in HC. Less saline water ($\text{EC}_{\text{IW}} < 0.5 \text{ dS m}^{-1}$ and especially $< 0.2 \text{ dS m}^{-1}$) exhibits corrosive effect and hastens the leaching of minerals and soluble salts from the soil. In some soils, excessive leaching of divalent Ca^{2+} greatly diminishes aggregate binding and stability ([Ayers and Westcot, 1985](#)). At high salt concentrations, clays exist as floccules and not as individual platy particles ([Shainberg *et al.*, 1989](#)). Use of a solution with TEC below flocculation value of clay particles causes a further decrease in pore radii and parts of the dispersed tactoids are subsequently trapped in the narrow pores ([Keren and Singer, 1988](#)).

Breaking of soil aggregates into microaggregates (*i.e.*, slaking) is seen in many cultivated soils; especially those subject to rapid cycles of wetting and drying. A high rate of slaking may create temporary surface seal and infiltration problem. When slaking is followed by clay dispersion, as observed under sodic conditions, problems of surface sealing, crusting, hardsetting, reduced infiltration, drainage congestion and poor workability arise over time ([So and Aylmore, 1993](#)). Under low ESP and high salinity conditions, mechanical impacts are mainly responsible for the disintegration of soil aggregates

and their compaction into a thin skin seal. In contrast, with rise in ESP and reduction in salinity, chemical dispersion processes tend to predominate and accelerate the dispersion and infiltration problems ([Agasi *et al.*, 1985](#)). Continued irrigation with sodic water hastens the rate of clay dispersion and eventually leads to the choking of water conducting pores and reduced HC. Sealing of water conducting pores by the dispersed particles results in low intake of water and limits the profile-water storage after rains or irrigation ([Acharya and Abrol, 1991](#)). The presence of a calcareous hard pan impervious to water may further exacerbate the infiltration problem. Based on a micromorphological study on 28 Alfisols of the semi-arid part of the IGP, [Pal *et al.* \(2003a\)](#) found that sodicity and poor hydraulic properties in these soils were caused by the rapid accumulation of CaCO_3 . Predominance of Na^+ among cations and CO_3^{2-} and HCO_3^- among anions proves conducive to the formation of large amounts of alkali salts and the consequent rise in pH (< 8.4). High pH leads to the precipitation of Ca^{2+} ions into CaCO_3 . CaCO_3 levels tend to increase with depth with concentrations as high as 10% in sub-soils compared to only 1-2% in the surface layers. Excessive CaCO_3 accumulation lowers $\text{Ca}^{2+}/\text{Na}^+$ ratio in soil solution and on SEC leading to high ESP and reduced exchangeable calcium percentage. Calcareousness may be seen either only in the sub-soil or throughout the soil profile.

Nutrient deficiency and ion toxicities

Nutrient constraints in sodic soils are primary created by the electron and proton activities (pE and pH). Low rates of water and oxygen flux may further reduce nutrient availability to plants in these dispersive soils ([Naidu and Rengasamy, 1993](#)). High pH conditions may persist throughout soil profile even in moderately sodic soils adversely affecting nutrient availability ([Singh, 2009](#)). Widespread deficiencies of OM, available N, Ca and Zn have been reported from the sodic soils of IGP. Sodic soils are mostly very low in organic carbon (OC) and N. Although organic amendments such as Farm Yard Manure (FYM) show an enhancing effect, reclaimed soils still remain deficient in OC ([Swarup, 1991](#)). Results

of a long term (12 y) study showed that sodic soils put under tree cover recorded marked improvements in OM content and enzymatic activities (urease and dehydrogenase) followed by those under grass cover. The least improvement was noted in gypsum ameliorated soils (Rao and Ghai, 1985). Zn deficiency can be overcome by dipping the roots of rice seedlings in 2% or 4% zinc oxide suspension in water (Sharma *et al.*, 1982) and by applying zinc-chelates such as Zn-DTPA and Zn-fulvate (Chand *et al.*, 1981). Regular use of sodic water, low in Ca^{2+} ($< 2 \text{ meq L}^{-1}$) and high in CO_3^{2-} , results in specific toxicity symptoms such as scorching and leaf burning in crop seedlings (Minhas and Bajwa, 2001). Under certain conditions, irrigation water may also contain toxic ions such as boron (B), fluoride (F) and nitrate (NO_3^-) posing additional risks to the soils and crops. Continued irrigation with B-saturated water is one of the main causes of B toxicity in soils which can be overcome by leaching with good quality water, use of amendments (*e.g.*, gypsum) and the cultivation of B tolerant crops (Nable *et al.*, 1997). About 62 million people in India are at high risk associated with excess F levels in groundwater; especially in the arid north-western regions. In areas having groundwater with residual alkalinity ($\text{Ca}^{2+} < \text{HCO}_3^-$), evapotranspiration leads to the precipitation of calcite which reduces Ca^{2+} activity and increases the $\text{Na}^+/\text{Ca}^{2+}$ ratio resulting in increased in F levels (Jacks *et al.*, 2005).

Sodic Soil Reclamation: Need and Rationale

Degraded lands remain underutilized for different reasons. For example, poor structure, Na^+ toxicity and waterlogging drastically lower the productivity of sodic soils. Over the years, constraints that could be managed through simple techniques have grown in complexity making it necessary to redesign the current approaches so that multiple stresses existing simultaneously can be effectively tackled. Available evidences suggest that appropriate technological interventions, either singly or in combination, will remain important to improve the quality and productivity of the degraded sodic soils. A number of chemical-based and plant-assisted techniques have been

standardized to give a new lease of life to such soils so that gains in crop productivity could lessen the pressure on prime lands. Concurrent improvements in soil and environmental quality are the intangible but highly important gains accruing from the sodic soil reclamation.

Chemical amendments

Maintenance of sufficient IR through tillage, amendment use and Na^+ leaching are the prerequisites to sustain crop production under sodic conditions. A wide range of chemicals, industrial by-products, composts, microbial inoculants and polymers have been used for improving the physico-chemical properties of sodic lands. Among several options, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is the most commonly used chemical to overcome the structural and nutritional limitations. Nonetheless, good quality agricultural-grade gypsum is becoming limited in supply. This has led to interest in other low cost and eco-friendly soil conditioners to sustain the reclamation programs (Sharma and Singh, 2015; Yunusa *et al.*, 2006).

Gypsum

Chemicals used to ameliorate sodic soils are categorized into three groups, *i.e.*, soluble calcium salts (*e.g.*, gypsum and calcium chloride), acids or acid forming substances (*e.g.* sulphuric acid, iron sulphate, sulphur and pyrite) and calcium salts of low solubility (*e.g.* ground limestone) (Abrol *et al.*, 1988). However, this categorization is only illustrative as a number of different amendments have been identified in the recent past and many new compounds are also being tested for their reclamation efficiency. Gypsum application enhances the availability of exchangeable Ca^{2+} to effectively remove the superfluous Na^+ from the SEC and thus arrests sodicity induced anomalies in soil physical conditions. Excess Na^+ is subsequently leached down by ponding the fresh water. Gypsum application, either alone or in combination with other amendments significantly improves the physical and chemical properties of the sodic soils (Table 2). Gypsum-based technology developed by the ICAR-CSSRI has become very popular among the farmers.

Table 2. Gypsum-use for improving the soil properties under sodic conditions.

Finding	Reference
Gypsum application in amounts equal to 50 % of gypsum requirement (GR) of soil is sufficient for the reclamation of sodic soils.	Singh <i>et al.</i> (1969)
Gypsum application (1.25 Mg ha ⁻¹) reduced yield loss in rice and wheat by 40% of their maximum potential yields in soils irrigated with high residual sodium carbonate (RSC= 10 me L ⁻¹) water in a semi-arid region.	Sharma <i>et al.</i> (2001)
Combined application of gypsum (5 Mg ha ⁻¹), FYM (10 Mg ha ⁻¹) and press mud (10 Mg ha ⁻¹) along with NPK fertilizers significantly decreased the soil pH and SAR and improved the rice and wheat yields over NPK treatment alone under continuous use of sodic irrigation water [RSC= 8.5 meq l ⁻¹ and SAR= 8.8 (m mol/l) ^{1/2}].	Yaduvanshi and Swarup (2005)
Trees species such as <i>Prosopis juliflora</i> , <i>Acacia nilotica</i> , <i>Casuarina equisetifolia</i> , <i>Terminalia arjuna</i> , <i>Pongamia pinnata</i> , <i>Eucalyptus tereticornis</i> and <i>Pithecellobium dulce</i> planted in auger-holes containing mixture of original soil, gypsum (4 kg), FYM (10 kg) and silt (20 kg), showed significantly higher growth and biomass production than trees raised in untreated sodic soils.	Singh <i>et al.</i> (2011)

Although exact rate of gypsum application varies with the factors such as original ESP level and the depth of reclamation, 10-15 Mg ha⁻¹ dose proves sufficient to reclaim the upper 15 cm soil in one hectare area for growing shallow rooted field crops such as rice and wheat. The impact of gypsum technology in India can be gauged by the fact that about 1.95 M ha sodicity-affected area has been reclaimed with the financial aid from World Bank and other organizations. Among different states, the maximum sodic area (0.80 M ha) has been ameliorated in Punjab followed by Uttar Pradesh (0.73 M ha) and Haryana (0.35 M ha) (Sharma *et al.*, 2016). It is desirable to incorporate gypsum to some depth as mixing confined to surface layers may give slow results. Gypsum (12.5 Mg ha⁻¹) incorporated in the surface soil lowered the pH, soluble salts and clay dispersion and increased OC and IR after five years. Yet, these effects were seen only in surface layers and slowly extended to the lower layers during the subsequent years. As a consequence, sub-soil sodicity remained too high for deep rooted crops (Chawla and Abrol, 1982).

Pyrite

Conjunctive use of pyrite (50% GR) and FYM (1%) decreased the soil pH and ESP, and increased rice and wheat yields in a highly sodic soil (pH= 10.6, ESP= 95%) under saline irrigation (EC_{IW}= 4 dS m⁻¹; Dubey and Mondal, 1993). Combined use of FYM and pyrite alleviated salt stress and improved the nutrient availability leading to high

grain and straw yields in wheat crop irrigated with high RSC water (Yadav and Chhipa, 2007). Application of pyrite (10 Mg ha⁻¹) significantly decreased the salt stress and enhanced IR and nutrient availability in pearl millet- wheat rotation irrigated with highly sodic (RSC= 10-20 me L⁻¹) water (Singh *et al.*, 2009).

Sulphur

A prerequisite to the successful application of sulphur and similar products such as pyrite in sodic soils is their complete oxidation for the best results. The high root zone pH in sodic soils, however, limits their oxidation and thus results in reduced amelioration efficiency. To be as efficient as soluble calcium salts, sulphur applied to the soil must be oxidized to produce adequate sulphuric acid to replace the exchangeable Na⁺. Due to these reasons, sulphur does not give optimum results compared to gypsum or sulphuric acid even when applied in chemically equivalent quantities (Abrol *et al.*, 1988).

Other chemical amendments

Besides high cost, very low solubility of gypsum in water (2.5 g l⁻¹) requires the use of large amounts of water to accelerate gypsum dissolution. As sodic soils are often impenetrable to water, Na⁺ leaching may also take considerable time. In many cases, calcium chloride (CaCl₂) may be easily available for use as an economical substitute for gypsum. Added advantage with CaCl₂ is that, in

contrast to gypsum and sulphur which are incorporated in soil prior to leaching, it may be directly mixed into irrigation water (Magdoff and Bresler, 1973). CaCl_2 is highly soluble in water and constitutes a direct source of soluble calcium. In sodic soils, it works in a manner similar to that of gypsum. It has been found that addition of CaCl_2 with gypsum considerably reduces the time required for reclamation (Abrol *et al.*, 1988).

Different acids and acid forming substances have also been evaluated as ameliorants for sodic soils. Sulphuric acid (H_2SO_4) and gypsum-like by-products were evaluated for their efficiency in reclaiming a calcareous sodic soil. Based on the prevention of crust formation, infiltration rate (IR) and reductions in salinity and ESP, H_2SO_4 was found the best ameliorant in comparison to lacto-gypsum, coal-gypsum and mined-gypsum. H_2SO_4 treated soils showed the highest IR (21 mm h^{-1}) compared to low IR (9-17 mm h^{-1}) with other amendments (Amezketta *et al.*, 2005). Use of H_2SO_4 gave results comparable to that of 25% GR in decreasing the SAR of a saline-sodic soil in rice-wheat-*Sesbania* cropping system (Zia *et al.*, 2007). Although it is an efficient amendment, use of H_2SO_4 has been hampered by the constraints in safe handling under field conditions (Abrol *et al.*, 1988).

Industrial by-products

Phosphogypsum

Phosphogypsum (PG) is an acidic by-product of wet-acid production of phosphoric acid from rock phosphate. Chemically hydrated CaSO_4 , it contains small amounts of essential nutrients, heavy metals and impurities. It is a good source of S and Ca for crops. Investigations have established the efficacy of PG as a substitute to mined gypsum and lime in overcoming sub-soil constraints such as acidity, Al toxicity, low nutrient availability and sodicity (Alcordero and Rechcigl, 1993). Application of powdered PG (5 Mg ha^{-1}) significantly enhanced IR from 0.9 mm h^{-1} in control to 8.3 mm h^{-1} in a sodic soil (ESP= 21) by preventing the crust formation (Agassi *et al.*, 1986). When applied to a saline-sodic soil (pH= 8.5, EC= 4.8 dS m^{-1}) leached with canal water (SAR= 4 and

EC= 2.16 dS m^{-1}), PG and CaCl_2 efficiently reduced the salt content. CaCl_2 removed 90 % of the total Na^+ and soluble salts whereas PG removed 79 and 60 %, respectively. Soil ESP decreased by about 90 % in both the cases. Owing to significantly low cost than CaCl_2 , PG was adjudged to be an efficient amendment for such soils (Gharaibeh *et al.*, 2014). Application of PG along with cultivation of Kallar grass (*Leptochloa fusca*) resulted in the greatest reduction in soil pH and ESP followed by PG when applied at 10 Mg ha^{-1} alone. Application of PG at 10 Mg ha^{-1} also led to higher yields of rice and wheat than other treatments (Nayak *et al.*, 2013).

Distillery spent wash

Distillery spent wash (DSW) is the residual liquid waste generated during alcohol production. Although safety standards are in place, sometimes inadvertent discharge of DSW into rivers and streams creates environmental problems. Experimental findings indicate the value of PME as a potential organic amendment for sodic soils. When used with other organic inputs such as FYM and crop residues, PME significantly improves OC and nutrient contents, and enhances the activity of beneficial soil enzymes. Application of 50% PME along with bio-amendments improved the soil properties and pearl millet growth in a sodic soil (Kaushik *et al.*, 2005). PME application increased the yield of wheat and rice crops grown in sequence. Soil OC and available K content of the soils also increased. Despite significant improvements in saturated HC, bulk density and volumetric water content, soil pH did not change while salinity increased indicating the possibility of salinity development in long run with higher levels of PME (Pathak *et al.*, 1999).

Fly ash

Fly ash (FA) is produced in large amounts as a by-product by coal- and lignite-based thermal power plants. In India, about 50% of the FA is used by the cement and concrete industries and new avenues are being explored for the use of remaining amounts (Chatterjee, 2011). In order to overcome the problems in safe disposal of this problematic waste, efforts have been made to

utilize it the reclamation of degraded soils. Conjunctive use of acidic FA and gypsum decreased SAR and improved nutrient availability, saturated HC and soil water retention in a sodic soil (pH= 9.07, EC= 3.87 dSm⁻¹, ESP= 26) leading to higher rice and wheat yields than control indicating the possibility of partial gypsum substitution (up to 40% of GR) with FA (Kumar and Singh, 2003). At 10 and 20 Mg ha⁻¹ doses, FA considerably lowered soil pH, soluble salts and Na⁺ saturation. Soil pH reduced from 10.0 to 8.3 and Na⁺ saturation decreased from 64.5% to 24.0% after reclamation. Appreciable increase in rice and wheat yields was seen in the ameliorated soils (Tiwari *et al.*, 1992). Although FA can improve soil fertility, texture and water-holding capacity, it may also raise the pH and salinity of the treated soils. In some cases, build-up of toxic metals is also seen (Carlson and Adriano, 1993).

Press mud

Press mud (PM), a by-product of sugar mills, is rich in several plant nutrients. Application of PM reduced irrigation induced increase in soil SAR compared with the untreated soil (EC_e= 6 dS m⁻¹, SAR= 20 (m mol L⁻¹)^{1/2}). Improvement in N, P and K contents and decrease in Na⁺ in maize shoots and roots explained the observed increases in plant growth and biomass production with incremental additions of PM (Muhammad and Khattak, 2009). Application of gypsum with PM significantly increased plant Zn uptake and rice yield in a saline-sodic soil (Chand *et al.*, 1980). Application of a mixture consisting of FYM, PM and humic acid decreased EC_e from 6.5 to 3.9 dS m⁻¹ in the experimental soil resulting in high nutrient uptake and profuse growth of sorghum plants (Sharif *et al.*, 2014).

Organic wastes and composts

Different organic amendments (*e.g.*, mulches and composts) improve the physico-chemical properties of SAS by enhancing the cation exchange capacity, water retention and nutrient availability to the plants (Hanay *et al.*, 2004). Although these amendments are a low cost alternative to the expensive chemicals (Lakhdar *et al.*, 2009), some of them such as MSWC may

sometimes cause unintended side effects in plants due to the presence of heavy metals necessitating laboratory analysis before actual field application to ensure that their sustained use would be safe for soil and plant health.

Mulching

Mulching with crop residues and organic materials increases OC, formation of water-stable aggregates and water retention. By reducing the impact of rain drops, mulching lessens the runoff induced soil erosion. Mulches also insulate the soil from scorching heat and act as strong barrier to the evaporative loss of water. These favourable effects together contribute to improve the root zone environment for higher plant productivity (Mulumba and Lal, 2008). Straw mulching in brackish water (salt content of 3-5 g l⁻¹) irrigated wheat-summer maize rotation soils significantly lowered salt accumulation compared to no-mulch treatments (Pang *et al.*, 2010). Continuous covering of saline-sodic soils with 10-15 cm thick layer of tephra mulch for 20 years virtually eliminated salt hazard as evident from drastic reductions in EC_{se} (=1.5 dS m⁻¹) and ESP (=9) compared to the extremely saline-sodic (EC_{se}= 43 dS m⁻¹, ESP= 44) un-mulched soils. Both of the soils were not irrigated during the experimental period. Reductions in salinity and sodicity in the mulched soils were ascribed to the favourable changes in soil moisture regime, improved water flux, reduced evaporation and the restricted upward movement of Na⁺ and other salts (Tejedor *et al.*, 2003).

Animal manures

Application of FYM and other animal manures such poultry manure (PM) significantly improves the physico-chemical properties of SAS. In a long-term experiment, FYM treated calcareous soils irrigated with high RSC water (= 10-12.5 mmol L⁻¹) showed increase in rice and wheat yields by 38 and 26%, respectively, over control. In comparison, 50% GR treatment caused only about 18% yield increase in both the crops. Further yield improvements did not occur with the combined use of gypsum and FYM suggesting that FYM alone is an effective solubilizing agent for

precipitated CaCO_3 in calcareous soils irrigated with sodic water (Choudhary *et al.*, 2011). FYM application (25 Mg ha^{-1}) decreased pH, EC and ESP and enhanced water IR and available water in a sodic soil (pH= 9.3). Supplemental use of gypsum further enhanced the reclamation efficiency of FYM (Makoi and Ndakidemi, 2007). Sheep manure, PM and gypsum were added to a sodic soil at a rate of 5%. NaCl-CaCl_2 solutions having different SAR (=10 and 40) and a constant ionic strength ($= 50 \text{ mmol l}^{-1}$) were used for leaching. Sheep and poultry manure enriched soils showed higher accumulation of cations such as Ca^{2+} , Mg^{2+} and K^+ and showed increased leaching of Na^+ leading to low ESP (Jalali and Ranjbar, 2009). An organic mixture consisting of PM, crop residues and saw dust improved the fertility, carbon content and biological activity in clayey sodic sub-soil (Clark *et al.*, 2007).

Municipal solid waste compost

Municipal solid waste compost (MSWC) incorporation in soil hastens the dissolution of precipitated CaCO_3 leading to increased soluble Ca^{2+} content and the consequent displacement the harmful Na^+ ions from the SEC. In some cases, conjunctive use of gypsum and MSWC in SAS may give crop yields comparable to those obtained in normal soils (Avnimelech *et al.*, 1992). Addition of MSWC, either alone or in combination with 50% recommended dose of fertilizers significantly enhanced the enzymatic activity (dehydrogenase, alkaline phosphatase and urease), improved microbial biomass carbon and nutrient availability in a saline-sodic soil ($\text{EC}_e = 7.2 \text{ dS m}^{-1}$ and pH= 8.4) over control. These improvements in soil conditions led to significant increase in grain and straw yields of mustard and pearl millet crops grown in rotation (Meena *et al.*, 2016). Application of MSWC (40 Mg ha^{-1}) reduced the severity of salt-stress in facultative halophyte *Hordeum maritimum*- an important fodder crop in the Mediterranean region- by enhancing chlorophyll and protein levels and Rubisco activity leading to higher carbon assimilation for biomass production (Lakhdar *et al.*, 2008). Sequential application of gypsum and MSWC improved the HC, OM and water stable aggregates and

decreased the salt content in a saline-sodic soil (pH= 9.65, $\text{EC} = 12.6 \text{ dS m}^{-1}$, $\text{ESP} = 44.22$). Although gypsum application appreciably decreased salinity and sodicity, it did not improve physical properties implying the synergistic action of MSWC with gypsum (Hanay *et al.*, 2004).

Polymers and nano-scale materials

Over the years, many polymer-based compounds and nano-enhanced materials have been tested and found effective in improving the degraded soils. They improve the aggregate stability and IR and thus decrease surface runoff and structural loss in sodic soils. Application of polyacrylamide (PAM) solution increased seedling emergence and seedling dry weight of tomato grown in a sodic soil (Wallace *et al.*, 1986). Addition of small amounts of PAM efficiently controlled runoff at low (~ 12) ESP levels (Levy *et al.*, 1995). PAM (10 ppm) improved water movement throughout the effective root zone that resulted in Na^+ leaching. Polymer application significantly decreased CaCO_3 concentrations in the top 45 cm layer indicating solubilization and redistribution of calcite. It also reduced soil EC_e and SAR (Ganjegunte *et al.*, 2011).

Microbial inoculants

A range of microorganisms have been tested for overcoming salt-stress in a cost-effective and environmental friendly way. Blue green algae lessen the sodicity stress by decreasing the soil pH, EC_e and ESP with concurrent improvements in water permeability, soil aggregation and nutrient availability; especially in moderately affected soils (Subhashini and Kaushik, 1981). Although effective in alleviating salt stress in crops, use of microbial inoculants is limited due to higher costs and lack of technical know-how. To circumvent these constraints, a low-cost microbial bio-formulation 'CSRBIO', based on a consortium of *Bacillus pumilus*, *Bacillus thuringiensis* and *Trichoderma harzianum* on dynamic media, has been developed. It acts as a soil conditioner and nutrient mobilize and significantly increases the productivity of rice, banana, vegetables and gladiolus in sodic soils (Damodaran *et al.*, 2013).

Drainage and land shaping interventions in waterlogged sodic soils

In waterlogged lands, watertable rise leads to the saturation of crop root zone resulting in restricted water and air flux. About 2.46 M ha land area in irrigated commands of the country suffers from waterlogging, either seasonally or permanently. Seasonal waterlogging may be caused by heavy rainfall, drainage congestion and floods. In case of permanent waterlogging, there is prolonged ponding of water over the land surface. Sub-surface waterlogging, where watertable lies within 2 m from the surface, also affects many soils, especially those in salt-affected regions. This condition often remains undetected for a long time and adversely affects soils and crops by creating anaerobic conditions, osmotic stress, salinity and nutrient toxicities (NRSA, 2014). Large tracts of waterlogged sodic soils are found in irrigated commands of Punjab and Uttar Pradesh states. In sodic soils of the IGP, temporary water inundation frequently occurs in the winter season and adversely affects wheat crop as nutrient availability is sharply reduced in an oxygen deficient environment ([Sharma and Swarup, 1988](#)).

South-western part of Punjab is severely affected by sodicity, salinity and the associated problem of waterlogging. In addition to conventional techniques such as biodrainage and conjunctive use of canal and sodic groundwater, a new technology called multiple well points system has been developed to ensure sustainable skimming of freshwater floating over brackish groundwater in aquifers of this region. A study revealed that about 41,000 such wells installed in Muktsar, Faridkot and Ferozepur districts have lowered the watertable by 1-7 m leading to 10-20% increase in crop yields. The cost of installation of a 4-well point system is about Rs 45000 per set ([Gupta and Singh, 2014](#)). A linear programming algorithm based inter-seasonal irrigation system planning model has been developed to maximize the farm incomes through the conjunctive use of fresh and gypsum-treated sodic water ([Panda *et al.*, 1996](#)). Secondary sodicity affected area has considerably increased in the Sarda-Sahayak Canal command area of

Uttar Pradesh. The problem is particularly severe in regions having poor drainage and predominance of natural salts. It has been shown that integrated drainage solutions involving land modification, interceptor drain and biodrainage could be immensely useful in rehabilitating such waterlogged lands ([Sharma *et al.*, 2007](#); [Dagar *et al.*, 2016](#)). Even waterlogged sodic soils (pH= 10.0) lying barren for decades can be put to productive use by simple land shaping interventions for creating fish pond and raised-and- sunken beds. In sunken beds, watertable lies at about 1.0 m depth which not only prevents salt movement through capillary rise but also promotes salt leaching. Rice, water chestnut, integrated rice-fish culture or fish culture alone are the attractive land use options for the sunken beds. Although a large number of crops can be grown on raised beds, vegetable crops and banana are recommended for higher economic returns ([Verma *et al.*, 2015](#)).

Irrigation scheduling and management

It is often seen that owing to infiltration and permeability problems there is least utilization of rain water in sodic soils necessitating frequent irrigations resulting in reduced irrigation efficiency. Sodic lands should be properly leveled before irrigation to create a uniform soil surface. If left unleveled, water application depth will be high leading to low water application efficiencies and water inundation due to poor infiltration. Crop yields (*e.g.*, wheat) may improve by about 1.5 fold in properly leveled fields ([Tyagi, 1984](#)). Irrigation management in sodic soils differs from the normal soils with regard to timing, depth and frequency of water application. It is especially true for crops like wheat which exhibit moderate salt tolerance but are susceptible to excessively wet soils. Irrigation at critical stages (crown root initiation, tillering and milk stage) led to significantly higher wheat grain yield in a sodic soil (pH= 9.2, ESP= 38) as compared to other treatments ([Sharma *et al.*, 1990](#)). In mustard, single irrigation at rosette stage one month after sowing ensured significantly higher relative growth rate, branching and seed and straw yields compared to one irrigation at pod formation stage and unirrigated plots in a partially reclaimed sodic soil

(pH= 8.8, ESP= 23; [Sharma and Singh, 1993](#)). There is a possibility of using sodic water (RSC up to meq L⁻¹) in rice crop with appropriate irrigation scheduling and higher N applications in a semi-arid climate having ≥ 500 annual rainfall ([Sharma and Sharma, 1999](#)). Sprinkler and LEWA (Low Energy Water Application) methods of irrigation not only gave 10-20% higher grain yield than farmers' practice (surface irrigation) but also saved 30-40% irrigation water indicating their role in water and energy saving in a sodic soil ([Singh et al., 2016](#)). Use of gypsum-beds can effectively reduce the sodicity hazard in areas where irrigation with sodic groundwater is common. Water flowing through gypsum-beds picks Ca²⁺ (3-5 meq L⁻¹) and is considerably less harmful than original Na⁺saturated water. Long-term studies have shown that decline in ESP is almost similar under both bed and soil application of gypsum. Nonetheless, rice crop responds favourably to the bed treatment. Bed application can also lower the costs incurred in grinding and applying gypsum to the soil and ponding of water for Na⁺ leaching ([Bajwa and Choudhary, 2014](#)).

Phytoremediation

Phytoremediation involves the use of plants to remove the contaminants from the soil and

environment. It is a low-cost and ecologically sustainable alternative to the costly chemical and engineering interventions that often also hamper the soil quality. Compared to the use of plant species capable of hyper-accumulating toxic ions in heavy metal contaminated soils, phytoremediation of calcareous sodic soils is mainly based on the ability of plant roots to increase the dissolution rate of calcite to maintain sufficient Ca²⁺ in soil solution to effectively replace Na⁺ from the SEC ([Qadir et al., 2007](#)). Root and microbial respiration enhance the availability CO₂ resulting in high partial pressure of CO₂ (PCO₂) for the accelerated dissolution of calcite. Elevated soil CO₂ dissolves in the water to produce H₂CO₃ which dissociates to release H⁺ and HCO₃⁻. Released H⁺ then reacts with soil CaCO₃ to produce Ca²⁺ for Na⁺ displacement from the SEC ([Qadir et al., 2006](#)). Phytoremediation is an attractive option to reclaim sodic soils as it involves negligible cost and less effort and gives desired results (*e.g.*, amelioration to greater soil depth, better aggregate stability, improved hydraulic properties and nutrient availability) with intangible gain in terms of carbon sequestration ([Qadir et al., 2007](#)). In India, several agroforestry and grass species have been successfully used to reclaim the sodic soils ([Dagar et al., 2014](#)).

Table 3. Agroforestry models for sodic soil reclamation.

Results	Reference
Gypsum treatment considerably enhanced growth and biomass production in mesquite than control (soil pH= 10.4, ESP= 90, no gypsum). Litter fall and profuse root growth during subsequent years significantly decreased soil pH and salts with improvements in OC and NPK availability.	Singh et al. (1989a)
Results of an 8y field trial in alkali soil indicated that growth and biomass production of mesquite was greater in sole stand than when interplanted with the Kallar grass, but soil improvement was greater in the mixed tree-grass treatment.	Singh (1995)
Microbial biomass carbon, OC, inorganic N and N mineralization rate were significantly higher under <i>Acacia</i> , <i>Eucalyptus</i> and <i>Populus</i> -based agri-silvicultural systems compared to both rice-barbeem sequence and single species plantations in a moderately sodic soil. Soil carbon increased by 11-52% in integrated tree-crop systems.	Kaur et al. (2000)
Thirty different forest species and 15 strains of <i>Prosopis</i> were evaluated in a highly alkali soil (pH ≥ 10). Only <i>Prosopis juliflora</i> , <i>Tamarix articulata</i> and <i>Acacia nilotica</i> were found to be promising under such conditions 7 y after planting. <i>Eucalyptus tereticornis</i> survived but produced very low biomass.	Dagar et al. (2001)
Significant decrease in soil pH, electrical conductivity, ESP and increase in OC and available NPK was recorded under <i>Prosopis juliflora</i> , <i>Acacia nilotica</i> and <i>Casuarina equisetifolia</i> plantations in a strongly sodic soil (pH ₂ = 8.8-10.5, ESP= 85-92).	Singh et al. (2011)

Agroforestry models

Tree-assisted reclamation of sodic soils has been found viable under Indian conditions (Table 3). The success of agroforestry in SAS largely depends on suitable agronomic management with factors such as method and depth of planting, planting distance, irrigation water availability and the economic nature of crop greatly influencing the extent of reclamation. [Singh *et al.* \(1988\)](#) found that establishment and growth in mesquite (*Prosopis juliflora*) were considerably higher when planted in auger-holes containing 3 kg gypsum and 8 kg FYM than those raised on trenches in a highly alkali soil (ESP= 94). Singh (1996) noted that air-dried shoot and root biomass of mesquite in a strongly alkali soil (pH= 10.3) were the maximum in auger holes of 90 cm depth compared to shallow depth (30 cm) in the trench and pit methods of planting. In trenches and pits, root growth was confined to the upper 60 cm surface while roots in the auger hole planted trees grew over 2.5 m deep piercing the hard CaCO_3 layer and bringing further improvements in soil properties. [Singh *et al.* \(1989b\)](#) observed that growth and biomass production in mesquite trees as well as green forage yield of Kallar grass (*Leptochloa fusca*) were significantly higher when trees were planted at 4 m x 4 m spacing and the side branches were looped in comparison to close space (2 m x 2 m) planting without looping. In arid and semi-arid regions, low water availability often hampers tree and crop establishments in sodic soils. This problem can partly be overcome by rainwater harvesting. However, under extremely arid conditions (mean annual rainfall ~300 mm) even rainwater collection may not give desirable results due to strong competition for water use between tree and grass roots and the adverse effects of sodicity on water movement and availability (Grewal and Abrol, 1986). Use of some potential species in sodic soil reclamation is constrained by their less remunerative nature. For example, [Singh *et al.*, \(1997\)](#) noted that *Acacia*-based system was more efficient in sodicity alleviation than those involving *Populus* and *Eucalyptus* but the benefit-cost ratio was the highest (2.88) in *Populus*-based system and the lowest (1.86) in *Acacia*-based system. Dagar (2014) has given extensive review of reclaiming salt-

affected soils through agroforestry practices.

Cropping with Kallar grass for two years in a degraded sodic soil (pH= 10.6, ESP= 95%) and *in situ* biomass decomposition gave results comparable to the gypsum treated soils ([Kumar *et al.*, 1994](#)). Sodic soils put under the same grass, either alone or in combination of gypsum, showed appreciable reductions in soil pH (from 10.6 to 9.45) and in ESP (95 to 47.5) after 3 years. Total OC and available nitrogen increased by about 64% and 38%, respectively, over the original soil ([Batra *et al.*, 1997](#)). Aromatic grasses such as palmarosa (*Cymbopogon martinii*) and lemon grass (*C. flexuosus*) can be successfully grown in moderately sodic soils (pH ~9.2) without any significant reduction in essential oil yield. These grasses not only produce essential oils used for industrial purposes but also gradually ameliorate the sodic soils ([Dagar *et al.*, 2004](#)).

Besides monetary benefits, tree and grass plantations on sodic lands also act as strong carbon sinks. Gupta *et al.* (2015) found that OC storage (up to 1 m soil depth) in a natural grassland ecosystem in sodic soils (pH= 8.0-10.2) was 24.7-16.7 Mg C ha⁻¹ over a period of 15 years. Integration of trees with grasses further improved carbon storage by 15-57 %. Wicke *et al.* (2013) evaluated the greenhouse gas balance and the economic performance of agroforestry systems in SAS of South Asia. They found carbon sequestration over the plantation lifetime of 24 Mg CO₂-eq. ha⁻¹ in a rice-*Eucalyptus camaldulensis* system on moderately saline soils in coastal Bangladesh, 6 Mg CO₂-eq. ha⁻¹ in the rice-wheat- *Eucalyptus tereticornis* system on saline-sodic soils in Haryana, India and 96 Mg CO₂-eq. ha⁻¹ in *Acacia nilotica* plantation on saline-sodic soils in Punjab province of Pakistan. Carbon sequestration translates into economic value by increasing the net present value of these plantations.

Salt tolerant cultivars in field crops

Salt tolerant cultivars (STCs) capable of growing in un-reclaimed or partially reclaimed soils represent a sustainable approach to obtain high productivity in SAS. This strategy assume seven greater importance in sodic areas still uncovered by the gypsum-based package and other

technologies. Again, they are an attractive option for the poor farmers lacking material resources to use the costly chemicals. STCs developed in different crops (Table 4) have been adopted in many parts of Punjab, Haryana, Uttar Pradesh and other states (ICAR-CSSRI, 2015). Many promising lines such as CSR 46 in rice, KRL 283 in wheat and CS 58 in Indian mustard, have been identified and are being evaluated for release. Several potential genetic stocks have also been developed for the use as parents in future selection and hybridization programs.

Table 4. Salt tolerant cultivars developed and released.

Crop	Cultivar
Rice	CSR 10, CSR 13, CSR 23, CSR 27, CSR 30, CSR 36 and CSR 43
Wheat	KRL 1-4, KRL 19, KRL 210 and KRL 213
Chickpea	Karnal Chana- 1
Indian Mustard	CS 52, CS 54 and CS 56
Dhaincha	CSD-123 and CSD 137

Over the last three decades, many investigations have been conducted to understand the mechanisms imparting salt tolerance in the STCs. Gupta and Sharma (1990) found that *Sesbania* followed by rice and wheat were the most tolerant to sodicity (high threshold ESP ≥ 15) among 20 crops tested. CSR 3 and Kharchia 65 were ranked as the most tolerant genotypes in rice and wheat crops, respectively. Ionic composition and water uptake were the major traits governing the salt tolerance. Tolerance to sodic conditions in rice (Sharma, 1986) and wheat (Sharma, 1991) seem to be due to maintenance of a low leaf Na^+/K^+ ratio. Surekha *et al.* (2013) found that such salt tolerant rice genotypes maintain higher leaf chlorophyll, starch and proline levels than semi-tolerant and sensitive genotypes to lessen the salt effects. Rao *et al.* (2002) screened salt-tolerant (CSG 8962), salt-sensitive (CSG 8890), high nodulation selection (CSG 9372) and two commonly grown chickpea cultivars (BG 256 and C 235) in sodic soils. They found that pH 8-9 was the critical upper limit except in CSG 9372 in which nodulation was least affected at pH 9.0-9.2 allowing higher rates of symbiotic N fixation than

sensitive genotypes. Sharma and Sinha (2012) noted that STCs of Indian mustard such as CS 52 and CS 54 give about 20% more seed yield and about 36% more oil yield under saline (up to EC_e 9 dS m^{-1}) and sodic (up to pH 9.3) conditions compared to other high yielding varieties such as Varuna and Kranti.

Despite the availability of a large number of STCs, their low adoption by the farmers has generated interest in farmer participatory varietal selections so that farmers' preferences- crucial to the large-scale adoption of a variety- are duly considered by the researchers. Singh *et al.* (2014) screened a rice collection in a farmer participatory mode which culminated with the identification of a high yielding, sodicity tolerant ($\text{pH}_2 = 9.9$) rice genotypes CSR-89IR-8. Subsequent to the large-scale adoption of CSR-89IR-8 in the target sodic areas of IGP, it was officially released as variety CSR 43 in 2011. Marker-assisted and genomics-based approaches are also being employed to accelerate the pace of genetic improvement for developing high yielding and multiple stress (*e.g.*, salt, drought and waterlogging) tolerant cultivars. Twenty two rice genotypes including 18 *SALTOL* QTL introgressed lines were evaluated under normal and sodic ($\text{pH} = 9.5$) conditions. *SALTOL* lines IR 84645-305-6-1-B, IR84649-275-3-2-B and IR84649-292-3-1-B performed significantly better in terms of seedling stage salt tolerance, grain yield and stress tolerance index compared to others (Ali *et al.*, 2013). Mapping of a recombinant inbred line population derived from CSR 27 (salt tolerant) and MI 48 (salt sensitive) cross revealed 8 significant QTL intervals on chromosomes 1, 8, and 12 for the salt ion concentrations and a QTL controlling salt stress susceptibility index for spikelet fertility co-located on chromosome 8 (Pandit *et al.*, 2010).

Salt tolerant fruit crops

Identification of fruit varieties capable of yielding under salt stress conditions is necessary to promote crop diversification in sodic environments. Litchi cv. Rose Scented performed well in partially reclaimed sodic soils ($\text{pH} = 8.5-9.0$) when planted in sand and FYM (20 kg each per pit) ameliorated pits. Drip irrigation (4 drippers plant⁻¹) further

improved plant growth by overcoming the physical constraints and low HC ([Saxena and Gupta, 2006](#)). Ten different fruit species were evaluated in a highly sodic (pH= 10.0). Auger-hole and pit methods of planting were tested using 5-20 kg of gypsum as amendment. In general, tree survival and growth rates were better with the pit method. Increasing amounts of gypsum had a positive but non-significant effect on tree growth. After 7 years, Indian jujube (*Ziziphus mauritiana*), jamun (*Syzygium cumini*), guava (*Psidium guajava*), aonla (*Emblica officinalis*) and karonda (*Carissa carandas*) were found to be suitable species for such soils. Prolonged water stagnation during two consecutive monsoon seasons caused heavy mortality in bael (*Aegle marmelos*), pomegranate (*Punicagranatum*) and sapota (*Achras zapota*) ([Dagar et al., 2001](#)). Tamarind (*Tamarindus indica*) can also be successfully grown in partially reclaimed SAS with added advantage of intercropping with low water requiring and remunerative crops such as lentil, gram, sorghum and berseem ([Dagar et al., 1995](#)).

Two salt tolerant polyembryonic mango (*Mangifera indica*) rootstocks (ML-2 and GPL-3) have been identified ([Kannan et al., 2014](#)). Experiments have also been started to identify high yielding and salt tolerant genotypes in bael (*Aegle marmelos*), Indian jujube, guava and pomegranate. Bael cv. Narendra Bael-5 and guava cv. Allahabad Safeda perform well under saline, shallow watertable (~ 2 m below surface) conditions (ICAR-CSSRI, 2015). Soil properties under four fruit trees (guava, litchi, mango, jamun), two agroforestry systems (*Eucalyptus tereticornis* and *Prosopis alba*) and RWCS system in a reclaimed sodic soil were studied. Although soil pH and bulk density increased with depth in all the land uses, the minimum pH (6.81) was recorded under litchi (*Litchi chinensis*) and the maximum (9.52) under *Eucalyptus* at 1.5-2.0 m depth. Overall highest SOC storage (133 Mg C ha⁻¹) as well as maximum passive pool C (76 Mg C ha⁻¹) was noted in the guava land use. Improvements in soil properties under fruit trees may be due to *in situ* decomposition of the litter and subsequent deposition in the root zone over the years ([Datta et al., 2015](#)).

Sustaining the productivity of reclaimed sodic soils

The foregoing account explains that it is possible to reclaim and manage even the highly deteriorated sodic lands through simple techniques. Yet, one or more constraints tend to limit the widespread use of some of these technologies. For example, although gypsum application is a feasible approach for overcoming the structural and nutritional constraints in sodic soils, decrease in the availability and quality of agricultural-grade gypsum has been reported ([Sharma et al., 2016](#)). In addition, resodification of the previously gypsum-amended sodic lands has also increased. Resodification implies the reappearance of sodic patches resulting in stunted crop growth and low yields in a sizeable area of the land. A study was conducted to assess the sustainability of sodic land reclamation in Etawah district of Uttar Pradesh using remote sensing and ground truth data. Results showed that out of the total (3,905 ha) reclaimed area, about 27% had relapsed showing the signs of deterioration after a period of improvement ([Yadav et al., 2010](#)). The probable causative factors behind resodification, *inter alia*, nearness to canal, hard pan in sub-soil, poor drainage and shallow watertable indicated that such reversion is mainly due to poor on-farm water management.

Other studies have also shown that imprudent irrigation and fertilizer management, excessive tillage and climate variability are taking a toll on soil quality and crop productivity in many reclaimed tracts of IGP. [Gathala et al. \(2014\)](#) found that relentless natural resource degradation and escalating production costs in RWCS of IGP can be overcome by the adoption of conservation agriculture practices. Based on a comparison of four cropping system scenarios including the farmers' practice, they concluded that resource conservation technologies such as reduced tillage, residue management, crop substitution and innovative crop establishment methods efficiently enhanced the system productivity and profitability. Zero-tillage direct-seeded rice with residue retention provided equivalent or higher yield with 30-50% saving in irrigation water use than farmer-

managed puddled transplanted rice. Replacement of rice with zero-tillage maize was equally profitable but with 88-95% less irrigation water use. Inclusion of mungbean in the rotation further increased system productivity and economic returns.

Challenges and Way Forward

The success of sodic soil reclamation depends on the adequate availability of Ca^{2+} rich amendments (e.g., gypsum) to remove the excess Na^+ ions from the soil exchange complex followed by leaching with fresh water. However, growing gypsum shortages are stalling the reclamation projects in many sodicity-affected regions. This state of affair has enhanced the interest in low-cost alternative amendments for lessening the pressure on limited gypsum reserves. Several alternative amendments have been found effective in partly or entirely substituting gypsum. Nonetheless, heavy metals present in some of these substitutes (such as fly ash and municipal solid waste compost) may sometimes cause unintended side effects in the soils and plants. Integrated use of easily available amendments in combination with salt tolerant varieties can be a more effective option than the use of a single chemical.

Fresh water allocation to the agricultural sector has also significantly decreased in the recent years. Added to this, excessive withdrawal has deteriorated water-quality in many salt-affected regions. Water woes may get worse due to adverse impacts of climate change. These observations point to the need to develop strategies for using marginal quality saline and sodic water in soil reclamation. Phytoremediation through salt-tolerant trees and grasses, which require low water compared to field crops and act as strong carbon sinks, is also an attractive option to curtail the amendment costs. However, as long gestation period and low economic returns have hindered the adoption of even potential trees and grasses there is a need to identify early-bearing and high yielding trees capable of enduring multiple stresses with little or no use of amendments. Salt tolerant cultivars available in different field and horticultural crops also give stable yields with reduced or no use of amendments; especially in

partially reclaimed sodic soils. Domestication of potential halophytes needs immediate attention at various levels including the improvement in germ plasm. Growing problem of resodification can be overcome by diversification with low water requiring crops and resource conservation technologies such as mulching and micro-irrigation. Farmers should be sensitized about the importance of land shaping techniques and irrigation scheduling to harness the potential of waterlogged sodic lands which otherwise remain barren. Many direct and indirect effects of climate change on precipitation patterns, higher atmospheric temperatures, increase in frequency of droughts, floods and storms, greenhouse gas emissions- would drastically limit agricultural productivity particularly in sodic soils under arid and semi-arid regions in the country. Research involving microbial component for developing multi-stress tolerant germplasm, making nutrients available to the crops and enrichment of nutrients both in soil and plants needs priority.

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