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Soil Salinity and Food Security in India

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India would require around 311 million tons of food grains (cereals and pulses) during 2030 to feed around 1.43 billion people, and the requirement expectedly would further increase to 350 million tons by 2050 when India's population would be around 1.8 billion. To achieve food security in the country, the attempts need to focus on both area expansion under agriculture as well as rise in crop productivity. Massive urbanization is putting pressure on agricultural lands, resulting in shrinking of land holdings. The possibility of area expansion under agriculture, therefore, exists in restoring the degraded lands. Nearly 147 million ha of land is subjected to soil degradation, including 94 million ha from water erosion, 23 million ha from salinity/alkalinity/acidification, 14 million ha from water-logging/flooding, 9 million ha from wind erosion and 7 million ha from a combination of factors due to different forces. Government of India has fixed a target of restoring 26 million ha of degraded lands, including salt-affected soils, by the year 2030 to ensure food security for the people. Around 6.74 million ha area in the country is salt-affected. Estimates suggest that every year nearly 10% additional area is getting salinized, and by 2050, around 50% of the arable land would be salt-affected. Saline soils occupy 44% area covering 12 states and one Union Territory, while sodic soils occupy 47% area in 11 states. The ICAR-Central Soil Salinity Research Institute and many State Agricultural Universities are engaged in studying salt-affected soils and developing reclamation technologies and strategies. Several innovative technologies have been developed and on-farm tested. Gypsum-based sodic soil reclamation, sub-surface drainage of water-logged saline lands, salt tolerant crop varieties and improved agroforestry techniques are some of the well-adapted technologies in the country. Reclamation of 2.18 million ha of salt-affected soils (2.07 million ha barren sodic soils and 0.11 million ha saline soils) has contributed more than 17 million tons of food grains per annum to the country's food basket, with additional annual income of Rs. 15.5 billion, and employment generation of 2.8 million man-days. Other technologies of management of salt-affected soils, viz. alternate land-use systems, saline aquaculture, cultivation of salt tolerant crop varieties, agro-forestry, phytoremediation, bioremediation etc. have positively impacted food and nutritional security, women empowerment, involvement of landless laborers and minimizing rural migration etc. The ongoing consistent research efforts for the management and reclamation of such soils would hopefully continue ensuring food security in the country. The Government needs to make policies favorable for implementation of reclamation technologies in the country.

Keywords: degraded lands, salinization, saline soils, sodic soils, reclamation technologies, food security

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INTRODUCTION

India supports nearly 18% of the world's human population and 15% of the world's livestock population on merely 2.4% of the world's geographical area (Bhattacharyya et al., 2015). Since independence, India has made significant achievement in agriculture sector. Food grain production increased by about 5.5 times, from merely 50 million tons in 1950 to 275 million tons in 2017, making India not only self-sufficient but net exporter of food grains. According to Tiwari (2020), with a record production of rice and wheat at 116.48 and 103.60 million tons, respectively, the country registered record food grain production of 285.17 million tons in 2018–19. While the increase in food grain production during 1949–65 was mostly due to area expansion under cultivation (Narain, 1977; Vaidyanathan, 1986), after mid-sixties, the adoption of a package of high yielding inputs, including use of high yielding varieties, assured irrigation, use of plant protection measures and credit support was responsible for increased production (Dantwala, 1986). It ushered *green revolution* in India.

In spite of the technological innovations in agriculture, which dramatically increased food production in the past few decades (Godfray et al., 2010), food security globally is being challenged by several factors including climate change (Parry et al., 1999; Rosenzweig et al., 2004; Godfray et al., 2010), unabated land and environmental degradation (Oldeman, 1998; Pimentel, 2006), deforestation, intensive cropping, and biodiversity loss (Foley et al., 2005; Lotze-Campen et al., 2008; Tscharntke et al., 2012), land use change (Lotze-Campen et al., 2008; Godfray et al., 2010), fresh water scarcity (Rijsberman, 2006; Lotze-Campen et al., 2008), increased population pressure, increased urbanization and huge food wastage (Parfitt et al., 2010), dietary transition (Rijsberman, 2006; Godfray et al., 2010), poverty and social inequality (Elobeid et al., 2000) etc. Sustainability of rice-wheat cropping system in the Indo-Gangetic plains of India has been challenged, as evidenced by the stagnating rice-wheat yields and declining factor productivity during the last about three decades, by the fast receding water table, climate variability, deteriorating soil health, environmental pollution, and secondary salinization (Aggarwal et al., 2004).

Population growth in India has also kept pace with food production. According to the 2017 revision of the World Population Prospects, India's population stands around 1.32 billion (UNDESA, 2017), although, with the Government policies and public awareness, India's population growth rate has shown decline from 2.3% in late 1970s and early 1980s to around 1.13% in 2017 (Halawar, 2019). Even at this growth rate, India is projected to be the world's most populous country by 2024. The massive population increase (despite the slowing down of the growth rate) and substantial income growth demand an extra about 2.5 million tons of food grains annually, besides significant increases in the supply of livestock, fish, and horticultural products. The growth in food grain productivity has stagnated around 2% per annum.

The changing lifestyle and food habits of the people, due to the sustained economic growth, literacy and awareness, are other challenges associated with food security in India. People in general are shifting from staple food grains toward high-value horticultural and animal products (Kumar et al., 2007; Mittal, 2007). Although it may lower per capita food grain requirement, yet overall demand for food grains would increase for increasing population and increasing food needs of livestock and poultry. The grain requirement for rearing cattle and poultry etc. is comparatively high because of low and variable efficiency with which various animals convert grains into protein. **Table 1** provides global average feed conversion efficiencies for different animal categories and production systems. To produce 1 kg of beef, pork, poultry, and herbivorous species of farmed fish (such as carp, tilapia, and catfish), it takes around 7, 4, 2, and < 2 kg of grains, respectively. Currently, livestock supply 13% of energy to the world's diet but consume one-half the world's production of grains to do so (Smith et al., 2013). India would require around 311 million tons of food grains (including pulses) during 2030, and the requirement would further increase to 350 million tons by 2050 (Kumar et al., 2016). At the current growth rate in agricultural production, food security in India appears to be a big challenge.

TABLE 1 | Global average feed conversion efficiency per animal category and production system.

Animal category	Feed conversion efficiency (kg dry mass feed/kg output)
Beef cattle	46.9
Sheep and goat	30.2
Pig	5.8
Broiler chicken	4.2
Layer chicken	3.1
Dairy cattle	1.9

Dry mass feed includes grains (fit for consumption by human beings), forage and other materials (not fit for human consumption).
Source: Mekonnen and Hoekstra (2010).

The projections of higher food requirements due to demographic, economic, and trade liberalization are exerting heavy pressures on India's limited land and water resources. It is estimated that nearly 174.4 million ha of land is potentially exposed to various degradation forces. Land degradation in some regions of India, especially in arid and semi-arid tracts (desertification), is touching irreversible limits. Land degradation has become a big challenge to policy makers who need to balance the multiple goals of poverty eradication, food security, and sustainable land management.

Soil salinization alone has rendered significant chunks of land unproductive or less productive. Soil salinization is a global and dynamic problem and is projected to increase in future under climate change scenarios, viz. rise in sea level and impact on coastal areas, rise in temperature and increase in evaporation etc. Precise statistics on the recent estimates of global extent of salt-affected soils are not available and different data sources provide variable information (Shahid et al., 2018). The global figure of 954.83 million ha as reported by Szabolcs (1989) has been considered authentic. However, figures such as 932.2 million ha (Sparks, 2003) and 952.2 million ha (Arora et al., 2016) have also been reported. According to Mandal et al. (2018), more recent estimates show an increasing trend in global salt-affected area with an area of 1,128 million ha. According to an estimate, 20% of total cultivated and 33% of irrigated agricultural lands worldwide are afflicted by high salinity (Shrivasata and Kumar, 2015). Around 52 million ha lands are salt-affected in South Asia (Mandal et al., 2018). Around 85% area worldwide is only slightly to moderately affected by high salt concentrations while the remainder 15% suffers from severe to extreme limitations for crop cultivation (Wicke et al., 2011). In India, the salt-affected soils constitute nearly 5% of the net cultivated area, spreading from Jammu & Kashmir (Ladakh region) in north to Kanyakumari in south, and Andaman & Nicobar Islands in the east to Gujarat in the west.

Soil salinization, in addition to reducing net cultivable area, has serious implications for agricultural productivity and quality, the choice of cultivable crops, biodiversity, water quality, supply of water for critical human needs and industry, the longevity of infrastructure and the livelihood security of the people. For all important crops, average yields in salt stressed environments are only a fraction, somewhere between 20 and 50% of record yields (Shrivasata and Kumar, 2015). Estimates suggest global economic losses due to soil salinization around US $ 27.3 billion per year (Qadir et al., 2014).

Growing trend in the salt-affected soils in India is becoming a threat to national food security and economic development. A paradigm shift is, therefore, needed in the policy and methodology of food production in the country. Food security attempts need to focus on both area expansions under agriculture as well as rise in crop productivity. Restoration of degraded lands, including salt-affected soils, offers a potential opportunity of sustaining food security in the country. With this thing in mind, the Government of India has fixed a target of restoring 26 million ha of degraded lands by the year 2030.

SOIL SALINITY AND SOIL SALINIZATION

Soil salinity is an index of the concentration of salts in soil and is usually expressed as electrical conductivity (EC). Soil salinization is a process by which there is build-up of salt concentration in soil to such a level that impacts on the agricultural production, environmental health, and economics and quality of life. Soil salinization involves a combination of processes like evaporation, salt precipitation and dissolution, salt transport, and ion exchange etc.

The salt-affected soils contain excessive concentrations of either soluble salts or exchangeable sodium or both due to inadequate leaching of base forming cations. The major soluble mineral salts are the cations: sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and the anions: chloride (Cl^-), sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and nitrate (NO_3^-). Hyper-saline soil water may also contain boron (B), selenium (Se), strontium (Sr), lithium (Li), silica (Si), rubidium (Rb), fluorine (F), molybdenum (Mo), manganese (Mn), barium (Ba), and aluminum (Al), some of which can be toxic to plants and animals (Tanji, 1990).

Soil salinization may occur through both natural and anthropogenic reasons. Out of 932.2 million ha salt-affected soils worldwide, the extent of human-induced salinization is 76.6 million ha (Oldeman et al., 1991; Mashali, 1995; Shahid et al., 2018). Arid and semi-arid regions, where evaporation rates are high and fresh waters are scanty to flush out the excess salts from soil, favor the formation of such soils. Gupta and Abrol (1990) have extensively reviewed processes of soil salinization.

a. ***Natural processes of soil salinization (i.e., primary salinization)***

- *Weathering of parent material*: During the process of weathering of rock minerals or sediments with high salt content (physically, chemically, and biologically), salts are released and made soluble. They are transported away from their source of origin through surface or groundwater streams. In arid regions, the concentration of salts gradually increases until they start precipitating in soil due to limited natural precipitation and leaching, high evaporation and transpiration rates. Low-lying areas with high groundwater table and locked topography favor salinization.
- *Fossil salts*: The fossil salt deposits (e.g., marine and lacustrine deposits) are also responsible for salinization in arid regions. Fossil salts can be dissolved under water storage or water transmission structures causing salinization (Bresler et al., 1982).
- *Salinization in coastal lands*: The ingression of sea-water along the coast increases salt contents in coastal areas (Rao et al., 2014). The salt-laden winds and rains (sea sprays) along sea coasts carry oceanic salts along with them in quantities sufficient to cause salinization in coastal areas. The sea sprays may contain salt content as high as 14.2 $\mu g\ m^{-3}$ (Prospero, 1979), and may show impact as deep as 80 km inland or even more. The coastal regions are also exposed to the risk of progressive salinization of land due to processes like storms, cyclones, tidal surges, flooding etc.
- *Transport of salts in rivers*: The salts brought down from the upstream by rivers to the plains and their deposition along with alluvial materials and weathering of rocks may also cause salinization.

b. ***Anthropogenic reasons of soil salinization (i.e., secondary salinization)***

- *Land clearing for cultivation*: Replacement of perennial vegetation with annual crops, may result into soil salinization due to saline seepage process. Change of land use from natural forest vegetation to annual food crops decreases evapotranspiration and increases leaching. The presence of impermeable/less permeable subsoil layers may intercept the percolating water passing through saline sediments resulting in lateral seepage, causing salinization in low lying areas (Doering and Sandoval, 1976).
- *Incorrect irrigation*: Indiscriminate use of brackish and saline irrigation water, poor drainage conditions, rising water tables etc., lead to secondary salinization of land and water resources (Rao et al., 2014). Even

irrigation with good quality water over a period of time in the absence of proper soil-water-crop management practices may cause salinization. Fall of civilizations like Mesopotamia, Nile Valley, Mohanzoadaro, and Indus Valley are glaring examples of imminent occurrence of salinity following irrigation (Dagar, 2005). Currently worldwide 310 million ha area is irrigated, out of which 20–33% area is estimated to be salt-affected (Glick et al., 2007; Jamil et al., 2011; Qadir et al., 2014; Shahid et al., 2018). Irrigation with sea water causes salinization in coastal areas.

- *Over extraction of groundwater*: It brings salts to soil surface where they get precipitated when water evaporates (Rao et al., 2014).
- *Canal water seepage*: It is a serious problem leading to rise in water table and salinity development along the banks of canals. Water-logging and soil salinization in the Indira Gandhi Nahar Priyojna (IGNP) area in India is a glaring example of this process. Around 50% of the command area of IGNP has experienced water-logging (Tewari et al., 1997).
- *Over-use of agro-chemicals*: Over-use of chemical fertilizers and soil amendments (lime and gypsum) may also lead to soil salinization.
- *Use of waste effluents:* Use of sewage sludge and/or untreated sewage effluent, dumping of industrial brine onto the soil etc. may also cause soil salinization. Of particular concern is the entry of heavy metals into soils.

At several occasions the socio-economic and political considerations become extremely important in accelerating soil salinization processes. Many times, such factors are beyond the control of individual farmers. Some of such examples, especially in developing countries, may be the ill-conceived or poorly implemented irrigation schemes, intensive vs. extensive irrigation, over-irrigation due to zero water pricing, small and scattered land holdings etc. It is, therefore, the responsibility of respective governments to take appropriate policy decisions and corrective measures in order to keep a check on soil salinization.

CHARACTERISTICS OF SALT-AFFECTED SOILS

The salt-affected soils are classified into three groups depending on the nature and concentration of salts present in them:

i. *Saline soils* (also called "white alkali" or "solonchak" soils): soils containing calcium, magnesium, and sodium as predominant exchangeable cations (Ca and Mg more than Na), and sulfate, chloride, and nitrate the predominant anions; sodium adsorption ratio (SAR) <13; exchangeable sodium percentage (ESP) <15 of total CEC; pH <8.5; EC of saturation extract >4 dS m^{-1}; white color due to white crust of salts on the surface; good permeability for water and air; salt problems in general; the salt concentration is enough to adversely affect the growth of most crop plants; mostly found in arid or semi-arid regions where less rainfall and high evaporation rates tend to concentrate the salts in soils; rarely found in humid regions.

ii. *Sodic soils* (also called "non-saline sodic soils" or "alkali soils," or "solonetz"): soils high in exchangeable sodium compared to calcium and magnesium; sodium carbonate and sodium bicarbonate are the predominant salts; SAR >13; ESP >15; pH = 8.5–10.0; EC of saturation extract < 4 dS m^{-1}; black color; poor permeability for water and air; soils formed due to exchange of Ca^{2+} and Mg^{2+} ions by Na^{+} ions; sodium problems.

iii. *Saline-sodic soils*: these soils are transitional between saline and sodic soils; SAR >13, ESP >15, pH >8.5; EC of saturation extract >4 dS m^{-1}; air and water permeability depends on the sodium content; soils formed due to combined processes of salinization and alkalization; problems with sodium and other salts; leaching converts these soils into sodic soils.

EXTENT OF SOIL SALINIZATION IN INDIA

Around 60% of the total geographical area of the country is cultivable (arable), of which nearly 80% (141 million ha) is under crops and about 6% (10 million ha) is under rangelands (Mythili and Goedecke, 2016). The remaining arable lands are not cultivated. Nearly 147 million ha of land is subjected to soil degradation, including 94 million ha from water erosion, 23 million ha from salinity/alkalinity/acidification, 14 million ha from water-logging/ flooding, 9 million ha from wind erosion and 7 million ha from a combination of factors (Bhattacharyya et al., 2015; Mythili and Goedecke, 2016).

Around 6.727 million ha area in India, which is around 2.1% of geographical area of the country, is salt-affected, of which 2.956 million ha is saline and the rest 3.771 million ha is sodic (Arora et al., 2016; Arora and Sharma, 2017). Around 2.347 million ha of the salt-affected soils occur in the Indo-Gangetic plains of the country, of which 0.56 million ha are saline and 1.787 million ha are sodic (Arora and Sharma, 2017). Nearly 75% of salt-affected soils in the country exist in the states of Gujarat (2.23 million ha), Uttar Pradesh (1.37 million ha), Maharashtra (0.61 million ha), West Bengal (0.44 million ha), and Rajasthan (0.38 million ha) (Mandal et al., 2018).

Salt affected soils in India are spread in four major agriculturally important ecological regions in 15 states across the country and Andaman & Nicobar Islands, and they are:

i. Semi-arid Indo-Gangetic alluvial tract of Punjab, Haryana, UP, Delhi, parts of Bihar and West Bengal
ii. Arid and semi-arid tracts of Gujarat, Rajasthan, Madhya Pradesh, and Maharashtra
iii. Peninsular regions of Maharashtra, Karnataka, Tamil Nadu, Andhra Pradesh, and Orissa
iv. Coastal-alluvial region of Andhra Pradesh, Orissa, Tamil Nadu, Kerala, Karnataka, Maharashtra, Gujarat, and Island of Andaman & Nicobar.

The salt-affected soils in India broadly fall in two categories: sodic soils and saline soils. At certain places, with mean annual rainfall

TABLE 2 | Extent of salt-affected soils in India ('000 ha).

Sr. No.	State	Saline soils	Sodic soils	Total
1.	Gujarat	1680.570	541.430	2222.000
2.	Uttar Pradesh	21.989	1346.971	1368.960
3.	Maharashtra	184.089	422.670	606.759
4.	West Bengal	441.272	0.000	441.272
5.	Rajasthan	195.571	179.371	374.942
6.	Tamil Nadu	13.231	354.784	368.015
7.	Andhra Pradesh	77.598	196.609	274.207
8.	Haryana	49.157	183.399	232.556
9.	Bihar	47.301	105.852	153.153
10.	Punjab	0.000	151.717	151.717
11.	Karnataka	1.893	148.136	150.029
12.	Orissa	147.138	0.000	147.138
13.	Madhya Pradesh	0.000	139.720	139.720
14.	Andaman & Nicobar Island	77.000	0.000	77.000
15.	Kerala	20.000	0.000	20.000
Total	2956.809	3770.659	6727.468	

Source: NRSA (National Remote Sensing Agency) Associates (1996) and Adapted from Arora and Sharma (2017).

TABLE 3 | State-wise share (%) of salt-affected soils in India.

State	Sodic soils	Saline soil	Coastal saline soils	Total
Gujarat	14.3	71.2	37.1	32.9
Uttar Pradesh	35.6	1.3	–	20.3
Maharashtra	11.2	10.4	0.6	9.0
West Bengal	–	–	35.4	6.5
Rajasthan	4.7	11.4	–	5.6
Tamil Nadu	9.4	–	1.1	5.5
Andhra Pradesh	5.2	–	6.2	4.1
Haryana	4.8	2.9	–	3.4
Bihar	2.8	2.8	–	2.3
Punjab	4.0	–	–	2.2
Karnataka	3.9	0.1	–	2.2
Orissa	–	–	11.8	2.2
Madhya Pradesh	3.7	–	–	2.1
Andaman & Nicobar Islands	–	–	6.2	1.1
Kerala	–	–	1.6	0.3
J & K	0.5	–	–	0.3
Total	100 (3.78)	100 (1.71)	100 (1.25)	100 (6.74)

Figures in parentheses indicate total area in million ha. Source: Adapted from Mandal et al. (2018).

around 550 mm, saline-sodic soils are also found in the form of narrow band separating saline and sodic soils (Arora and Sharma, 2017), but because their chemical properties and management are almost the same as the sodic soils, they are grouped with sodic soils category (Qadir et al., 2007). Majority of the sodic soils occur in Indo-Gangetic region of India. They originate primarily due to weathering of rocks and minerals containing high sodium minerals, irrigation with groundwater containing excessive quantities of carbonates and bicarbonates, rise in groundwater table due to introduction of canal irrigation and salt laden run-off from the adjoining areas and un-drained basins. The saline soils are widespread in the canal irrigated arid and semi-arid regions. **Table 2** shows the distribution of salt-affected soils in India.

Mandal et al. (2018) distinguished salt-affected soils into three categories (**Table 3**). According to these workers sodic, saline, and coastal saline soils are spread over 56, 25, and 19% area in the country (**Table 3**). Sodic soils are confined in the Indo-Gangetic plains, arid and semi-arid region of western and central India, and Peninsular region in the southern India. Largest area under saline soils (71.2%) occurs in the state of Uttar Pradesh. More than 72% of coastal saline soils occur in the states of Gujarat and West Bengal. Largest area under sodic soils (35.6%) occurs in the state of Gujarat.

Introduction of the canal irrigation projects without proper provision of drainage has led to wide spread salinity in the country. Substantial salt-affected area occurs in different canal commands viz., *Sharda Sahayak* in Uttar Pradesh; *Tungabhardra* in Karnataka; *Indira Gandhi Nahar Pariyojana* (IGNP), *Chambal and Tawa* in Rajasthan and Madhya Pradesh; and *Mahi* and *Ukai command area* in Gujarat (Mandal et al., 2010). Continuous seepage from the canals has resulted into rise in water tables and subsequent upward flux of salts to the surface, water-logging, formation of marshy lands, increased soil salinity, and decreased biodiversity. Two glaring examples include: (i) salinization of around 0.37 million ha area in Sharda Sahayak Canal Command region in Utter Pradesh within a span of three decades; (ii) salinization of around 0.18 million ha area in the Indira Gandhi Nahar Priyojana (IGNP) region in Rajasthan within few years of introduction of irrigation project (Singh, 2009).

Use of brackish irrigation waters has caused secondary salinization in about 17% of irrigated lands in the country (Shahid et al., 2018). Good quality irrigation water is scarce in the country. Increasing pressure of producing more food per unit available arable land forces for extensive use of brackish groundwater for irrigation. Ground water surveys indicate that poor quality waters being utilized in different states are 32–84% of the total groundwater development (Minhas, 1999). Many more areas with good quality aquifers are endangered with contamination as a consequence of excessive withdrawals of groundwater.

The salinized areas in India continue to increase each year due to introduction of irrigation in new areas (Patel et al., 2011). The rate of increase is around 10% annually (Jamil et al., 2011). According to Sharma et al. (2014a), unless preventive/ameliorative attempts are taken, the salt-affected areas are estimated to treble, i.e., increase from 6.74 to 16.2 million ha by 2050.

Delineation and digitization process of salt-affected soils in India is on. Fifteen salt- affected states have been mapped on 1:250,000 scale and digitization on 1:50,000 scale is in progress. The planning and execution of soil reclamation programmes by the policymakers and stakeholders are based on the state-wise data and maps of saline and sodic soils (Mandal et al., 2010). The first approximation of water quality map of India has been published (Sharma et al., 2014a), adding great value in executing the plans effectively.

ECOLOGICAL, AGRICULTURAL, AND SOCIAL CONCERNS OF SOIL SALINIZATION

The soil salinization has tremendous environmental, ecological, agricultural, and social impacts in terms of shrinkage of agricultural lands, low agricultural productivity, uncertain and unstable livelihood security, low economic returns, and poor quality of life. Excess salts in soil affect the metabolism of soil flora and fauna, leading ultimately to the destruction of all soil life, transforming fertile and productive lands into barren and desert lands. Soils are rendered useless agriculturally as well as for several other purposes (e.g., construction work). The salt accumulation damages existing infrastructure, farm machinery, waterways, roads etc. History records that soil salinization was partly responsible for the collapse of ancient civilizations like Mesopotamia, Nile Valley, Mohanzoadaro, and Indus Valley (Dagar, 2005).

Salinity affects almost all aspects of plant development including germination, vegetative growth, and reproductive development due to drought and high soil salinity, and harsh environmental conditions (Machado and Serralheiro, 2017). Plants in salt-affected environments experience two types of stress, the osmotic stress and nutrient stress. The osmotic stress is due to low osmotic potential of water in saline soils which adversely affects water absorption by plants. Nutrient stress is due to both toxicity (Na, Cl, B) and deficiency of plant nutrients (N, Ca, K, P, Fe, Zn). It also results in nutritional imbalances. Soil salinity significantly reduces phosphorus uptake by plants because phosphate ions precipitate with Ca ions (Bano and Fatima, 2009). The enhanced Na^+ absorption in sodic soils reduces K^+ absorption which adversely affects the enzymatic activities involved in metabolic processes like photosynthesis and protein synthesis (Hauser and Horie, 2010), which is detrimental for plant growth (Katiyar-Agarwal et al., 2005). Reduced leaf area, chlorophyll content and stomatal conductance in salt-affected soils also affect photosynthesis (Netondo et al., 2004).

Apart from high ESP and nutrient deficiencies and toxicities, other constraints for plant growth in sodic soils include poor soil physical conditions, viz. low water and air permeability, high runoff, low water holding capacity, surface crusting, and hard setting. They affect plant root penetration, seedling emergence, and tillage operations (Murtaza et al., 2006).

Although salinization has strong implications on socio-economic aspects, yet very few publications are available in literature (Shahid et al., 2018). Social consequences of soil salinization include decline in agricultural harvest, low income, change of livelihood options and related social constraints. The estimates show that the global annual cost of salt-induced land degradation in irrigated areas could be US$ 27.3 billion in terms of lost crop production (Qadir et al., 2014). Annual global income loss due to salinization of irrigated lands has been estimated around US$ 12 billion (Ghassemi et al., 1995). The inflation-adjusted cost of salt-induced land degradation in 2013 was estimated at US $ 441 per ha, with global economic losses pegged at US $ 27.3 billion per year (Qadir et al., 2014).

The estimates based on 2012–14 moving average data suggest that due to soil salinization India loses annually 16.84 million tons of farm production (cereals, oilseeds, pulses, and cash crops) valued at Rs. 230.20 billion (Mandal et al., 2018). It has strong implications on the national economy. The state of Uttar Pradesh topped the list with 7.69 million tons production loss, followed by Gujarat state with 4.83 million tons production loss. In terms of monetary loss, Gujarat topped the list with Rs. 100.63 billion loss, followed by Uttar Pradesh with Rs. 81.29 billion loss. Gujarat and Uttar Pradesh have the largest salt-affected area (>50% of cultivated area) in the country. These two states alone share around 79% monetary losses in the country. All these states deserve policy attention for management of salt-affected areas to reduce the crop production and monetary loss.

Peoples' living standard, daily life activities and socio-economic conditions are adversely affected. Farmers in response to salinity problem are forced to shift their livelihood strategies (Ziaul Haider and Zaber Hossain, 2013). Farmers in salt-affected areas are generally resource constrained and require financial and technical assistance to sustain their livelihood efforts (Oo et al., 2013).

Such degraded ecosystems, nevertheless, offer immense opportunities to harness the productivity potential through appropriate technological interventions. Even marginal to modest gains in crop yields in such soils would mean dramatic improvements in the lives of thousands of poor farmers in salinity affected regions in a country facing many challenges in agriculture.

TECHNOLOGICAL INTERVENTIONS

After decades of experiments globally including ICAR-CSSRI, Karnal and several SAUs in India, understanding the problems of salt-affected soils, poor-quality irrigation waters, water dynamics, causes of salt accumulation and behavior of plants under salt stresses, recommendations have emerged as technologies for reclamation and management of salt-affected soils, viz. gypsum technology for reclamation of sodic soils, developing salt tolerant crop varieties, guidelines for use of poor quality waters, rehabilitation of salty lands using forestry species, etc. (Mandal et al., 2018). There may be two approaches to tackle problem of soil salinity. One, to reclaim salt-affected soils; two, to manage salt-affected soils as they exist, i.e., without reclamation, using alternate suitable agricultural options such as cultivation of salt tolerant crops, saline aquaculture etc. The choice depends on the feasibility of reclamation and the cost effectiveness.

Not all salt-affected soils can be reclaimed practically and economically. While it is feasible to reclaim alkali and sodic soils by specific amendments and manage thereafter, the coastal salt-affected soils and black soils cannot be fully reclaimed. They require continuous soil and water management practices for their productive uses. Indian Council of Agricultural Research (ICAR)-Central Soil Salinity Research Institute (CSSRI) was established in India in 1969 to work exclusively on salt-affected soils. In addition, several State Agricultural Universities, especially those located in salt-affected regions, are also engaged in soil salinity research. Their efforts have resulted in the development of several technological interventions for the reclamation and management of salt-affected soils and use of poor quality water for irrigation in different agro-ecological zones of the country (Sharma et al., 2011). The popularity of gypsum-based sodic soil reclamation, sub-surface drainage of water-logged saline lands, salt tolerant crop varieties and improved agroforestry techniques are a few laudable testimonies to the research credentials of these research Institutes.

Reclamation and Management of Saline Soils

Salt leaching with ponded fresh water, sub-surface drainage, mulching between two irrigations and during fallow period, irrigation management are some of the effective and well-known technological intervention to tackle the problems of water-logging and soil salinity (Smedema and Ochs, 1998; Gupta, 2002; Arora and Sharma, 2017). The sub-surface drainage technology has been successfully adopted in Haryana, Rajasthan, Gujarat, Punjab, Andhra Pradesh, Maharashtra, Madhya Pradesh, and Karnataka, restoring around 110,000 ha waterlogged saline soils (Sharma et al., 2014a).

The adoption of sub-surface drainage technology in saline soils resulted in 3-fold increase in farmers' income. The yields of paddy, wheat and cotton increased by about 45, 111, and 215%, respectively (Sharma et al., 2014a). Besides, it significantly increased cropping intensity and socio-economic benefits in terms of on-farm employment generation (Singh, 2009). The sub-surface drainage technology was able to generate around 128 man-days additional employment per ha per annum (Sharma et al., 2011).

The cost of installation of sub-surface drainage system per hectare was estimated Rs. 74,000 for medium to coarse-textured soils with 67 m spacing and Rs. 1,15,000 for fine-textured black soils with 30 m spacing, with a benefit/cost ratio of around 2.71 (Raju et al., 2016). The reclaimed area contributed about 0.56 million tons of foodgrains and an income generation of Rs. 8.60 million annually (Raju et al., 2016, 2017).

The technology is useful but constrained by bottlenecks like higher initial costs, operational difficulties, lack of community participation and the problems of safe disposal of drainage effluents, for the rapid adoption of this technology (Singh, 2009). Successful implementation of sub-surface drainage projects demands a collective approach and responsibility duly supported by appropriate institutional arrangements (Ritzema et al., 2008). In majority of the salinity affected regions, however, the community participation appears lacking as evidenced by the non-existent or non-functional water-user organizations for irrigation as well as drainage projects. It slows down the up-scaling of reclamation technologies in salt-affected areas.

Reclamation and Management of Sodic Soils

The technology package based on chemical amendments consists of the components such as land leveling, bunding, flushing, drainage for removal of excess water, good quality irrigation water, application of amendments, selection of crops and efficient nutrient management. Different chemical amendments used for the reclamation of sodic soils may be grouped into two categories: soluble calcium sources (e.g., gypsum, calcium chloride, and phospho-gypsum) and acids or acid formers (e.g., elemental sulfur, sulphuric acid, sulfates of iron and aluminum, pyrites and lime sulfur). Farmyard manure and pressmud are also used as amendments for reclaiming sodic soils. Chemical amendments require moisture (rainfall or irrigation) to activate the chemical processes that can reduce sodium levels or leach salts from the root zone. The organic amendments, on the other hand, are capable of alleviating problems associated with excessive salts or sodium without supplemental irrigation.

The amount and type of chemical amendments required for reclamation of sodic soils depend primarily on soil pH, EC, and ESP. Soluble calcium sources are recommended for use in non-calcareous soils while for calcareous soils acids or acid-formers are recommended. Gypsum followed by pyrites has emerged as the most preferred and acceptable chemical amendment for sodic soils in India due to their easy availability and low cost (Abrol et al., 1988; Tyagi and Minhas, 1998). Pyrite was much less effective than gypsum (Tyagi, 1998). The pyrites to be effective for reclamation must contain at least 5–6% soluble S (Sharma and Swarup, 1990).

Gypsum requirement for restoring an alkali soil depends on the initial exchangeable sodium percentage (ESP), texture and mineralogy of soil, depth of soil to be reclaimed and tolerance of crops to sodicity. A good correlation exists between soil pH and gypsum requirement (Abrol et al., 1973). Generally, 10–15 Mg ha^{-1} gypsum is required for the reclamation of alkali soils (Abrol and Bhumbla, 1971).

The addition of organic materials in conjunction with gypsum hastens the reclamation process and also reduces the gypsum requirement (Chorum and Rengasamy, 1997; Vance et al., 1998; Arora and Sharma, 2017). Addition of organic material increases soil microbial biomass while gypsum lowers soil pH (Wong et al., 2009). Industrial byproducts such as phosphogypsum, pressmud, molasses, acid wash, and effluents from milk plants help in the reclamation of sodic soils by providing Ca directly or indirectly by dissolving soil lime (Arora and Sharma, 2017). However, care should be taken that toxic elements like F, which is present in large quantities in products like phosphogypsum, are not added to soil (Chhabra et al., 1980). The equivalent amounts of other amendments relative to gypsum are given in **Table 4**.

The gypsum-based alkali land reclamation technology has found large scale on-farm adoption in the country. Nearly 2.07 million ha of barren sodic soils have been brought under

TABLE 4 | Equivalent quantities of some common amendments for sodic soil reclamation.

Amendment	Relative quantity
Gypsum ($CaSO_4$ $2H_2O$)	1.00
Calcium chloride ($CaCl_2.2H_2O$)	0.85
Sulphuric acid (H_2SO_4)	0.57
Iron sulfate ($FeSO_4.7H_2O$)	1.62
Aluminum sulfate [$Al_2(SO_4)_3.18H_2O$]	1.29
Sulfur (S*)	0.19
Pyrite (FeS_2^*) (30% S)	0.63
Pressmud (Lime sulfur, 9% Ca, 24% S)	0.77

**Based on assumption of 100% oxidation of materials like sulfur or pyrite in order to be as effective as soluble calcium compounds. Since in practice this assumption is not fulfilled, their effectiveness is much lower than gypsum.*
Source: Choudhary and Kharche (2015).

cultivation, contributing 16-17 million tons of paddy and wheat per annum to the country's food basket. Farmers are harvesting 5 t ha^{-1} of rice and 3 t ha^{-1} of wheat from third year onwards in such reclaimed lands (Mandal et al., 2018). Besides, it also provides an employment opportunity to about 2.8 million man days annually. Financial viability for investment on gypsum technology has been found positive with benefit/cost ratio of 2.47 (Tripathi, 2011). Sharma et al. (2011) calculated the economics for reclamation of sodic soils by considering 10% discount rate. The reclamation cost was estimated to be around Rs. 56,000/ha, with B:C of 1.52, internal rate of return 21.4% and payback period of 3 years.

Reclamation and Management of Coastal Saline Soils

A number of technologies have been standardized and perfected to restore coastal saline soils and sustain crop production in them. *Rabi* cropping in mono-cropped coastal saline soils, salt tolerant rice cultivars, rainwater harvesting in dugout farm ponds, integrated rice-fish culture and efficient nutrient management have been successfully practiced (Sharma and Chaudhari, 2012). An innovative "*Doruvu*" technology has become popular in coastal regions of the country. The technology involves skimming of shallow depth fresh water floating on the saline water and storing in dug-out conical pits, locally called "*Doruvus*."

Multi-storeyed integrated agroforestry systems involving fish or shrimp culture, poultry, plantation crops, cattle, and diversified arable crops etc. seem to have potential in these areas. Khan et al. (2014) reported an average yield advantage of 20–30% over the existing rice yield of 2.9–3.3 t ha^{-1} by using biocompost @ 2–6 t ha^{-1} in sodic soils of Uttar Pradesh.

Initial cost on land excavation for constructing farm ponds, paddy-cum-fish culture and raised-sunken beds in coastal salt-affected areas was around Rs. 145, 136, and 88 thousand, respectively, with benefit/cost ratio of 1.20–1.58 (Mandal et al., 2018). Such techniques in coastal areas of West Bengal increased cropping intensity from 114 to 186% which resulted in increase in farmers' income from Rs. 5,644 ha^{-1} (wet rice) to Rs. 1,43,982 ha^{-1} (wet rice-fish-vegetables) (Mandal et al., 2017). Similar encouraging results were obtained through land modification technology (pond based and raised and sunken bed) under sodic soils in Uttar Pradesh (Verma et al., 2012).

Phytoremediation of Salt-Affected Soils

Phytoremediation of salt-affected soils refers to the processes of removing excess salts from soil by growing different type of plants. Growing of salt tolerant trees, shrubs, and grasses is a cost-effective and environmental-friendly way of restoring salt-affected soils (Mishra et al., 2003; Qadir et al., 2007). Different species of salt tolerant trees, shrubs, and grasses have been identified and put to use (**Table 5**). Excellent reviews are available in literature on phytoremediation, e.g., Dagar (2014) for inland salt-affected lands, Dagar et al. (2014a) for coastal regions and Dagar and Minhas (2016) for use of poor-quality waters, etc.

Plants remove excess salts from soil through root absorption and accumulate them in their biomass, a process called *phyto-accumulation or phyto-extraction*. It decreases exchangeable sodium and soluble salt concentrations in soil. They also augment soil organic carbon and nutrient content thereby gradually improving physical (bulk density, porosity, infiltration, water holding capacity etc.), chemical (nutrient concentrations), and biological (microbial population) properties of soils and overall soil productivity (Bhojvaid and Timmer, 1998; Kaur et al., 2000; Mishra et al., 2003; Nosetto et al., 2007; Qadir et al., 2007). Tree plantation, besides making degraded lands productive, provides fuel wood, and forage and helps in moderating climate change impacts through carbon sequestration (Dagar, 2005; Sharma et al., 2011). It has been estimated that reforestation of 75 million ha degraded lands with suitable trees and grasses/crops has the potential to sequester carbon in above-ground as well as below-ground C biomass to the tune of about 4 Pg of carbon (Dagar and Swarup, 2003).

Reclamation of sodic and saline waterlogged soils through afforestation and agroforestry practices is well established and documented (Dagar, 2005; Dagar et al., 2014b; Dagar and Minhas, 2016). Some of the promising species for sodic soil reclamation include *Prosopis juliflora*, *Acacia nilotica*, *Casuarina equisetifolia*, *Tamarix articulate, Eucalyptus tereticornis,* and *Leptochloa fusca* (Singh et al., 1994; Dagar et al., 2016), and for waterlogged saline soils include *Prosopis juliflora*, *Tamarix articulata*, *Casuarina glauca*, *Acacia farnesiana*, *Acacia nilotica*, *Acacia tortilis*, and *Parkinsonia aculeata* (Dagar and Tomar, 2002). Plant species like *Eucalyptus tereticornis*, *Populus deltoids,* and *Tectona grandis* are effective for reclaiming sodic soils (Singh et al., 1994).

Dagar et al. (2001a) used raised-sunken bed technology to successfully establish trees like pomegranate (fruit tree) and *Salvadora persica* (a non-edible oil yielding tree) on sodic soils. These trees were grown on raised beds to avoid damage due to water stagnation. In highly sodic soils of semiarid regions, having kankar pan in upper 2-m soil layer, Dagar et al. (2001b) used auger hole planting technique for successfully planting the forest tree species like *Tamarix articulata, Prosopis juliflora,* and *Acacia nilotica.*

TABLE 5 | Soil ECe and SAR reduction through phytoremediation and chemical amendments using different plants ($_i$ initial, $_f$ final).

Amendment/plant species	ECe_i (dS m^{-1})	ECe_f (dS m^{-1})	ECe reduction (%)	SAR_i	SAR_f	SAR reduction (%)	Remarks
Sesbania aculeata	7.5	5.5	27	55.6	43.5	22	1st year
Leptochloa fusca	7.4	5.3	28	57.9	44.7	23	
Sorghum bicolor	7.8	6.4	18	62.3	55.1	12	
Gypsum	9.0	7.2	20	73.0	53.3	27	
Sesbania aculeate	5.5	4.4	20	43.5	30.1	31	2nd year
Leptochloa fusca	5.3	4.9	8	44.7	32.5	27	
Sorghum bicolor	6.4	6.0	6	55.1	40.0	27	
Gypsum	7.2	6.8	6	53.3	24.7	54	

Source: Qadir et al. (1997).

Many grass species suited for sodic soils have been identified but all of them could not find field application due to the reason that they absorb and accumulate sodium and other toxic elements in their foliage and, thus, are unfit as fodder. Efforts are on to identify and popularize those grass species which can retain high proportion of sodium in their root system, rendering the shoots palatable for cattle. However, Biswas and Biswas (2014) have advocated that most of the field crops are less tolerant than grasses to alkali environment. Para grass (*Brachiaria mutica*), rhodes grass (*Chloris gayana*), matricaria (*Matricaria recutila*), Karnal grass (*Leptochloa fusca*) have been found the most promising grass spp. suitable for alkali soils. *Aeluropus lagopoides, Chloris barbata, Echinocloa colonum, Dicanthium annulatum, Sporobolus helvolus, Phragmites* spp., and *Sida* spp. have been identified the other promising grasses for rehabilitation of saline soil. Large tracts of salt-affected community and government lands lying barren have been restored and put to best productive use through adoption of agroforestry techniques and agronomic practices.

Promising agro-forestry models, fruit-based agro-forestry models, silvi-pastoral models etc. along with appropriate planting and management techniques have been developed specifically for saline/sodic/saline-sodic etc. conditions (Singh et al., 1994; Dagar et al., 2008, 2015; Sharma et al., 2014b). Under saline irrigation conditions medicinal and aromatic plants such as isabgol (*Plantago ovata*), aloe (*Aloe barbadensis*), kalmeg (*Andrographis paniculata*), *Matricaria chamomilla*, *Vetiveria zizanioides*, *Cymbopogon martini,* and *Cymbopogon flexuosus* have been found to produce high biomass (Tomar et al., 2003a,b; Dagar et al., 2004, 2006; Tomar and Minhas, 2004).

Salt-affected Vertisols (i.e., black cotton soils) are difficult and tedious to restore compared to alluvial sandy loam soils of Indo-Gangetic Plains. The high clay content of these soils makes them vulnerable even at low salt and exchangeable sodium concentrations. Major chunk (about 1.21 million ha) of salt-affected black cotton soils (Vertisols) is found in Gujarat. Such soils also occur in appreciable extent in Karnataka, Maharashtra, and Rajasthan. Commercial cultivation of salt tolerant plants like *Salvadora persica* (a halophyte, non-edible oil tree), dill (*Anethum graveolens*) a spice crop, industrial species like Euphorbia and Mulethi (*Glycyrrhiza glabra*), castor and sunflower has been found useful in reclaiming these soils and have largely been practiced by the farmers (Rao et al., 2000, 2003; Sharma and Chaudhari, 2012; Arora et al., 2013).

Large stretches of canal irrigated lands in many arid and semi-arid regions have become unproductive due to water-logging and the subsequent secondary salinization. Water seepage from canals and faulty on-farm water management practices together create shallow water table conditions. Higher capillary salinization in such areas has caused significant increase in root zone salinity (Chhabra and Thakur, 1998). The conventional approaches to reclaim such lands are expensive, difficult to operate and pose problems in the safe disposal of saline drainage effluents and so have necessitated interest in other viable alternatives such as bio-drainage (Chhabra and Thakur, 1998; Ram et al., 2011). Analogous to energy-operated water pumps, bio-drainage is a proven technology to arrest salinity build-up in canal commands with growing of suitable tree species (e.g. eucalyptus, poplar, and bamboo) (Singh, 2009). Efforts are on in exploring combined applications of bio-drainage and suitable land modifications to effectively utilize the water-logged salt-affected soils (Sharma et al., 2011).

Bio-Remediation

The bio-remediation approach, which involves plant-microbial interaction, has received increased attention worldwide for enhancing productivity of salt-affected soils (Arora et al., 2014). The microorganisms have the capability of rapid adjustment toward environmental changes and deterioration, and thus can play an important role in the maintenance and sustainability of any ecosystem. Microorganisms possess some unique properties such as salt stress tolerance, genetic diversity, synthesis of compatible solutes, production of plant growth promoting hormones, bio-control potential, and their interaction with crop plants. If these traits are suitably exploited, microorganisms can play a significant role in alleviating salt effects on crop plants (Shrivasata and Kumar, 2015).

Microorganisms present in the rhizosphere could promote plant growth and yield in salt stress environment in different ways, directly and indirectly (Dimkpa et al., 2009). For example, some plant growth-promoting rhizobacteria may directly stimulate plant growth and development by providing plants with fixed nitrogen, phytohormones, iron (sequestered by bacterial siderophores), and soluble phosphate (Hayat et al., 2010), while others may indirectly benefit plants by protecting them against soil-borne diseases, mostly caused by pathogenic fungi (Lutgtenberg and Kamilova, 2009) by inducing cell wall structural modifications, biochemical and physiological changes leading to synthesis of proteins and chemicals involved in plant defense mechanisms (Arora and Sharma, 2017).

Halophilic bacteria have the potential to remove sodium ions from soil and increase metabolic and enzymatic activities in plants. Arora et al. (2016) used halophilic bacteria for the remediation of saline and sodic soils. In a field experiment, bio-inoculation of wheat seeds with halophilic bacteria increased grain and straw yield of wheat in a sodic soil by 18.1 and 24.2%, respectively. The bacterial inoculation improved soil properties by decreasing soil pH from 9.4 to 8.6, increasing microbial biomass C from 82 to 137 µg/g. Similarly, in a pot experiment irrigated with saline water (5% NaCl), inoculation of halophilic bacterial consortium increased fresh weight, dry weight, shoot length, and root length of maize plants by 194.5, 98.97%, 15.37 and 7.4 cm, respectively, compared to the uninoculated control plants. Arora et al. (2014) could enhance wheat yield by 10–12% in salt-affected soil (EC = 156 dS/m) by using phosphatic solublizing bacteria and *Rhizobium* strains.

A low-cost microbial bio-formulation "CSR-BIO," a consortium of *Bacillus pumilus*, *Bacillus thuringenesis,* and *Trichoderma harzianum,* is rapidly becoming popular with the farmers in many states (Damodaran et al., 2013). This bio-formulation acts as a soil conditioner and nutrient mobilizer and has been found to increase the productivity of the high value crops such as banana, vegetables, and gladiolus in sodic and normal soils by 22–43%.

CULTIVATION OF SALT TOLERANT CROPS AND CROP VARIETIES

Cultivation of salt tolerant crops and crop varieties is another way to address the problem of soil salinization. This technique is viable and cost effective and suits well to the small and marginal farmers who without financial support are unable to bear the high costs of chemical amendment-based reclamation technologies. Salt tolerant varieties of rice, wheat, mustard, and other crops, grasses, shrubs, fruit trees, and medicinal and aromatic plants have been developed/identified for commercial cultivation in salt-affected soils (Singh, 2009; Sharma et al., 2011). The relative tolerance of some crops to total salinity (EC) and sodicity (ESP) is shown in **Tables 6**, **7**, respectively.

Use of salt tolerant varieties of field crops is another practical option to manage salt-affected soils with the poor farmers, especially small and marginal, for whom chemical amendment technologies are not feasible without Government subsidies (Arora and Sharma, 2017). Several varieties of important field crops like rice, wheat and mustard, having potential to yield reasonable economic returns in saline and sodic soils, have been developed (Singh and Sharma, 2006).

Cultivation of salt tolerant multipurpose trees, bushes, and grasses, fruit plants, medicinal and aromatic plants etc. on salt-affected village community lands, road-side lands, lands along the railway tracks, Government lands etc. is another opportunity of managing salt-affected soils (Singh et al., 1994; Minhas et al., 1997; Tomar et al., 2003b).

Tissue culture techniques find usefulness in developing suitable salt-tolerant trees and crops of high economic value.

TABLE 6 | Relative tolerance of some crops to salinity (EC).

Field crops	Threshold salinity (dS m^{-1})	Vegetable crops	Threshold salinity (dS m^{-1})	Fruit crops	Threshold salinity (dS m^{-1})
Barley	8.0	Sugarbeet	7.0	Citrus	1.7
Cotton	7.7	Peas	3.4	Strawberry	1.0
Sorghum	6.8	Tomato	2.5		
Wheat	6.0	Cucumber	2.5		
Soybean	5.0	Spinach	2.0		
Sunflower	4.8	Cabbage	1.8		
Groundnut	3.2	Potato	1.7		
Rice	3.0	Cauliflower	1.5		
Maize	1.7	Broccoli	1.3		
Sugarcane	1.7	Raddish	1.2		
		Onion	1.2		
		Carrot	1.0		

Adapted from Grieve et al. (2012).

TABLE 7 | Relative tolerance of some crops to soil sodicity (ESP).

Tolerant (ESP = 35–50)	Moderately tolerant (ESP = 35–50)	Sensitive (ESP <15)
Karnal grass *(Leptochloa fusca)*	Wheat *(Triticum aestivum)*	Gram/Chickpea *(Cicer arietinum)*
Rhodes grass *(Chloris gayana)*	Barley *(Hordeum vulgare)*	Mash *(Phaseolus mungo)*
Para grass *(Brachaaria mutica)*	Oat *(Avena sative)*	Lentil *(Lens esculenta)*
Bermuda grass *(Cynodon dactylon)*	Shaftal *(Trifolium resupinatum)*	Soybean *(Glycin max)*
Rice *(Oryza sativa)*	Lucern *(Medicago sativa)*	Groundnut *(Arachis hypogea)*
Dhaincha *(Sesbania aculeate)*	Turnip *(Brassica rapa)*	Sesamum *(Sesamum oriental)*
Sugarbeet *(Beta vulgaris)*	Sunflower *(Helianthus annus)*	Mung *(Phaseolus aureus)*
Teosinte *(Euchlaena maxicana)*	Safflower *(Carthamus tinctorius)*	Pea *(Pisum sativum)*
	Berseem *(Trifolium alexandrinum)*	Cowpea *(Vigna unguiculata)*
	Linseed *(linum usitatissimum)*	Maize *(Zea mays)*
	Onion *(Allium cepa)*	Cotton *(Gossypium hirsutum)*
	Garlic *(Allium sativum)*	
	Pearl millet *(Pennisetum typhoides)*	

Source: Abrol and Bhumbla (1979).

It may be noted, however, that crop production on salt-affected soils is generally costlier and crop yields are usually low, net returns are low and the risk of crop failures continues even after suitable amendments are provided (Minhas and Sharma, 2003).

Saline Aquaculture

Inland saline aquaculture (land-based aquaculture using saline groundwater) is being commercially practiced in many saline tracts of Australia, Israel, and USA (Allan et al., 2009). This knowledge was used in India also to make the saline water-flooded soils profitable. The experience in many parts of south-western Haryana and Punjab have shown that the degraded soil and water resources could be put to profitable use by shrimp and fish farming (Purushothaman et al., 2014). At Nain Experimental Farm, Panipat, Haryana (India), under conditions of high salinity of pond water (25 dS m^{-1}), low water availability and high evaporation losses, fish growth of about 400–600 g in 6-month and 600–800 g in 1-year period was observed (CSSRI, 2013).

In coastal areas of Andhra Pradesh, many farmers have converted their rice fields into brackish water fish farms for reason of high remuneration from aquaculture. They store brackish water, drawn from the sea through creeks and drains, in big tanks for raising high value prawns. Estimates suggest that nearly 0.2 million ha is under saline aquaculture in the coastal districts of Andhra Pradesh. Many small and marginal farmers (>50%), however, found this technology (prawn farming) highly risky with unstable returns, and hence abandoned after few years (Singh, 2009).

Multi-Enterprise Agriculture Models

Integrated multi-enterprise models comprising different components, viz. field and horticultural crops, fishery, cattle, poultry, and beekeeping etc. are being developed and tested to address the specific needs of small and marginal farmers especially in post reclamation phase. The models have been standardized for specific conditions such as saline soils of Haryana, water-logged sodic soils of Uttar Pradesh, highly saline black soils of Gujarat and coastal saline soils of West Bengal (Singh, 2009; Sharma and Chaudhari, 2012). The aim is to sustain resource use efficiency, high and regular income and employment generation to the farmers. The models drastically reduce the production costs by synergistic recycling of resources among different components.

A multi-enterprise model developed and evaluated by ICAR-CSSRI Karnal for reclaimed sodic land generates net annual income of Rs. 2.65 lakh (Chinchmalatpure et al., 2015). The model on daily basis generates a gross income of Rs. 400–700 and net income of Rs. 250–500 from about 1.0 ha land area when fisheries, dairy, horticulture, poultry, duckery, and mushroom cultivation are integrated and by-products of these enterprises are recycled within the system. Biogas produced (2 m^3 per day) in the Model adequately meets the energy requirements of farmer's family.

RECLAMATION OF SALT-AFFECTED SOILS AND FOOD SECURITY IN INDIA

It is estimated that due to soil salinization India loses around Rs. 230.20 billion annually in terms of crop production loss to the tune of 16.84 million tons (Mandal et al., 2018). The Indian Government, therefore, has attached highest priority to the policy planning for the reclamation of degraded lands, including salt-affected soils in the country. The Indian Government is keen to restore 26 million ha of degraded lands by the year 2030 in order to ensure food security in the country. Significant research efforts have been made during the last 4 decades with encouraging results. The response of the farming community in salt-affected regions is overwhelming.

Sharma and Chaudhari (2012) reported reclamation of 1.5 million ha of salt-affected soils in the country, with addition of around 15 million tons of food grains to the national food basket annually. It provided additional income of around Rs. 13.5 billion per annum, and also generated 8.33 million man-days per year in terms of on-farm and off-farm rural employment opportunities. According to a recent publication of Mandal et al. (2018), around 2.18 million ha salt-affected soils (0.11 million ha saline soils and 2.07 million ha sodic soils) have been reclaimed in India. The reclamation has been achieved through gypsum technology in saline soils and sub-surface drainage technology in sodic soils. It has contributed an estimated 17.16 million tons of food-grains per annum (16.6 million tons from saline soils and 0.56 million tons from sodic soils) to the national food basket, with additional income of as high as Rs. 15.5 billion annually (Mandal et al., 2018).

The technological interventions on other aspects of salt-affected soils such as alternate land-use systems, saline aquaculture, cultivation of salt tolerant crop varieties, agroforestry, phytoremediation, bioremediation etc. have proved their worth by positively influencing food and nutritional security, women empowerment, involvement of landless laborers and minimizing rural migration, besides restoration of the ecological balance by its positive impact on environment (Sharma and Chaudhari, 2012).

CONCLUSION

Soil salinization is a serious problem challenging food security in India. It is a dynamic process caused by several natural and human-induced processes, and quite often, the socio-economic and political considerations become extremely important in accelerating the processes of soil salinization. Many times, such factors are beyond the control of individual farmers and call for the attention of the policy makers. It becomes the responsibility of respective governments to take appropriate policy decisions and corrective measures in order to keep a check on soil salinization and also to restore the soils already affected by salts.

Several on-farm tested technologies are available for the reclamation and management of salt-affected soils. The efforts put-in by Government agencies and farmers for the reclamation and rehabilitation of salt-affected soils in the country so far have been encouraging. Nevertheless, in order to achieve the target of reclamation of 26 million ha of salt-affected soils, concerted efforts are needed by all the stakeholders. The site-specific restoration programmes be conceived and implemented in mission mode with the genuine participation of the local farmers. The farmers need to be incentivized rather than subsidized to undertake corrective measures. Under the scenario where the cultivable lands are shrinking due to increased urbanization, the restoration and management of salt-affected soils offer a potential hope of land expansion and production enhancement for future food security in the country.

AUTHOR CONTRIBUTIONS

PK contributed in conception and first draft preparation. PKS reviewed, analyzed, and provided interpretation. All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

REFERENCES

Abrol, I. P., and Bhumbla, D. R. (1971). *Saline and Alkali Soils in India: Their Occurrence and Management*. FAO World Soil Research Report. 41, FAO, Rome.

Abrol, I. P., and Bhumbla, D. R. (1979). Crop responses to differential gypsum applications in highly sodic soil and the tolerance of several crops to exchangeable sodium under field conditions. *Soil Sci.* 127, 79–85. doi: 10.1097/00010694-197902000-00004

Abrol, I. P., Dargan, S. K., and Bhumbla, D. R. (1973). *Reclaiming Alkali Soils.* Bulletin No. 2. Central Soil Salinity Research Institute, Karnal, 58.

Abrol, I. P., Yadav, Y. S., and Massoud, F. I. (1988). *Salt-Affected Soils and Their Management,* Soils Bulletin. No. 39. FAO, Rome, 131.

Aggarwal, P. K., Joshi, P. K., Ingram, J. S. I., and Gupta, R. K. (2004). Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formulation. *Environ. Sci. Policy* 7, 487–498. doi: 10.1016/j.envsci.2004.07.006

Allan, G. L., Fielder, D. S., Fitzsimmons, K. M., Applebaum, S. L., and Raizada, S. (2009). Inland saline aquaculture. *New Technol. Aquac.* 6, 1119–1147. doi: 10.1533/9781845696474.6.1119

Arora, S., Bhuva, C., Slanki, R. B., and Rao, G. G. (2013). Halophytes for bio-saline agro-forestry and phytoremediation of coastal saline lands. *J. Soil Water Conserv.*12, 252–259.

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

Arora, S., Singh, Y. P., Vanza, M., and Sahni, D. (2016). Bioremediation of saline and sodic soils through halophilic bacteria to enhance agricultural production. *J. Soil Water Conserv.* 15, 302–305. doi: 10.5958/2455-7145.2016.00027.8

Arora, S., Vanza, M., Mehta, R., Bhuva, C., and Patel, P. (2014). Halophilic microbes for bio-remediation of salt-affected soils. *African J. Microbio. Res.* 8, 3070–3078. doi: 10.5897/AJMR2014.6960

Bano, A., and Fatima, M. (2009). Salt tolerance in Zea mays (L.) following inoculation with Rhizobium and Pseudomonas. *Biol. Ferti. Soils.* 45, 405–413. doi: 10.1007/s00374-008-0344-9

Bhattacharyya, R., Ghosh, B. N., Mishra, P. K., Mandal, B., Rao, C. S., Sarkar, D., et al. (2015). Soil degradation in India: Challenges and potential solutions. *Sustainability* 7, 3528–3570. doi: 10.3390/su7043528

Bhojvaid, P. P., and Timmer, V. R. (1998). Soil dynamics in an age sequence of *Prosopis juliflora* planted for sodic soil restoration in India. *Fores. Eco. Manage.*106, 181–193. doi: 10.1016/S0378-1127(97)00310-1

Biswas, A., and Biswas, A. (2014). Comprehensive approaches in rehabilitating salt affected soils: a review on Indian perspective. *Open Trans. Geosci.* 1, 13–24. doi: 10.15764/GEOS.2014.01003

Bresler, E., McNeal, B. L., and Carter, D. L. (1982). *Saline and Soidic Soils: Principles-Dyanamics-Modeling*. New York, NY: Springer-Verlag, Berlin Heidelberg, 227.

Chhabra, R., Abrol, I. P., Dargan, K. S., and Gaul, B. L. (1980). Save on phosphatic fertiliozers in the initial years of alkali soils reclamation. *Indian Farm.* 30, 13–15.

Chhabra, R., and Thakur, N. P. (1998). Lysimeter study on the use of biodrainage to control waterlogging and secondary salinization in (canal) irrigated arid/semi-arid environment. *Irri. Drain. Sys.* 12, 265–288. doi: 10.1023/A:1006104428674

Chinchmalatpure, A. R., Ali, S., Kulshrestha, N., Singh, R. K., Bundela, D. S., Kumar, P., et al. (2015). *Intellectual Property Management and Commercialization of ICAR-CSSRI Technologies for Management of Salt-Affected and Waterlogged Soils of India*. Karnal: ICAR-Central Soil Salinity Research Institute, 62.

Chorum, M., and Rengasamy, P. (1997). Carbonate chemistry, pH and physical properties of alkaline sodic soil as affected by various amendments. *Aust. J. Soil Res.* 35, 149–161. doi: 10.1071/S96034

Choudhary, O. P., and Kharche, V. K. (2015). "Soil salinity and sodicity," in *Soil Science: An Introduction* (New Delhi: Indian Society of Soil Science), 353–384. Available online at: http://www.isss-india.org/index.aspx

CSSRI (2013). *Annual Report, 2013–14.* Central Soil Salinity Research Institute, Karnal.

Dagar, J. C. (2005). Salinity research in India: an overview. *Bull. Nat. Inst. Eco.* 15, 69–80.

Dagar, J. C. (2014). "Greening salty and waterlogged lands through agroforestry systems for livelihood security and better environment," in *Agroforestry System in India: Livelihood Security & Ecosystem Services, Advances in agroforestry*, Vol 10, eds J. C. Dagar, A. K. Singh, and A. Arunachalam (New Delhi: Springer), 273–332.

Dagar, J. C., Khajanchi, L., Jeet, R., Mukesh, K., Chaudhary, S. K., Yadav, R. K., et al. (2016). Eucalyptus geometry in agroforestry on waterlogged saline soils influences plant and soil traits in North-West India. *Agric. Ecosyst. Environ.* 233, 33–42. doi: 10.1016/j.agee.2016.08.025

Dagar, J. C., and Minhas, P. S. (2016). Agroforestry for the management of waterlogged saline soils and poor-quality waters. *Adv. Agron.* 13:210. doi: 10.1007/978-81-322-2659-8

Dagar, J. C., Pandey, C. B., and Chaturvedi, C. S. (2014a). "Agroforestry: a way forward for sustaining fragile coastal and island agro-ecosystems," in *Agroforestry System in India: Livelihood Security & Ecosystem Services, Vol. 10.* eds J. C. Dagar, A. K. Singh, and A. Arunachalam (New Delhi: Springer), 185–232.

Dagar, J. C., Sharma, H. B., and Shukla, Y. K. (2001a). Raised and sunken bed technique for agroforestry on alkali soils of northwest India. *Land Degrad. Dev.* 12, 107–118. doi: 10.1002/ldr.442

Dagar, J. C., Singh, A. K., and Arunachalam, A. (2014b). Agroforestry system in India: livelihood security & ecosystem services. *Adv. Agron.* 10:400. doi: 10.1007/978-81-322-1662-9

Dagar, J. C., Singh, G., and Singh, N. T. (2001b). Evaluation of forest and fruit trees used for rehabilitation of semiarid alkali-sodic soils in India. *Arid Land Res. Manag.* 15, 115–133. doi: 10.1080/15324980151062742

Dagar, J. C., and Swarup, A. (2003). "Potential of afforestation and agroforestry in carbon sequestration for mitigating climate changes," in *Agroforestry: Potentials and Opportunities,* eds P. S. Pathak and R. Newaj (Jhansi: Agrobios (India) and Indian Society of Agroforestry), 43–63.

Dagar, J. C., and Tomar, O. S. (2002). "Utilization of salt-affected soils & poor quality waters for sustainable biosaline agriculture in arid and semiarid regions of India," in *Proceedings of the ISCO Conference* (Beijing).

Dagar, J. C., Tomar, O. S., and Kumar, Y. (2006). Cultivation of medicinal isabgol (*Plantago ovate*) in different alkali soils in semi-arid regions of northern India. *Land Degrad. Dev.* 17, 275–283. doi: 10.1002/ldr.700

Dagar, J. C., Tomar, O. S., Kumar, Y., and Yadav, R. K. (2004). Growing three aromatic grasses in different alkali soils in semi-arid regions of northern India. *Land Degrad. Dev.* 15, 143–151. doi: 10.1002/ldr.598

Dagar, J. C., Tomar, O. S., Minhas, P. S., and Singh, G. (2008). *Dryland Biosaline Agriculture- Hisar Experience.* Technical Bulletin No. 6/2008. Central Soil Salinity Research Institute, Karnal, 28.

Dagar, J. C., Yadav, R. K., Tomar, O. S., Minhas, P. S., Yadav, G., and Lal, K. (2015). Fruit-based agroforestry systems for saline water-irrigated semi-arid hyperthermic camborthids soils of north-west India. *Agroforest. Syst.* 90, 1123–1132. doi: 10.1007/s10457-015-9889-4

Damodaran, T., Rai, R. B., Jha, S. K., Sharma, D. K., Mishra, V. K., Dhama, K., et al. (2013). Impact of social factors in adopon of CSRBIO- A cost effective, eco-friendly bio-growth enhancer for sustainable crop production. *South Asian J. Exper. Bio.* 3, 158–165.

Dantwala, M. L. (1986). Strategy of agricultural development since independence, in *Indian Agricultural Development Since Independence,* eds M. L. Dantwala et al. (New Delhi: Oxford and lBH Publishing Co. Pvt. Ltd), l—15.

Dimkpa, C., Weinand, T., and Ash, F. (2009). Plant-rhizobacteria interactions alleviate abiotic stress conditions. *Plant Cell Environ.* 32, 1682–1694. doi: 10.1111/j.1365-3040.2009.02028.x

Doering, E. J., and Sandoval, F. M. (1976). Hydrology of saline seeps in the Northern Great *Plains. Trans. ASEA*. 19, 856–861. doi: 10.13031/2013.36134

Elobeid, A., Jensen, H. H., and Smith, L. C. (2000). The geography and causes of food insecurity in developing countries. *Agri. Econ.* 22, 199–215. doi: 10.1111/j.1574-0862.2000.tb00018.x

Foley, J. A., Defries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., et al. (2005). Global consequences of land use. *Science* 309, 570–574. doi: 10.1126/science.1111772

Ghassemi, F., Jakeman, A. J., and Nix, H. A. (1995). *Salinisation of Land and Water Resources: Human Causes, Extent, Management and Case Studies*. Wallingford: CABI Publishing.

Glick, B. R., Cheng, Z., Czarny, J., and Duan, J. (2007). Promotion of plant growth by ACC deaminase-producing soil bacteria. *Eur. J. Plant Pathol.* 119, 329–339. doi: 10.1007/s10658-007-9162-4

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., et al. (2010). Food security: the challenge of feeding 9 billion people. *Science* 327, 812–818. doi: 10.1126/science.1185383

Grieve, C. M., Grattan, S. R., and Maas, E. V. (2012). "Plant Salt Tolerance," in *ASCE Manual and Reports on Engineering Practice No. 71 Agricultural Salinity Assessment and Management, 2nd Edn*. eds W. W. Wallender and K. K. Tanji (Reston, VA: ASCE), 405–459.

Gupta, R. K., and Abrol, I. P. (1990). "Salt-affected soils: their reclamation and management for crop production," in *Advances in Soil Science, Vol. 11*. eds R. Lal and B. A. Stewart (New York, NY: Springer), 223–288. doi: 10.1007/978-1-4612-3322-0_7

Gupta, S. K. (2002). A century of subsurface drainage research in India. *Irri. Drain. Sys.* 16, 69–84. doi: 10.1023/A:1015525405522

Halawar, S. V. (2019). The trend analysis of major food grains in India. *Int. J. Curr. Microbio. Appl. Sci.* 8, 353–360. doi: 10.20546/ijcmas.2019.803.044

Hauser, F., and Horie, T. (2010). A conserved primary salt tolerance mechanism mediated by HKT transporters: a mechanism for sodium exclusion and maintenance of high K^+/Na^+ ratio in leaves during salinity stress. *Plant Cell Enviroin.* 33, 552–565. doi: 10.1111/j.1365-3040.2009.02056.x

Hayat, R., Ali, S., Amara, U., Khalid, R., and Ahmed, I. (2010). Soil beneficial bacteria and their role in plant growth promotion: a review. *Ann. Microbiol.* 60, 579–598. doi: 10.1007/s13213-010-0117-1

Jamil, A., Riaz, S., Ashraf, M., and Foolad, M. R. (2011). Gene expression profiling of plants under salt stress. *Crit. Rev. Plant Sci.* 30, 435–458. doi: 10.1080/07352689.2011.605739

Katiyar-Agarwal, S., Verslues, P., and Zhu, J. K. (2005). "Plant nutrition for food security, human health and environmental protection," in *Mechanisms of Salt Tolerance in Plants,* eds C. J. Li et al., (Beijing: Tsinghua University Press) 44–45.

Kaur, B., Gupta, S. R., and Singh, G. (2000). Soil carbon, microbial activity and nitrogen availability in agroforestry systems on moderately alkaline soils in northern India. *Appl. Soil Ecol.* 15, 283–294. doi: 10.1016/S0929-1393(00)00079-2

Khan, A. H., Singh, A. K., Mubeen, Singh, S., Zaidi, N. W., Singh, U. S., et al. (2014). Response of salt-tolerant rice varieties to biocompost application in sodic soil of eastern Uttar Pradesh. *Am. J. Plant Sci.* 5, 7–13. doi: 10.4236/ajps.2014.51002

Kumar, P., Joshi, P. K., and Mittal, S. (2016). Demand *vs* supply of food in India - futuristic projection. *Proc. Indian Nat. Sci. Acad.* 82, 1579–1586. doi: 10.16943/ptinsa/2016/48889

Kumar, P., Mruthyunjaya., and Dey, M. M. (2007). Long-term changes in food basket and nutrition in India. *Econ. Polit. Wkly.* 42, 3567–3572. doi: 10.2307/40276502

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A., and and Lucht, W. (2008). Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. *Agric. Econ.* 39, 325–338. doi: 10.1111/j.1574-0862.2008.00336.x

Lutgtenberg, B., and Kamilova, F. (2009). Plant-growth-promoting rhizobacteria. *Annu. Rev. Microbiol.* 63, 541–556. doi: 10.1146/annurev.micro.62.081307.162918

Machado, R. M. A., and Serralheiro, R. P. (2017). Soil salinity: effect on vegetable crop growth. management practices to prevent and mitigate soil salinization. *Horticulturae* 3:30. doi: 10.3390/horticulturae3020030

Mandal, A. K., Sharma, R. C., Singh, G., and Dagar, J. C. (2010). *Computerized Database on Salt-Affected Soil in India*. Technical Bulletin. CSSRI, Karnal, 28.

Mandal, S., Burman, D., Mandal, U. K., Lama, T. D., Maji, B., and Sharma, P. C. (2017). Challenges, options and strategies for doubling farmers' income in West Bengal- reflections from coastal region. *Agri. Eco. Res. Rev*. 30, 89–100. doi: 10.5958/0974-0279.2017.00024.6

Mandal, S., Raju, R., Kumar, A., Kumar, P., and Sharma, P. C. (2018). Current status of research, technology response and policy needs of salt-affected soils in India – a review. *Ind. Soc. Coastal Agri. Res.* 36, 40–53.

Mashali, A. M. (1995). "Integrated soil management for sustainable use of salt-affected soils and network activities," in *Proceedings of the International Workshop on Integrated Soil Management for Sustainable Use of Salt-Affected Soils* (Manila: Bureau of Soils and Water Management), 55–75.

Mekonnen, M. M., and Hoekstra, A. Y. (2010). A global and high-resolution assessment of the green, blue and grey water footprint of wheat. *Hydrol. Earth Syst. Sci.* 14, 1259–1276. doi: 10.5194/hess-14-1259-2010

Minhas, P. S. (1999). "Use of Poor-quality Waters," in *50 Years of Natural Resource Management Research,* eds G. B. Singh and B. R. Sharma (Karnal: Central Soil Salinity Research Institute), 327–346.

Minhas, P. S., and Sharma, O. P. (2003). Management of soil salinity and alkalinity problems in India. *J. Crop Prod.* 7, 181–230. doi: 10.1300/J144v07n01_07

Minhas, P. S., Singh, Y. P., Tomar, O. S., Gupta, R. K., and Gupta, R. K. (1997). Saline water irrigation for the establishment of furrow planted trees in north western India. *Agrofor. Syst.* 35, 177–186. doi: 10.1007/BF00122778

Mishra, A., Sharma, S. D., and 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 Eco. Manage.* 184, 115–124. doi: 10.1016/S0378-1127(03)00213-5

Mittal, S. (2007). What affect changes in cereal consumption? *Econ. Polit. Weekly*, 444–447.

Murtaza, G., Ghafoor, A., and Qadir, M. (2006). Irrigation and soil management strategies for using saline-sodic water in a cotton-wheat rotation. *Agric. Water Manage.* 81, 98–114. doi: 10.1016/j.agwat.2005.03.003

Mythili, G., and Goedecke, J. (2016). "Economics of Land Degradation in India," in *Economics of Land Degradation and Improvement- A Global Assessment for Sustainable Development,* eds E. Nkonya, A. Mirzabaev, and J. von Braun (Cham: Springer), 431–469.

Narain, D. (1977). Growth and productivity in Indian agriculture. *Ind. J. Agric. Econ.* 32, 1–44.

Netondo, G. W., Onyango, J. C., and Beck, E. (2004). Sorghum and salinity: II. Gas exchange and chlorophyll fluorescence of sorghum under salt stress. *Crop Sci.* 44, 806–811. doi: 10.2135/cropsci2004.8060

Nosetto, M. D., Jobbagy, E. G., Toth, T., and Di Bella, C. M. (2007). The effects of tree establishment on water and salt dynamics in naturally salt-affected grasslands. *Oecologia* 152, 695–705. doi: 10.1007/s00442-007-0694-2

NRSA (National Remote Sensing Agency) and Associates (1996). *Mapping Salt-Affected Soils of India, 1:250,000 Mapsheets, Legend*. Hyderabad: NRSA.

Oldeman, L. R. (1998). *Soil Degradation: A Threat to Food Security*. Wageningen: International Soil Reference and Information Centre.

Oldeman, L. R., Hakkeling, R. T. A., and Sombroek, W. G. (1991). *World Map of the Status of Human-Induced Soil Degradation. An Explanatory Note. Second*

Revised Edition. Wageningen: International Soil Reference and Information Center (ISRIC), 35.

Oo, A. N., Iwai, C. B., and Saenjan, P. (2013). Food security and socio-economic impacts of soil salinization in northeast Thailand. *Inter. J. Environ. Rural Dev.* 4, 76–81.

Parfitt, J., Barthel, M., and Macnaughton, S. (2010). Food waste within food supply chains: quantification and potential for change to 2050. *Philos. Trans. R. Soc. B.* 365, 3065–3081. doi: 10.1098/rstb.2010.0126

Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G., and Livermore, M. (1999). Climate change and world food security: a new assessment. *Global Environ. Change.* 9, 51–67. doi: 10.1016/S0959-3780(99)00018-7

Patel, B. B., Patel, B. B., and Dave, R. S. (2011). Studies on infiltration of saline–alkali soils of several parts of Mehsana and Patan districts of north Gujarat. *J. Appl. Technol. Environ. Sanitation.* 1, 87–92.

Pimentel, D. (2006). Soil erosion: a food and environmental threat. *Environ. Dev. Sustain.* 8, 119–137. doi: 10.1007/s10668-005-1262-8

Prospero, J. M. (1979). Mineral and sea salt aerosol concentrations in various ocean regions. *J. Geophys. Res.* 84, 725–731. doi: 10.1029/JC084iC02p00725

Purushothaman, C. S., Raizada, S., Sharma, V. K., Harikrishna, V., Venugopal, G., Agrahari, R. K., et al. (2014). Production of tiger shrimp (*Penaeus monodon*) in potassium supplemented inland saline sub-surface water. *J. Appl. Aquacul.* 26, 84–93. doi: 10.1080/10454438.2014.882214

Qadir, M., Oster, J. D., Schubert, S., Noble, A. D., and Sahrawat, K. L. (2007). Phytoremediation of sodic and saline-sodic soils. *Adv. Agron.* 96, 197–247. doi: 10.1016/S0065-2113(07)96006-X

Qadir, M., Quillerou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R. J., et al. (2014). Economics of salt-induced land degradation and restoration. *Nat. Res. Forum*. 38, 282–295. doi: 10.1111/1477-8947.12054

Qadir, M., Qureshi, R. H., and Ahmad, N. (1997). Nutrient availability in a calcareous saline-sodic soil during vegetative bioremediation. *Arid Soil Res. Rehabil.* 11, 343–352. doi: 10.1080/15324989709381487

Raju, R., Thimmappa, K., Kumar, P., Kumar, S., and Tripathi, R. S. (2016). Reclamation of saline soils through subsurface drainage technology in Haryana - an economic impact analysis. *J. Soil Sali. Water Quali.* 8, 194–201.

Raju, R., Thimmappa, K., Pathan, A. L., and Siddyya. (2017). Saline soil reclamation through subsurface drainage in Karnataka - an economic impact analysis. *J. Farm. Sci.* 30, 74–78.

Ram, J., Dagar, J. C., Lai, K., and Singh, G. (2011). Biodrainage to combat waterlogging, increase farm productivity and sequester carbon in canal command areas of northwest India. *Curr. Sci.* 100, 1673–1680.

Rao, G. G., Khandelwal, M. K., Arora, S., and Sharma, D. K. (2014). Salinity ingress in coastal Gujarat: appraisal of control measures. *J. Soil Sali. Water Qual.* 4, 102–113.

Rao, G. G., Nayak, A. K., and Chinchmalatpure, A. R. (2000). *Dill (Anethum graveolens): A Potential Crop for Salt-Affected Black Soils*. CSSRI Tech. Monograph 1, CSSRI, RRS, Anand, India.

Rao, G. G., Nayak, A. K., and Chinchmalatpure, A. R. (2003). *Salvadora persica*: *A Life Support of Salt-Affected Black Soils*. Technical Bulletin 1/2003, CSSRI, RRS, Bharuch, India.

Rijsberman, F. R. (2006). Water scarcity: fact or fiction? *Agric. Water Manage.* 80, 5–22. doi: 10.1016/j.agwat.2005.07.001

Ritzema, H. P., Satyanarayana, T. V., Raman, S., and Boonstra, J. (2008). Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: lessons learned in farmers' fields. *Agri. Water Manage.* 95, 179–189. doi: 10.1016/j.agwat.2007.09.012

Rosenzweig, C., Strzepek, K. M., Major, D. C., Iglesias, A., Yates, D. N., McCluskey, A., et al. (2004). Water resources for agriculture in a changing climate: international case studies. *Glob. Environ. Change A* 14, 345–360. doi: 10.1016/j.gloenvcha.2004.09.003

Shahid, S. A., Zaman, M., and Heng, L. (2018). "Soil salinity: historical perspectives and a world overview of the problem," in *Guideline for Salinity Assessment, Mitigation and Adaptation using Nuclear and Related Techniques* (Cham: Springer), 43–53. doi: 10.1007/978-3-319-96190-3_2

Sharma, D. K., and Chaudhari, S. K. (2012). Agronomic research in salt-affected soils of India: an overview. *Ind. J. Agron.* 57, 175–185.

Sharma, D. K., Chaudhari, S. K., and Singh, A. (2014a). *CSSRI Vision 2050*. Central Soil Salinity Research Institute, Karnal, India.

Sharma, D. K., Chaudhari, S. K., and Singh, A. (2014b). In salt-affected soils: agroforestry is a promising option. *Ind. Farming.* 63, 19–22.

Sharma, D. K., Dey, P., Gupta, S. K., and Sharma, P. C. (2011). *CSSRI Vision 2030*. Central Soil Salinity Research Institute, Karnal, 38. Available online at: http://krishikosh.egranth.ac.in/handle/1/50338 (accessed December 26, 2019).

Sharma, P., and Swarup, A. (1990). *Microbial Oxidation of Pyrites in Relation to Its Efficiency for Reclamation of Alkali Soils*. Annual Report, Central Soil Salinity Research Institute, Karnal, India.

Shrivasata, P., and Kumar, R. (2015). Soil salinity: a serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi J. Biologi. Sci.* 22, 123–131. doi: 10.1016/j.sjbs.2014.12.001

Singh, G. (2009). Salinity-related desertification and management strategies: Indian experience. *Land Degrad. Dev.* 20, 367–385. doi: 10.1002/ldr.933

Singh, G., Abrol, I. P., and Cheema, S. S. (1994). Agroforestry techniques for the rehabilitation of salt lands. *L. Degrad. Rehabil.* 5, 223–242. doi: 10.1002/ldr.3400050306

Singh, K. N., and Sharma, P. C. (2006). *Salt Tolerant Varieties Released for Saline and Alkali Soils*. Central Soil Salinity Research Institute, Karnal, India.

Smedema, L. K., and Ochs, W. J. (1998). Needs and prospects for improved drainage in developing countries. *Irrig. Drain. Syst.* 12, 359–369. doi: 10.1023/A:1006101717310

Smith, J., Sones, K., Grace, D., MacMillan, S., Tarawali, S., and Herrero, M. (2013). Beyond milk, meat, and eggs: role of livestock in food and nutrition security. *Anim. Front.* 3:2. doi: 10.2527/af.2013-0002

Sparks, D. L. (2003). *Environmental Soil Chemistry*. Elsevier Academic Press, 352. Available online at: www.elsevier.com (accessed November 14, 2019).

Szabolcs, I. (1989). *Salt-Affected Soils*. Boca Raton, FL: CRC Press Inc. 274.

Tanji, K. K. (1990). "Nature and Extent of Agricultural Salinity," in *Agricultural Salinity Assessment and Management, ASCE Manuals and Reports on Engineering Practice.* No 71. ed K. K. Tanji (New York, NY: ASCE), 1–17.

Tewari, V. P., Arrawatia, M. L., and Kumar, K. (1997). Problem of soil salinity and water logging in Indira Gandhi Canal area of Rajasthan State. *Ann. Biol.*13, 7–13.

Tiwari, R. (2020). India clocks record foodgrain production in 2018-19. *The Economic Times* (accessed February 12, 2020).

Tomar, O. S., and Minhas, P. S. (2004). Performance of medicinal plant species under saline irrigation. *Ind. J. Agron.* 49, 209–211.

Tomar, O. S., Minhas, P. S., Sharma, V. K., and Gupta, R. K. (2003a). Response of nine forage grasses to saline irrigation and its schedules in a semi-arid climate of northwest India. *J. Arid Environ.* 55, 533–544. doi: 10.1016/S0140-1963(02)00285-9

Tomar, O. S., Minhas, P. S., Sharma, V. K., Singh, Y. P., and Gupta, R. K. (2003b). Response of 31 tree species and soil conditions in a plantation established with saline irrigation. *For. Ecol. Manage.* 177, 333–346. doi: 10.1016/S0378-1127(02)00437-1

Tripathi, R. S. (2011). Socio-economic impact of reclaiming salt-affected lands in India. *J. Soil Salin. Water Qual.* 3, 110–126.

Tscharntke, T., Clough, Y., Wanger, T. C., Jackson, L., Motzke, I., Perfecto, I., et al. (2012). Global food security, biodiversity conservation and the future of agricultural intensification. *Biolog. Conserv.* 151, 53–59. doi: 10.1016/j.biocon.2012.01.068

Tyagi, N. K. (1998). "Management of salt-affected soils," in *Fifty Years of Natural Resource Management Research,* eds G. B. Singh and B. R. Sharma (New Delhi: Indian Council of Agricultural Research), 363–401.

Tyagi, N. K., and Minhas, P. S. (1998). *Agricultural Salinity Management in India*. Central Soil Salinity Research Institute, Karnal, 526.

UNDESA (2017). *World Population Prospects: The 2017 Revision.* ESA.UN.org (custom data acquired via website). United Nations Department of Economic and Social Affairs, Population Division (accessed September 10, 2017).

Vaidyanathan, A. (1986). *India's Agricultural Development in a Regional Perspective.* R.C. Dutt Lectures on Political Economy, Centre for Studies in Social Sciences, Calcutta.

Vance, W. H., Tisdeel, J. M., and McKenzie, B. M. (1998). Residual effects of surface application of organic matter and calcium salts on the sub-soil of a red-brown earth. *Aust. J. Exptl. Agri.* 38, 595–600. doi: 10.1071/EA97102

Verma, C. L., Sharma, D. K., Singh, Y. P., Singh, R., Mishra, V. K., Nayak, A. K., et al. (2012). "Management of seepage water in canal command through integrated farming system to harness the productivity of waterlogged sodic soils," in *Abstracts 2nd National Seminar on Management of Salt-affected Soils and Water-Challenges of 21st Century, Indian Society of Soil Salinity and Water Quality, March 16-17, 2012* (Lucknow), 136.

Wicke, B., Smeets, E., Domburg, V., Vashev, B., Gaiser, T., Turkenburg, W., et al. (2011). The global technical and economic potential of bioenergy from salt-affected soils. *Energy Environ. Sci.* 4, 2669–2681. doi: 10.1039/C1EE01029H

Wong, N. L., Dalal, R. C., and Greene, R. S. B. (2009). Carbon dynamics of sodic and saline soils following gypsum and organic material additions: a laboratory incubation. *Appl. Soil Ecol.* 40, 29–40. doi: 10.1016/j.apsoil.2008.08.006

Ziaul Haider, M., and Zaber Hossain, M. (2013). Impact of salinity on livelihood strategies of farmers. *J. Soil Sci. Plant Nut.* 13, 417–431. doi: 10.4067/S0718-95162013005000033

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