Soil salinity under climate change: Challenges for sustainable agriculture and food security

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Highlights

- Distribution, causes and climate change vulnerability of salt-affected soil highlighted.
- Management strategies of salt-affected soil under climate change discussed.
- Socioeconomic and environmental impacts of management strategies reviewed.
- Different innovative reclamation strategies warrant future research.

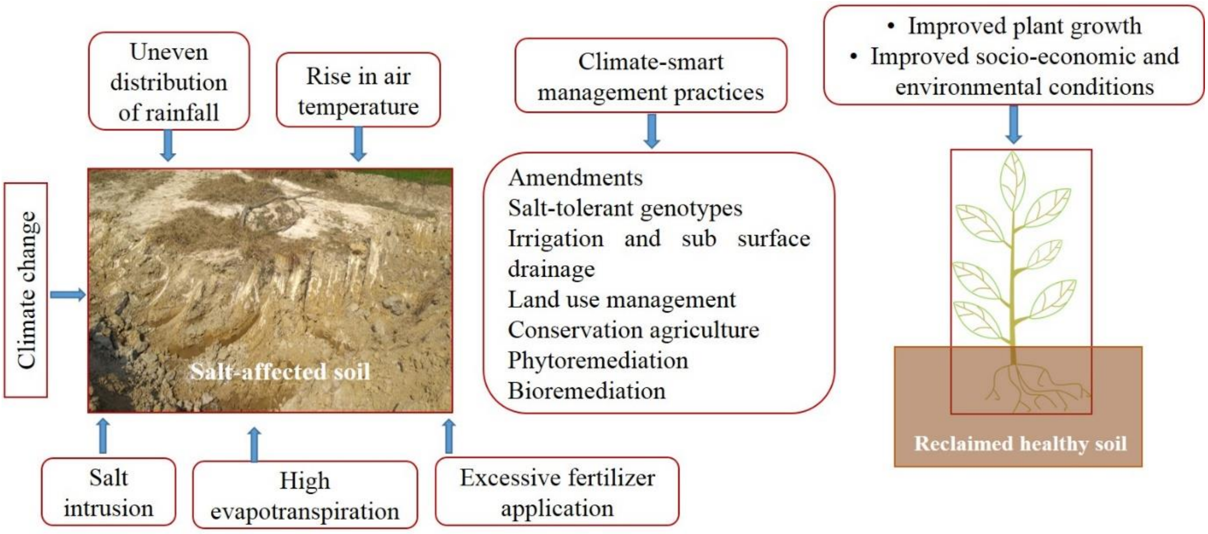
Abbreviations

CSSRI	Central Soil Salinity Research Institute
GHGs	Greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
FAO	Food and Agriculture Organization
CSMPs	Climate smart management practices
CA	Conservation agriculture
EC_e	Electrical conductivity of the saturated paste extract
EC_{iw}	Electrical conductivity of irrigation water
ESP	Exchangeable sodium percentage
Mha	Million hectare

ILO	International Labour Organization
PTEs	Potentially toxic elements
FGD	Flue gas desulphurization
RDN	Recommended dose of N
RDF	Recommended dose of fertilizer
OC	Organic carbon
SOC	Soil organic carbon
MSW	Municipal solid waste
RW	Rice-wheat
mmol	millimole concentration
SAR	Sodium adsorption ratio
DSR	Direct seeded rice
SSD	Sub surface drainage
CL	Corn cropland
AF	Alfalfa forage
AG	Monoculture *Lyemus chinensis* grassland
AG +M	Monoculture *Lyemus chinensis* grassland for hay (mowing)
MBC	Microbial biomass carbon
RG	Regrowth grassland
ROM	Rice-okra-mentha
PTR	Puddled transplanted rice
US$	United States Dollar
FP	Farm pond,
RF	Deep furrow and high ridge
PCF	Paddy cum fish
CSCA	Climate smart conservation agriculture
Sc	Scenario
RWMS	Rice-wheat-mungbean system
MW	Maize-wheat

ZT	Zero tillage
R_m	Residue mulch
PGPR	Plant growth promoting rhizobacteria
ACC	1-aminocyclopropane-1-carboxylate deaminase
IAA	Indole acetic acid
VAM	Vesicular arbuscular mycorrhizae
EPS	Extra-cellular polymeric substances
B: C	Benefit-cost ratio
IRR	Internal rate of return

Graphical abstract



Abstract

Soil salinity is one of the major and widespread challenges in the recent era that hinders global food security and environmental sustainability. Worsening the situation, the harmful impacts of climate change accelerate the development of soil salinity, potentially spreading the problem, in the near future, to currently unaffected regions. This paper aims to synthesise information from published literature about the extent, development mechanisms, and current mitigation strategies for tackling soil salinity, highlighting the opportunities and challenges under climate change situations. Mitigation approaches such as application of amendments, cultivation of tolerant genotypes, suitable irrigation, drainage and land use strategies, conservation agriculture, phytoremediation, and bioremediation techniques have successfully tackled the soil salinity issue, and offered associated benefits of soil carbon sequestration, and conservation and recycling of natural resources. These management practices further improve the socio-economic conditions of the rural farming community in salt-affected areas. We also discuss emerging reclamation strategies such as saline aquaculture integrated with sub surface drainage, tolerant microorganisms integrated with tolerant plant genotypes, integrated agro-farming systems that warrant future research attention to restore the agricultural sustainability and global food security under climate change scenario.

Key words: Salt-affected soil; Climate change; Soil reclamation; Environmental quality; Farmers' livelihood; Sustainability

1. Introduction

Soil salinity is one of the largest global challenges in the arid and semi-arid regions that severely affects agricultural production (El hasini et al., 2019). Soil salinity already covers 20% of total cultivated, and 33% of the irrigated agricultural lands worldwide (Srivastava and Kumar, 2015) and expected to increase at a faster rate than now by the year 2050 (Central Soil Salinity Research Institute (CSSRI), 2014). For example, the percentage of saline soils in Bangladesh had increased from less than 1% in 1990 to 33% in 2015 mainly due to sea water intrusion in the coastal areas resulting from excessive extraction of ground water sources (Rahman et al., 2018). The salt stress in soil is becoming prominent also due to other anthropogenic activities (e.g., over-application of groundwater and synthetic fertilizers) of the ever-increasing global population pressure (United Nations, 2011).

Recently, the alarming impact of climate change on the build-up of soil salinity has attracted widespread research attention. The rise in atmospheric greenhouse gases' (GHGs) concentrations and the consequent increase in air temperature and decline in relative humidity together with extreme events of rainfall are probable indicators of climate change that have huge impact on the pace of soil salinity development (IPCC, 2013; Haj-Amor and Bouri, 2019). The climate change could accelerate salt water intrusion into fertile soils due to sea level rise and excess groundwater extraction in the dry regions of the world could also increase soil and groundwater salinity (Dasgupta et al., 2015). It is estimated that about 600 million people living in the coastal zones throughout the world could be affected by salinization (Wheeler, 2011; Dasgupta et al., 2015). Numerous studies reporting the impact of climate change on crop yield indicate positive (e.g., wheat yield increased with increased CO_2 concentration under optimal temperature) or negative (e.g., 3.8% drop in maize yield during 1980 to 2008) impacts, which could be balanced equally up to 2030 worldwide, but after that a clear dominance of the negative impact on crop yields will be visible (The Food and Agriculture Organization (FAO), 2017). Moreover, about 40 million people would be at risk due to malnourishment if the current pace of climate change continues (FAO, 2017). Therefore, climate change is likely to become one of the primary obstacles to sustainable agriculture and global food security (Corwin, 2020). Rising air temperature, extreme events of rainfall, weather conditions (e.g., prolonged droughts and floods), changing soil fertility and health, and new pest infestations coupled with increasing salt-affected areas are major factors contributing to stagnant agricultural growth (Corwin, 2020). Climate-smart agriculture is considered a pragmatic approach to ensuring food security in the challenging environment (Jat et al., 2019a). The climate smart management practices (CSMPs) include site-specific reclamation management strategies (e.g., amendments, irrigation and drainage), conservation agriculture (CA) and use of stress-tolerant genotypes. These practices may deliver co-benefits in the forms of reduced GHG emission, and enhance soil carbon sequestration and ecosystem services. Therefore, CSMPs are the need of the hour to tackle soil salinity under current and future climatic conditions.

Most of the literature is concentrated on desalination of brine water using reverse osmosis, and electro-remediation (Werber et al., 2017). These technologies have been proven effective for domestic water supply, but are expensive for irrigation of agricultural crops. Very limited literature is available concerning the complete management practice packages of soil salinity (Saifullah et al., 2018; Meena et al., 2019), especially under the varying climatic scenarios. A review paper portraying our current status of knowledge about the soil salinity management strategies under climate change scenarios aiming for food security is thus very important. In this article, we therefore aim to provide a holistic overview of global status of salt-affected soils, its relationship with climate change and food security along with various successful cost-effective climate smart reclamation strategies for salt-affected soils. We critically discuss about amendments, irrigation and drainage strategies, CA, land use patterns, bioremediation and phytoremediation approaches for the management of soil salinity. Further, we shed lights on the environmental and economic implications of those strategies and suggest future research directions.

2. Methodology adopted for the review

A large number of published reports (n= 140) covering salt-affected soils were collected to make an initial assessment on salt-affected soil genesis, classification, extent of distribution, mechanisms of salt stress and mitigation strategies on the basis of the topic and hypothesis

(Khan, 2019). We covered literature reviews based on information available from sciencedirect.com, springer.com, wiley.com, FAO reports, CSSRI technical bulletins, Scopus and Google Scholar databases using relevant keywords such as salinity, sodicity, reclamation, salt tolerance, and climate sustainability. After systematic review and content analysis, we identified the key management practices and key challenges associated with certain reclamation strategies. Finally, we reached to the conclusions and future research recommendations focussing on the hypothesis and objective of this review.

3. Soil salinity and its global extent

Soil salinity is classified based on pH of saturated soil paste, electrical conductivity of saturated paste extract (EC_e) and exchangeable sodium percentage (ESP) (Richards, 1954). Salt-affected soil includes saline soil, sodic soil and saline-sodic soil. Saline soils have pH <8.5, EC_e >4 dS/m and ESP <15 containing soluble salts of Cl^- and SO_4^{2-} of Na^+, Ca^{2+}, and Mg^{2+}. On contrary, sodic soils have pH >8.5, EC_e <4 dS/m and ESP >15 containing soluble salts of CO_3^{2-} and HCO_3^- of Na^+, Ca^{2+} and Mg^{2+} (Richards, 1954). Saline-sodic soil shows the characteristics of both saline and sodic soils. These soils are characterized by pH >8.5, EC_e >4 dS/m and ESP >15 and contain a mixture of Cl^-, SO_4^{2-}, CO_3^{2-} and HCO_3^- salts of Na^+, Ca^{2+}, and Mg^{2+}. Salt-affected soils are distributed in 954 million hectare (Mha) area of 120 countries of the world, and contribute to 7-8% productivity loss (Table 1) (Meena et al., 2019). Among these, Australia shares the highest area of salt-affected soils constituting more than 50% of the sodic soils worldwide (Shahid et al., 2018).

India is currently having 121 Mha of degraded land out of which 6.73, Mha area is covered by salt-affected soil (NAAS, 2012). Out of this, 2.96 Mha is saline, and 3.77 Mha is sodic soil (Tripathi et al., 2011). Thus, India’s 2% of the total geographic area is salt-affected, which poses a potential threat to India’s sustainable agriculture and food security.

4. Mechanisms of salt tolerance in plants

Soil salinity results in increased EC_e, poor soil structure and low soil water potential (ψ_w). The development of salt stress in plants could be described in two ways: (i) osmotic phase, and (ii) ionic phase (Figure 1) (Munns and Tester, 2008; Sirault et al., 2009). Osmotic phase takes place within few minutes of salt accumulation in root zone. Stomata closure, increase in leaf temperature and inhibited shoot elongation are the fundamental indicators of plants during osmotic phase, because of low soil water potential and thick inner wall of the guard cells. Conversely, the ionic phase starts after few minutes to few hours in different cases of salt input which involves salt accumulation in shoots over a long period of time and leads to leaf senescence and premature abscission.

5. Interrelationship between soil salinity, climate change and food security

Climate change refers to long-term changes in weather conditions and climate systems. As a result, the global air temperature has increased by 1.5°C above the pre-industrialization level, and the rise in CO_2 concentration in the atmosphere has gone up 20 µmol/mol per decade since 2000, and now it has reached >400 µmol/mol (Corwin et al., 2020). Consequently, following drastic changes have already been observed, which greatly influence the development of soil salinity (Corwin, 2020):

(i) Increase in the frequency of extreme weather conditions such as rise in air temperature, evaporation rate, excessive rainfall and heat stress.

(ii) Global warming due to increased concentration of GHGs (e.g., CO_2, N_2O, CH_4) which trap the heat within the atmosphere.

(iii) Spatial and temporal variability of rainfall distribution leads to changes in soil moisture contents.

(iv) Increase in precipitation leads to soil erosion, groundwater recharge, infiltration and storage, whereas rise in temperature promotes the transpiration and moisture depletion from the soil profile.

(v) Rise in sea-level and sea water intrusion in the coastal areas limits their application for irrigation. It is projected that 130 million people will be inundated by rise in sea level within 120 years (Chen and Mueller, 2018).

Besides, excessive use of mineral fertilizers and groundwater during the post green revolution era added neutral soluble salts to the soil, which in turn contributed to salinity build up.

The livelihood of 40-50% people in Asia is highly dependent on agricultural practices, while the corresponding value is 66% for Africa (ILO, 2007). Reclamation of salt-affected soils can potentially contribute to increased production of millions of tonnes of food grains worldwide. Thus, a complete package of climate smart technologies for reclamation of salt-affected soils is the need of the hour. Some of these reclamation approaches, which may reduce the area under salt-affected soil, helping to maintain agricultural sustainability and global food security, are discussed in the subsequent sections.

6. Soil salinity mitigation approaches for sustainable agriculture and food security

Useful techniques for reclaiming salt-affected soils in affected countries along with their major cropping systems are given in Table 2. In addition to various organic and inorganic amendments, applications of microorganisms, halophytes, tree species, land use pattern change, CA, and innovative irrigation and drainage strategies have been employed to reclaim salt-affected soils worldwide.

6.1. Amendments

Organic amendments such as biochar, compost of municipal solid wastes (MSW) and inorganic amendments that are rich in Ca (e.g., fly ash, gypsum, phosphogypsum), and zeolites have been used to reclaim sodic soils (Singh et al., 2018a; Mishra et al., 2019). Application of the above amendment materials improve the soil bulk density, aggregate stability, hydraulic conductivity, and lower down the pH, EC, ESP of salt-affected soils (Mishra et al., 2019; Sundha et al., 2020). In addition, improved soil biological properties (e.g., soil enzymatic activities, microbial population, and microbial biomass N and P contents) are observed due to beneficial effects of amendments. A schematic diagram is presented in Figure 2 to elucidate the influences of various amendments on soil properties.

6.1.1. Gypsum

Gypsum is the most effective amendment for reclaiming sodic soil due to its wider availability, and substantial Ca^{2+} supply capacity. Ca^{2+} replaces Na^{+} from the soil colloids, and leaches $NaSO_4$ deeper in the soil profile (Eq. 1) (Singh et al., 2018a). A combination of gypsum and mineral langbeinite (rich in Mg^{2+} and K^{+}) resulted in significant reduction of soil exchangeable Na^{+} and sodium adsorption ratio (SAR), and improved soil saturated hydraulic conductivity (Aydemir and Najjar, 2005). Naturally available mined gypsum is of poor quality, and its availability to agriculture is limited due to excess mining within the cement industry. Phosphogypsum, a by-product of phosphate fertilizer production, is used as an alternative to gypsum to minimize the use of mineral gypsum (Singh et al., 2018a). However, phosphogypsum may contain traces of potentially toxic elements (PTEs) (e.g., Cd), and its solubility is less than gypsum. Flue gas desulphurization (FGD) gypsum, a by-product of FGD process involving the capture of sulphur gases in coal-fired power stations, is also a rich source of Ca^{2+}, hence can be used to replace Na^+ with Ca^{2+} from soil exchange sites (Seshadri et al., 2013).

$$2Na^+\text{- soil} + CaSO_4.2H_2O \rightarrow Ca^{2+}\text{- soil} + Na_2SO_4 \text{ (soluble)} \qquad \text{(Eq. 1)}$$

6.1.2. Compost

Composts such as green waste compost, green manure compost, and municipal solid waste compost were reported to increase soil salinity initially, but decreased it substantially in the later stage. El hasini et al. (2019) used a green waste compost (mixture of melon rind and olive pomace), sugarcane compost and gypsum to reclaim saline soils. They reported that the combined application of organic amendment (green waste compost) and gypsum (3.8 mg/g soil) increased the soil EC initially during 100 days due to the presence of dissolved salts in the compost and limited flushing. However, the EC was reduced to 2.80 from 16.65 dS/m after 120 days due to replacement of Na^+ with Ca^{2+} in soil exchange sites and solute leaching. Similarly, vermicompost at the rate of 10 t/ha in combination with 100% recommended dose of N (RDN) decreased the soil bulk density, pH, EC, ESP and soil solution Na^+ content of a degraded sodic soil by 2.0, 4.2, 26.5, 42.8, and 56.6%, respectively, and increased the soil organic carbon (SOC) content by 34.6% over control (Singh et al., 2019). The properties of degraded sodic soils could be improved considerably due to the decomposition of organic residues by enhanced microbial activity, microflora populations and displacement of excess Na^+ by Ca^{2+} in the soil exchange sites (Wang et al., 2014).

6.1.3. Municipal solid waste compost

Municipal solid waste (MSW) compost received wide acceptance for reclaiming sodic soils, and improved soil physicochemical properties when it was combined with gypsum, mineral fertilizers and other inorganic amendments (Sundha et al., 2020). Singh et al. (2018a) reported that application of gypsum (at the rate of 25% of the gypsum requirement) in combination with on-farm MSW compost at the rate of 10 t/ha reduced soil ESP and bulk density by 14 and 11%, respectively, and increased infiltration rate, SOC content and available N by 54, 10 and 13%, respectively, over recommended dose of gypsum. Similarly, a combined application of MSW (at the rate of 10 t/ha) along with 75% RDN improved the dehydrogenase activity in a sodic soil to the tune of 9.3 to 47.3% due to enhanced intra and extracellular enzyme secretions (Singh et al., 2019). Thus, to reclaim sodic soils, MSW compost could minimize the requirement of mineral gypsum. A similar study conducted by Meena et al. (2016) in saline soil, showed that soil nutrient availability (N, P and K) was improved by the application of rice, wheat straw compost in combination with 50% recommended dose of fertilizer (RDF) instead of MSW compost. The N, P and K availability was increased by 14, 17 and 9%, respectively, after pearl millet harvest, likely due to the slow release of nutrients from the compost in the degraded soil. However, the combined use of chemical fertilizers and compost might decrease the organic P fraction in the soil, likely due to the increased microbial activities in the rhizosphere (Chang Hoon et al., 2004). In contrast, Meena et al. (2018) reported that a combined application of MSW compost (at the rate of 8 t/ha) and 50% RDF increased all fractions of P in soil under a mustard and pearl millet cropping system, likely due to the addition of organic P through the compost. However, MSW added some amounts of PTEs to the soil, especially lead (Pb^{2+}) and chromium (Cr^{6+}) depending upon the raw materials of the MSW compost. The measured PTEs levels were well below the critical level for inducing soil pollution (Meena et al., 2019). Therefore, a holistic improvement of salt-affected soil properties (physicochemical and biological) could be achieved via MSW applications with or without fertilizers, or other amendments. However, care should be taken for the selection and application rates of MSW compost so that it does not pose the risk of a secondary pollution in reclaimed soils.

6.1.4. Biochar

Biochar has become popular for soil carbon sequestration, soil health improvement and reclamation of salt-affected soils. Depending upon the nature of feedstock and preparation conditions, biochar can contain a substantial amount of N, P, K, and micronutrients (Sun et al., 2017; Purakayastha et al., 2019). Additionally, N-losses via NH_3 volatilization and denitrification can be substantially reduced by biochar application, due to NH_4 adsorption inside biochar pore spaces (Mandal et al., 2016). However, high application rates of biochar can increase the volatilization loss of N due to high pH of biochar applied to soil (Sun et al., 2017). The availability of P in sodic soil can be enhanced by decreasing the pH by 0.3 unit, blocking the clay adsorption sites by dissolved organic carbon, and releasing organic acids for P mobilization in soil (Lashari et al., 2013). A wood-based biochar prepared from hardwood feedstock and pyrolyzed at 450˚C showed acidic pH (5.6) which could be used for reclamation of sodic soil (Shaheen et al., 2019). Acidic wood biochar (pH=3.25; pyrolysis temperature 650˚C) might also be used to reduce the pH of sodic soil (Qi et al., 2018). In contrast, biochar application could increase the soil pH too, which would decrease P availability due to precipitation of insoluble P compounds (Xu et al., 2016). The K availability was reported to be increased by 44% after biochar application in salt-affected soils depending upon soil types and biochar properties (Lin et al., 2015). Therefore, the selection of biochar feedstock and pyrolysis temperature are important factors to be considered before applying this amendment to salt-affected soils. Soil physical properties (e.g., bulk density, porosity, and water holding capacity) were also improved considerably due to porous nature of biochar (Burrell et al., 2016). Amini et al. (2016) noticed significant effect of biochar (acidic vs alkaline) on soil physical properties such as saturated hydraulic conductivity and aggregate stability in a saline-sodic soil. The organic molecules present in biochar helped to bind polyvalent cations and clay particles for improving the aggregation of particles in degraded salt-affected soils. The soil structure and SOC content were found to be improved in salt-affected soil by biochar application with a simultaneous lowering of ESP (Amini et al., 2016). Similarly, soil EC_e decreased by 42% following a combined application of poultry manure and biochar (Lashari et al., 2015). It is inferred that acidic biochar could be a potential amendment for the reclamation of sodic soils.

6.1.5. Fly ash

Fly ash is a combustion product of coal industry having potential role in reclaiming sodic soils when applied jointly with gypsum and green manure (Mishra et al., 2019). Fly ash, applied in combination with manure and gypsum (25% gypsum requirement), showed significantly higher rice yield than the control treatment, that consisted of the application of fly ash only (2.5% fly ash on mass basis i.e. 1.96 t/ha) (Mishra et al., 2019). The beneficial properties of fly ash, such as high Ca^{2+} content, low bulk density, and the presence of substantial amounts of sesquioxides, improved the physicochemical properties of the degraded soil (Shirale et al., 2017). In contrast, fly ash application in soil under rice crop did not significantly reduce the soil pH, but reduced 68.4% exchangeable Na^+ content of the soil (Lal et al., 2012). Fly ash derived from coal combustion is generally alkaline because of the addition of lime for capturing sulphur gases. However, FGD gypsum was reported to improve the N uptake of corn plants when applied together with N-fertilizers in the soil (Seshadri et al., 2013). Therefore, fly ash products could be a potential amendment for the reclamation of sodic soils due to their high Ca^{2+} supplying capacity.

6.1.6. Zeolites

Zeolites, a hydrated crystalline aluminosilicate of alkali and alkaline earth metals, can be used to reclaim saline soils. Zeolites such as clinoptilolite, erionite and heulandites are used as soil conditioners to improve soil properties and nutrient availability (Manjaiah et al., 2019). It was observed that Ca-rich clinoptilolite substantially improved the crop yield and quality of a saline soil due to adsorption of Na^+ and Cl^- in the mineral cavities (Noori et al., 2006). Similarly, 5% zeolite application to a saline soil increased Ca^{2+} concentration, and micronutrient Fe^{2+} and Mn^{2+} by 19 and 10%, respectively (Al-Busaidi et al., 2008). The mechanisms governing the salt removal process by zeolites are mainly ion exchange, adsorption, and salt storage (Wen et al., 2018). The possible ion exchange reaction of zeolites in salt-affected soil is shown in Eq. 2.

$$(2Na^+\text{- soil}) + (Ca^{2+}\text{-zeolites}) \rightarrow (Ca^{2+}\text{- soil}) + (\text{zeolites}) + (2Na^+\text{ solution}) \qquad \text{(Eq. 2)}$$

6.2. Irrigation and drainage strategies

Saline groundwater in the arid and semi-arid regions of the world has become a major challenge for water management to ensure agricultural sustainability (Yao et al., 2012). Almost 43% of world’s irrigated area is groundwater dependent (Minhas et al., 2019), out of which India (39 Mha) and China (19 Mha) share the maximum area under groundwater irrigation. Therefore, strategic water management techniques are required to tackle saline groundwater during crop production.

6.2.1. Irrigation techniques

South-Asian countries mainly focus on rice-wheat (RW) system to ensure food security, and this cropping system is resource intensive, viz. it entails high requirement of irrigation water (200-250 cm/yr), synthetic fertilizers, energy, and labour. A constant depletion of groundwater aquifers and salinity build up are becoming pronounced in South Asia. Irrigation with saline water was reported to increase salinity up to 12.2 dS/m, and SAR up to 20 (Yadav et al., 2007). Consequently, significant negative changes occurred in soil properties including reduced saturated hydraulic conductivity, aggregate stability and increased dispersion and run-off (Mandal et al., 2008). Hence, judicious application of irrigation water along with smart crop management practices is an essential approach to avoid salinity build up and tackle water scarcity in dry land areas (Minhas et al., 2020a). Saline and best quality available water have been used in a mixture to avoid the water salinity during pearl millet production and to compare yield of two varieties AVKB-19 and ICMV-15111 under saline soil (Makrana et al., 2019). The AVKB-19 showed 16.26 % higher grain yield than ICMV-15111 when good quality water was mixed with saline water for irrigation. Bed planting of crops, straw mulching, and micro irrigation (e.g., sprinkler, drip (surface and subsurface) irrigation) are known to save irrigation water, and improve N- use efficiency and grain yield. For example, drip irrigation with residue retention and raised bed planting in maize and wheat showed 13.7 and 23.1% higher yield, respectively, than furrow irrigation system without residue retention (Sandhu et al., 2019). The drip system (with residue retention) saved 88 and 168 mm of water, and increased water productivity by 66 and 259%, respectively, in CA-based wheat and maize compared to the conventional irrigation system. Moreover, sub-surface drip irrigation in combination with CA saved 48-53 and 42-53% of the irrigation water in rice and wheat, respectively, and saved overall 20% N input (Sidhu et al., 2019). Apart from drip system, irrigation techniques using sprinkler and low energy water application device saved 30-40% water compared to surface irrigation, and recorded 4.4 t/ha rice yield which was at par with maximum yield with surface irrigation in a sodic soil (Singh et al., 2018b). Kumar et al. (2019a) proposed novel matric potential based irrigation strategies for direct seeded rice (DSR) which could save substantial amount of water, and sustain the productivity of salt tolerant basmati rice (CSR30). They suggested that irrigations at or below -30 kPa (field capacity) during initial 90 days of rice growth, and at -15 kPa during rest of the growth period exhibited similar yield under traditional irrigation method. Thus, the use of saline water in conjugation with fresh water, sub-surface drip irrigation, and DSR techniques might effectively reduce the salinity effects, and tackle water scarcity in semi-arid and arid regions.

6.2.2. *Drainage strategies and groundwater recharge*

Agricultural drainage is important to remove excess water due to high precipitation, eliminate dissolved soluble salts from the soil profile, and maintain the groundwater table. However, due to lack of care, waterlogged salinity remains a severe problem in many productive areas of Australia, Middle East, United States, and Asia (Emadodin et al. 2012). Sub-surface drainage (SSD) was identified as one of the most important techniques to remove salts from 1.5 m depth (Nijland et al., 2005). Two types of SSD can be useful for the reclamation of saline soils: (i) horizontal sub-surface drainage which works up to 1.5-2.0 m depth of root zone, and involves a network of drain consisted of the main drain, lateral drains and collectors (Nijland et al., 2005), and (ii) vertical sub-surface drainage which is related to pumping of excess water by tube well (Bos, 2001). Srinivasulu et al. (2005) reported SSD installation (pipe drain) in 8 ha saline waterlogged area of Prakasam district of India (water table depth 0-3.7 m; EC_e: 1.3-18.6 dS/m) with 30 and 60 m drain spacing. Around 0.2-0.35 m lowering of water table depth, and 50.4 tonnes of salt accumulation in the pipes occurred during 1999-2002. Yields were increased by 50-100% in most of the crops due to installation of SSD, which is really a profitable solution to the farmers of salt-affected areas (Kamra et al., 2013). Bhattacharya (2007) reported that investments on surface drainage too are economically viable with yield benefits ranging from 20 to 28% in sugarcane, 20 to 25% in paddy, 32% in gram, and 50% in Indian bean.

Intensively irrigated agriculture suffers severely from long-term increase of salinity in the groundwater derived from irrigated permeable soils in arid and semi-arid regions (Foster et al., 2018). Groundwater recharge through preparation of artificial recharge structures using rainwater was found useful to minimize the salt load in surface water and groundwater.

Groundwater salinity of semi-arid area of Karnal district, India, was reduced to 1.33 from 1.36 dS/m within one year while alkalinity reduced from 6.63 to 1.33 meq/L with 3.16 m rise in groundwater table due to groundwater recharge events (Narjary et al., 2014). Similarly, 1.26 and 0.65 m rise in water table during monsoon through an artificial recharge structure was observed in Nirmana and Kutba village of Uttar Pradesh, India, with a reduced salinity level of the groundwater (e.g., EC declined from 0.90 to 0.24 dS/m in Kutba village) (Kumar et al., 2019b). Furthermore, the alkalinity of groundwater was reduced by 2-3 meq/L in Kaithal district of Haryana, India, which minimized crop damage from 35-40% in open field to 5-15% under groundwater recharge structure with a benefit to cost ratio of 1.93 (Kumar et al., 2020). Horriche and Benabdallah (2020) reported that an artificial recharge structure with 1500 m^3/day recharge rate minimized salt load by 5.7 g/L. Hence, groundwater recharge in saline areas is one of the feasible solutions for increasing the level of groundwater table and improving the groundwater quality.

6.3. Salt tolerant genotypes

Salt tolerant crops are an important tool for sustaining productivity in salt-affected regions. Plant salt tolerance has been demonstrated through specificity in ion accumulation and better partitioning of accumulated ions within plant cells and tissues. For example, wheat showed salt tolerance via: (i) salt exclusion, (ii) osmotic tolerance, and (iii) tissue tolerance (Munns et al., 2016). In addition, the salinity tolerance of wheat showed dependence on forms of N-fertilizers (NH_4^+ preferred) indicating that NO_3-N could be harmful (Elgharably et al., 2010). In case of barley, salt exclusion and osmotic tolerance were the main operative mechanisms both under hydroponic and saline soil growth conditions (Tavakkoli et al., 2012). Krishnamurthy et al. (2016) evaluated 131 rice accessions at normal (1.2 dS/m) and highly saline (10 dS/m) irrigation water, and found that root and shoot lengths were decreased by 52 and 50%, respectively, due to high Na^+/K^+ ratio in plants. They identified three accessions namely, IC 545004, IC 545486 and IC 545215 which were suitable as parent donors under saline conditions. Ravikiran et al. (2017) experimented with 192 genotypes of rice at normal (1.2 dS/m) and high salinity (12 dS/m) hydroponic conditions. They concluded that CST 7-1 and Arvattelu genotypes could be novel sources of seedling stage salinity tolerance among all the experimental genotypes. A comparison study between rice varieties CSR10 and MI48 was conducted, and CSR10 expressed lower Na^+/K^+ ratio in shoots than MI48 (Singh et al., 2018c). For mustard, a set of 97 salt tolerant genotypes were planted in highly saline soil (EC_e: 10.7 dS/m). The erucic acid content in mustard was increased under salinity by 12.2%, while oil, protein and crude fibre contents were decreased by 5.78, 29.31, and 20.45% (Singh et al., 2014). Tomato genotypes were also evaluated in salt solution (0, 1.0 and 3.0% NaCl salt concentration in Hoagland solution). Important traits of tomato genotypes such as % germination, and root shoot dry weight responded negatively towards high salinity for most of the tomato genotypes except Sel-7 and Arka Vikas (Singh et al., 2012). Sugarcane was also found salt tolerant (varieties-Co 6806, Co 7717 and Co 8208) in coastal saline areas of India, and but experienced major yield loss (~40%) under massive salt water intrusion in coastal areas (Balasundaram, 2004).

6.4. *Land use management*

Conversion of barren land to crop lands naturally improve the soil nutrients status and organic carbon inputs (Yu et al., 2018). Therefore, changes in land use systems of salt-affected soil through cropping systems, agroforestry, and fruit crops would improve the soil quality. Earlier, five land use systems comprised of corn cropland (CL), alfalfa perennial forage (AF), monoculture *Lyemus chinensis* grassland (AG), monoculture *L. chinensis* grassland for hay

(Mowing) (AG+M) and successional regrowth grassland (RG) were evaluated in salt-affected soil of north-eastern China (Yu et al., 2019) and it was revealed that SOC, total N, total P and total K contents of surface soils were increased by 40.42, 17.66, 15.71 and 11.5%, respectively due to addition of organic litter inputs from forage crops. Rice based cropping system showed promising impact for improving soil physicochemical properties and carbon content in the salt-affected canal command area of Indo-Gangetic Plain (Bhardwaj et al., 2019). Results suggested that rice-okra-mentha (ROM) and RW systems displayed a decreasing trend of ESP to the tune of 37 and 35.5%, respectively, and an increasing trend of carbon stock (4-70%) compared to barren sodic land due to addition of organic matter input. Likewise, Jatropha (*Jatropha curcas* L.) cultivation as an intercrop between sweet basmati rice and Matricaria was effective in increasing soil microbial biomass carbon (MBC) (+24.68% over control-no intercrop), microbial activity and improving soil properties in a degraded sodic soil of northern India. The above practice received 5288.4 US$/ha as economic return via Jatropha intercropping with the sweet basmati rice-Matricaria cropping system because of high yield and market value of sweet basmati rice and Matricaria flowers (Singh et al., 2016). Another study on the influence of different land uses (sorghum, paddy, forest, wetland, wasteland and meadow) on microbial community structure in saline-sodic soil suggested that bacterial abundance was maximum under wetland (1.03×10^9 copies/g dry weight of soil), whereas fungal population was maximum (5.83×10^6 copies/g dry weight of soil) under forest ecosystem, due to drying and wetting phenomenon in the former (Feng et al., 2019). In case of GHG emission, emission of CO_2 decreased (lowest in bare land) with increasing salinity, which might be due to the reduction of activity of heterotrophic microorganisms. The N_2O production increased with increasing salinity under *Tamarix chinensis* and *Phragmites australis* ecosystems due to increased ion concentrations, less solubility of N_2O, and low N_2O reductase activity (Zhang et al., 2018). However, N application increased the CO_2 emission under *Suaeda salsa* and *P.*

australis ecosystems, while N_2O emission was large under vegetative cover because of increased microbial activity (denitrifying bacteria) (Zhang et al., 2019).

Crop establishment methods such as dry seeded rice, non-puddled transplanted rice (non-PTR) provided 25-44% higher rice yield than rapeseed grown after puddled transplanted rice (PTR), while yields of maize were 8–13% higher when grown after either dry seeded rice or Non-PTR in coastal salt-affected areas of West Bengal, India (Sarangi et al., 2019). In addition, maize was found more profitable (US$301-405/ha) than rapeseed (US$ 5-113/ha) in coastal salt-affected soils of India. Impacts of different land shaping techniques such as farm pond (FP), deep furrow and high ridge (RF), and paddy cum fish (PCF) systems were studied for rainwater harvesting to improve the productivity of coastal saline soils of Sundarbans, India (Mandal et al., 2019). These areas receive 2.7 times higher annual rainfall than crop evapotranspiration. The estimated runoff was 19.5, 29.1 and 27.75% of the annual rainfall in FP, RF and PCF systems, respectively, whereas in rice-fallow system it was 34.6% of the annual rainfall. Additionally, the calculated water footprints were much higher in the rice-fallow and rice-rice ecosystems than the individual land shaping system, indicating an increased cropping intensity and high net farm income, during the summer and reduced salinity and waterlogging during the rainy season.

6.5. Climate smart conservation agriculture

Climate smart conservation agriculture (CSCA) works on the principles of conservation agriculture along with precise input management practices, i.e., nutrient, water, genotypes, labour, and pesticides. Conservation agriculture maintains three basic principles: (i) residue retention, (ii) minimum tillage, and (iii) crop diversification in order to enhance the productivity of agri-food systems through better adaptation to climate change (Aryal et al., 2016). A short description of CSCA based agro-ecosystem is presented in Figure 3.

The CSCA is becoming a potential mitigation strategy for soil salinity under climate change in Asian countries, especially in north western parts of India. Jat et al. (2018) evaluated four scenarios (Sc), namely conventional RW cropping system (Sc1), partial CA-based rice-wheat-mungbean system (RWMS) (Sc2), CA-based RWMS (Sc3), and CA-based maize-wheat-mungbean (Sc4) system to assess soil properties and carbon storage under CA-based treatments in a reclaimed sodic soil. Sc2 indicated remarkably lower soil bulk density (1.52 Mg/m^3) compared to the conventional system, while Sc3 and Sc4 showed greater organic carbon (OC) content (0.75 and 0.77% OC content under Sc3 and Sc4, respectively), and N availability (33 and 68% higher under Sc3 and Sc4, respectively) compared to Sc1. The SOC pools at surface soil showed the following order: Sc4 > Sc3 > Sc2 > Sc1 (Jat et al., 2019a). Around 34% higher soil respiration was noticed under different CA-based scenarios. The predominant phyla of soil bacteria in all scenarios were *Proteobacteria, Acidobacteria, Actinobacteria,* and *Bacteroidetes,* accounting for >70% of the identified phyla. The bacterial diversity was prominent under all CA-based maize-wheat-mungbean cropping systems (Choudhary et al., 2018a). Besides, lignocellulose degrading fungal species such as *Aspergillus flavus, Aspaergillus terreus, Penicilium pinophilum* and *Alternaria alternate* were present for residue decomposition (Choudhary et al., 2016). In this connection, maize-wheat (MW) system with zero tillage (ZT) and residue mulch (R_m) (MW/ZT +R_m) recorded 208, 263, 210 and 48% improvement in MBC, microbial biomass N, dehydrogenase activity, and alkaline phosphatase activity, while RW system under RW/ZT +R_m showed 83, 81, 44 and 13% improvement, respectively, as compared to RW/ conventional tillage without residue mulch (Choudhary et al., 2018b; Choudhary et al., 2018c). Therefore, the CSCA practices hold future potential to tackle soil salinity under climate change scenarios.

6.6. Phytoremediation

Phytoremediation is a well-known technique that uses plant species to accumulate salts in order to reduce their soil concentration. Mainly three kinds of approaches of phytoremediation are available to minimize soil salinity: (i) agroforestry, (ii) biodrainage, and (iii) halophytic plants.

6.6.1. Agroforestry

Salt-tolerant fruits, fodder, and tree species could survive under low water requiring saline irrigation in arid and semi-arid regions (Minhas et al., 2020b). Dagar et al. (2015a) used salt-tolerant fruit crops, namely *Carissa carandas*, *Emblica officinalis*, and *Aegle marmelos* along with companion crops such as *Hordeum vulgare*, *Brassica juncea*, *Cyamopsis tetragonoloba,* and *Pennisetum typhoides* in inter-row spaces, irrigated with (EC_{iw}: low= 4-5; high= 8.5-10.0 dS/m) saline water. Results suggested that *C. carandas* with *P. typhoides* and *H. vulgare* performed the best with saline water irrigation in sandy calcareous soil. Recently, Dagar and Yadav (2017) reported that fruit crops such as gooseberry (*E. officinalis*), ber (*Ziziyphus mauritiana*) and sapota (*Achras zapota*) could tolerate ESP up to 60 in sodic soil. Similarly, among agroforestry trees, *Prosopis juliflora* was considered suitable (pH > 10) for sodic soils followed by *Tamarix articulata* and *Acacia nilotica* (Dagar et al., 2001). However, *P. juliflora, T. articulata,* and *Salvadora persica* could be raised successfully in saline soils at up to EC_e 30-40 dS/m (Dagar and Yadav, 2017). In another experiment, alfalfa (*Medicago sativa*) was evaluated for five years, and it reduced salinity considerably and added high C and N in soil to improve the soil quality across the profile (Cao et al., 2012). Biomass mulching, root exclusion and salt removal through alfalfa shoots could be the mechanisms for reduced soil salinity. Medicinal aromatic plants like *Glycyrrhiza glabra* was also found suitable in alkali soil with high economic values in terms of net returns (2.4–6.1 t/ha forage, and 6.0–7.9 t/ha root biomass, per annum) (Dagar et al., 2015b).

6.6.2. Biodrainage

Biodrainage is a technique of using tree species that reduce the water table by transpiration, mainly in waterlogged areas. Ram et al. (2011) evaluated the performance of clonal Eucalyptus (*Eucalyptus tereticornis*) planted on field boundaries in a waterlogged soil, and found that groundwater table was lowered down by 2 m after 5 years. Till date, Eucalyptus has been the most efficient species for lowering down of water table in canal command areas (Dagar et al., 2016). Dagar et al. (2016) revealed that Eucalyptus lowered water table by 43.0 cm in 1 m × 1m, 38.5 cm in 1 m × 2 m, and 31.5 cm in 1 m × 3 m spacings during the fourth year of plantation compared with no tree plantation. In addition, a recent study showed that Eucalyptus stored carbon to the tune of 21.2-22.8 Mg/ha in surface soil under agri-silvicultre system (i.e., intercropping of timber and fuel wood species, and/or fruit and other useful trees with vegetables and other crops in a common space, at the same time) (Kumar et al., 2019c). However, it was recommended that high water demanding trees such as Eucalyptus (*E.* tereticornis), Populus (*Populus deltoides*) along with Panicum (*Panicum maximum*), and Leptochloa (*Leptochloa fusca*) could manage the waterlogged saline soil (Dagar, 2014).

6.6.3. Halophytes

Halophytes refer to the plants which can grow and adapt under saline conditions. Halophytes of the genera such as *Pandanus, Pongamia, Panicum, Plantago, Porterasia, Prosopis, Rhizophora, Salicornia, and Salvadora* are popular for the reclamation of salt-affected soils. Halophytes are classified according to their salt tolerance or exclusion, which is shown in Table 3 (Grigore and Toma, 2017).

Three key mechanisms of salt tolerance by the halophytes include: (i) avoidance, (ii) evasion, and (iii) tolerance (Batanouny, 1993; Hayat et al., 2019). Cultivation of *Atriplex halimus* decreased EC from 39.2 to 26.5 dS/m of saline-sodic soil, and from 6.2 to 4.9 dS/m of saline soil (Abdul-Kareem and Nazzal, 2013). Ravindran et al. (2007) reported that the halophytes (*Suaeda maritima* and *Sesuvium portulacastrum*) reduced EC_e and SAR of a saline soil (EC_e >4 dS/m and SAR >13) to a level of normal soil due to accumulation of large salt amounts in the plant tissues. Zahran and Abdel Wahid (1982) reported that *Juncus rigidus* reduced the soil EC from 33 to 22 dS/m during its growth cycle. In addition, mangroves having aerial roots were found useful and economic in coastal saline soil reclamation, protecting the coastal areas from tide and providing a common habitat for saline aquaculture with shrimps (Dagar and Yadav, 2017). Popular mangrove species include *Aegialitis rotundifolia, Aegiceras corniculatum, Avicennia marina, Avicennia officinalis,* and *Bruguera gymnorrhiza* which are habitat of Sundarban, and Andaman Islands in India (Dagar and Yadav, 2017). Therefore, halophytes offer an economic and ecological solutions for management of waterlogged saline soils.

6.7. Bioremediation

Bioremediation involves the use of various microorganisms or microbial consortium to reclaim salt-affected soil. The soil microbes include plant growth promoting rhizobacteria (PGPR), bacteria, mycorrhiza, and cyanobacteria able to reclaim salt-affected soil by producing various hormones and beneficial substances that enhance soil quality and plant growth.

6.7.1. Plant growth promoting rhizobacteria

Various PGPR showed their impact on salt-affected soil remediation by improving plant growth. The main mechanisms include production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase, indole acetic acid (IAA), and exopolysaccharides secretion to enhance crop growth (Singh, 2015). A list of PGPR along with their mechanisms on agricultural crops is given in Table 4 (modified from Choudhary et al., 2019).

6.7.2. Salt tolerant bacteria

Salt-tolerant bacteria generally show high requirement of salts, and exist in highly saline environment to regulate high osmotic pressure. The genera include *Ammoniphilus, Arthrobacter, Azospirillum, Bacillus, Brevibacillus, and Brevibacterium* which produce IAA, gibberellic acid, and other organic acids that can solubilize and transform nutrients present in soils. Some salt-tolerant endophytes have been reported to show similar mechanisms to PGPR for salt tolerance (Thijs et al., 2014). Research revealed that *Bacillus foraminis* and *Bacillus gibsonii* tolerated up to 7.5% NaCl (Arora et al., 2014). In addition, *Pseudomonas fluorescens*, and *Bacillus subtilis* were found successful in NH_3 production, while phosphate solubilisation was significantly higher under isolated *Acinetobacter baumannii* and *P. fluorescens* (Arora and Vanza, 2017). However, future researches should focus on salt-tolerant bacteria and their application to agricultural fields to avail success in this potential area.

6.7.3. Mycorrhiza

Mycorrhiza is the symbiotic association between roots of higher plants and fungi. Mycorrhiza is known for mobilization and solubilisation of nutrients even under saline environment. Reports are available on the beneficial impact of mycorrhiza such as improved mobility and availability of nutrients (Zn^{2+}, Cu^{2+}, P) in soils (Chang et al., 2018). Vesicular arbuscular mycorrhizae (VAM) generally helps in solubilisation of phosphate and P supply to plant roots in salt-affected soils because phosphate remains in precipitated forms due to presence of Ca^{2+}- and Mg^{2+}-based carbonate salts (Zhu et al., 2016). In addition, high K^+/Na^+ ratio maintenance by VAM fungi indicated their salt-tolerant mechanisms in saline soils (Wu et al., 2005). Contrasting reports are also available where VAM colonization in wheat was reported to be decreased by increasing salt concentration in the medium (Zhu et al., 2016). Other mechanism related to mycorrhizal action to salt-tolerance is the control of abscisic acid accumulation under osmotic stress (Auge et al., 2015). However, further investigations are needed to understand the molecular mechanisms of mycorrhiza under salt stress conditions.

6.7.4. Cyanobacteria

Cyanobacteria are gram negative, prokaryote, autotrophic, and blue-green bacteria. They can survive in extreme environments including under highly saline condition, and improve soil quality (Rossi et al., 2017). Mostly cyanobacteria were utilized as biofertilizer. It is a challenge to remove salts from soil using cyanobacteria in terms of quantity, but the use of cyanobacteria in association with salt-tolerant plants helps to increase the quantity of removed salts (Jesus et al., 2015). The main mechanisms employed by cyanobacteria are N-fixation, high biomass production, and extra-cellular polymeric substances (EPS) production that help the microorganisms to survive under salt stress conditions. The cyanobacterial genera which were used in different pot and field studies include *Anabaena*, *Nostoc*, *Calothrix*, and *Spirulina* (Li et al., 2019). Soil pH and EC were decreased (Singh and Singh, 2015), while soil fertility and soil enzyme activities were improved using *Nostoc ellipsosporum* HH- 205 and *Nostoc punctiforme* HH-206 under saline soil of India (Nisha et al., 2018). Additionally, *Anabaena laxa* RPAN8 showed 21-times higher acetylene reducing activity under salt stress condition, which was an indication of N-fixation (Babu et al., 2015). Similarly, the intracellular trehalose content of *Anabaena fertilissima* increased significantly under 250 mmol NaCl concentration (Swapnil and Rai, 2018). Besides, the IAA concentrations were found to be 20.05 and 27.17 µg/mL under 250 mmol NaCl in *Nostoc carneum* TUBT04 and *Nostoc commune* TUBT05, respectively (Chittapun et al., 2018). Gibberellins and cytokinins were also identified in *Nostoc kihlmani* and *Anabaena cylindrical*. However, potential application of cyanobacteria at field levels should be explored in integration with manure, biochar, and salt tolerant plants to evolve a green remediation technology for salt-affected soils.

7. Socio-economic and environmental impact

The monetary and environmental loss due to salinity, and the implication of proper management practices in the improvement of farmers' livelihood requires special attention, as described in the following sub-sections.

7.1. Socio-economic impact

Soil salinity caused crop growth and yield reductions which led to 27.3 billion US$ economic loss globally, and 1.2 billion US$ in India alone (Qadir et al., 2014). Among the mitigation technologies, SSD offered positive impact on farmers' socio-economic conditions. Manually installed SSD provided a benefit-cost (B: C) ratio of 1.26 with viable internal net return of 13.3% (Kamra et al., 2019). Reports revealed an approximate 40–50% yield increase in soybean-wheat cropping system compared to control (without SSD), which resulted in a B: C ratio of 2.6, and an internal rate of return (IRR) of 28% in Rajasthan, India (Sewa Ram et al., 2000). Even after 20 years of SSD installation, 15-20% additional economic benefit was obtained by the farmers compared to the sites without SSD (Tejawat, 2015). Furthermore, the socio-economic analysis of SSD indicated B: C of 1.5, IRR of 20%, and employment generation of 128 man-days/ha every year (Datta et al., 2000; Sewa Ram et al., 2000). Salt-tolerant genotypes played an outstanding role in the development of economy. Sharma (2010) reported that salt-tolerant rice, wheat and mustard varieties developed by CSSRI showed an estimated value of total annual produce around 4384, 46 and 69 million US$, respectively (calculated on the basis of the minimum support price rates of these crops in India for the years 2009 & 2010). The rice yield was increased to the tune of 1 t/ha where there was an existing practice of cultivating marginal salt-tolerant varieties (Sharma, 2010). The use of salt-tolerant genotypes reduced gypsum application by 10-15 t/ha for the reclamation of sodic soils (Mandal et al., 2018). Gypsum application to sodic soil gave positive impact with net value of 3771 US$/ha, B: C ratio of 2.47, IRR of 67% (Tripathi, 2011). The agricultural income generated from the reclaimed sodic soils was around 3410 million US$ in India (Mandal et al., 2018), which provided an opportunity of 2.8 million man days of jobs per annum. In coastal saline area of India, implementation of different land-shaping models along with best natural management practices resulted in enhanced farmers' income, allowing net returns from around 76 US$/ha for wet rice to 1935 US$/ha for wet rice-fish-vegetables (Mandal et al., 2018). Among agroforestry systems, *G. glabra*, a high value medicinal plant, produced 8000-10000 US$/ha in terms of root and biomass of high medicinal values (Dagar et al., 2015b).

7.2. Environmental impact

Climate change has many adverse environmental impacts on soil and groundwater salinity. Therefore, climate smart salinity management practices could provide different paths to alleviate salinity and its environmental impacts. The emission of CH_4 from salt-affected soils could be reduced by about 28-68% through biochar application, while the N_2O emission could be reduced by about 50% through manure application (Begum et al., 2019; Nguyen et al., 2020). Application of MSW compost to soils for the reclamation of salinity and sodicity might be harmful as the amendment contains multiple PTEs (e.g., Cd^{2+}, Cr^{6+}, Pb^{2+}, Zn^{2+}, and Cu^{2+}) (Meena et al., 2019). Therefore, MSW compost should be checked before soil application. Studies on groundwater salinity and toxicology due to climate change and salt leaching during the reclamation process also need research priorities.

8. Future research directions

Following are the thrust research areas that need worldwide future attention to sustain productivity of salt-affected soils under climate change conditions:

(i) Climate change impact on root zone salinity, solute movement at different depths, and the impact on soil properties of various agro-ecological regions of the world need immediate research attention using hydro-salinity modelling approaches (Corwin, 2020).

(ii) Sub-surface drainage integrated with inland saline aquaculture is a new area of research to achieve sustainable management of salt-affected soils. Experiments in this field should be conducted considering at the same time salt-load, soil nutrients, carbon loss. Their environmental impacts should then be assessed over long period (Castellano et al., 2019).

(iii) Halophytes have worldwide potential for salt tolerance (Hayat et al., 2019). The genes of halophytic plants could be transferred to crop genotypes in order to improve the salt-tolerance capacity of crops, especially for coastal saline areas.

(iv) Naturally available gypsum is scarce and of poor quality. Therefore, development of suitable alternative amendments to gypsum is the need of the hour.

(v) Functionalized biochar has enormous potential to manage sodic soils. Investigations on the impact of functionalized biochar on $CaCO_3$ dissolution in sodic soils, and on the associated soil properties should be pursued in the near future.

(vi) Salt-tolerant plant genotypes can cope up with soil salinity (Genc et al., 2019). Microbiological interventions with cyanobacteria on salt-tolerant plant roots and their integration with various organic amendments are a potential area of salt remediation warranting further research development (Rossi et al., 2017).

(vii) Integration of land shaping techniques with multi-enterprise agro-farming system is already performing well in coastal saline areas of West Bengal, India, and needs future research attention in coastal saline areas worldwide.

9. Conclusions

Climate change could accelerate the pace of soil salinity development all over the world and primarily in the arid and semi-arid regions. The different mitigation technologies, such as amendments (gypsum, biochar, MSW, zeolites), salt-tolerant genotypes, sub-surface drainage in waterlogged saline areas, micro-irrigation techniques (drip system), climate smart conservation agriculture, land shaping techniques, agroforestry, and microorganisms, have the capacity to reclaim salt-affected soils. These technologies can improve the physicochemical (pH, EC, bulk density, available soil nutrients) and biological properties (enzyme activities, MBC) of salt-affected soils worldwide, allowing to achieve improved soil health and productivity. The mitigation approaches are environmentally sound, and socio-economically viable to the farmers across various agro-ecological regions, and can be adopted according to the bio-physical and socio-economic conditions of the farming communities. Incessant research activities in this area (including a worldwide practice of the above technologies) would boost the global agricultural sustainability and food security in salt-affected regions.

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Conflict of interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

RM prepared the original draft. BS and NSB reviewed, edited and improved the draft. HSJ and PCS conceptualized and supervised the work, and reviewed and edited the draft.

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Tables

Table 1. Continent-wise area distribution of salt-affected soils (in Mha)

Continents	**Area under saline soil (Mha)**	**Area under sodic soil (Mha)**	**Total salt-affected area (Mha)**	**Sharing of the total global salt-affected area (%)**	**Reference**
North America	6.19	9.56	15.75	1.69	Fageria et al. (2011)
Mexico and Central America	1.97	0.00	1.97	0.21	Fageria et al. (2011)
South America	69.41	59.57	128.98	13.84	Fageria et al. (2011)
Africa	53.49	26.95	80.44	8.63	Fageria et al. (2011)
Australia and New Zealand	17.36	339.97	357.33	38.35	Fageria et al. (2011)
Europe	7.8	22.9	30.7	3.31	Shahid et al. (2018)
Asia	194.7	121.9	316.5	33.97	Shahid et al. (2018)
Total	350.92	580.85	931.67	100	Shahid et al. (2018)

Table 2. Country-wise salt reclamation strategies with major cropping systems in the world

Type of salt-related problem	**Countries**	**Popular methods of reclamation**	**Major cropping system**	**Reference**
Sodicity	Australia	Gypsum application	Wheat-pulses	Stevens and Pitt (2012)
Salinity and sodicity	India	Sub surface drainage, salt tolerant genotypes and gypsum application	Rice-wheat	CSSRI, 2014; Tiwari and Goel (2015)
Salinity and sodicity	China	Sub surface drainage, scraping out of salts and gypsum application	Rice-rice	Li et al. (2014)
Salinity and sodicity	United States & Mexico	Salt flushing, drainage, gypsum and organic amendment applications	Corn-wheat	Macmillan and Marciak (2001)
Salinity and sodicity	Pakistan	Sub surface drainage, amendments, salt-tolerant	Rice-wheat	Ahmed (2014)

		genotypes and gypsum application		
Salinity	Egypt	Sub surface drainage	Wheat-vegetables	El-Agha et al. (2019)
Salinity	Iraq	Sub surface drainage	Wheat-oil seeds/legume	Tiwari and Goel (2015)
Salinity	Iran	Drainage	Wheat-vegetables	Tiwari and Goel (2015)
Salinity	Israel	Drip irrigation	Wheat-vegetables	Girma and Abdulahi (2015)

Table 3. Classification of halophyte plants used for the reclamation of salt-affected soils

Class	**Definition**	**Example**
Euhalophytes	Plants that can accumulate salts and grow in saline condition having low respiration rate and salt permeable cell cytoplasm. They show succulence due to accumulation of salts and high osmotic potential.	*Salicornia europaea*, *S. maritima*, *Salosa soda and Halocnemum strobilaceum*
Cryno-halophytes	Plants that can grow in low to high salinity and excrete salts through salt glands in the leaves.	*Statice gmelini* and *Tamarix gallica*
Glyco-halophytes	Plants that have no capacity to salt permeability through cytoplasm but have limited capacity to grow in salts. These are mainly freshwater plants.	*Artemisia maritima.*

Table 4. List of plant growth promoting rhizobacteria and their mechanisms on agricultural crops in salt-affected soils

Microorganisms	Associated mechanisms	Crops	Reference
Enterobacter sp.	ACC deaminase	Okra	Habib et al. (2016)
Pseudomonas spp.	ACC deaminase	Tomato	Win et al. (2018)
Pseudomonas spp.	ACC deaminase	Wheat	Nadeem et al. (2013)
Klebsiella sp	IAA, organic acids	Oat	Sapre et al. (2018)
Azotobacter sp.	IAA, N-fixation	Maize	Rojas-Tapias et al. (2012)
Bacillus amyloliquefaciens	Gibberalic acid, abcisic acid	Soybean	Kim et al. (2017)
Enterobacter cloacae	IAA, ACC deaminase	Canola	Li et al. (2017)
Enterobacter sp.	ACC deaminase	Wheat	Sarkar et al. (2018)
Pseudomonas fluorescens and Azospirillum Brasilense	Phopshate solubilisation, auxin production	Wheat	Kadmiri et al. (2018)
Pseudomonas fluorescens and pseudomonas putida	ACC deaminase	Canola	Jalili et al. (2009)
Pseudomonas Fluorescens	IAA, siderophore	Black gram	Yasin et al. (2018)
Pseudomonas Fluorescens	IAA	Maize	Zerrouk et al. (2016)
Alcaligenes sp. and Bacillus sp.	ACC deaminase	Rice	Bal et al. (2013)

Enterobacter aerogenes and Pseudomonas Aeruginosa	ACC deaminase	Alfalfa	Liu et al. (2018)
Bacillales	ACC deaminase, siderophore production	Rice	Zhang et al. (2018)

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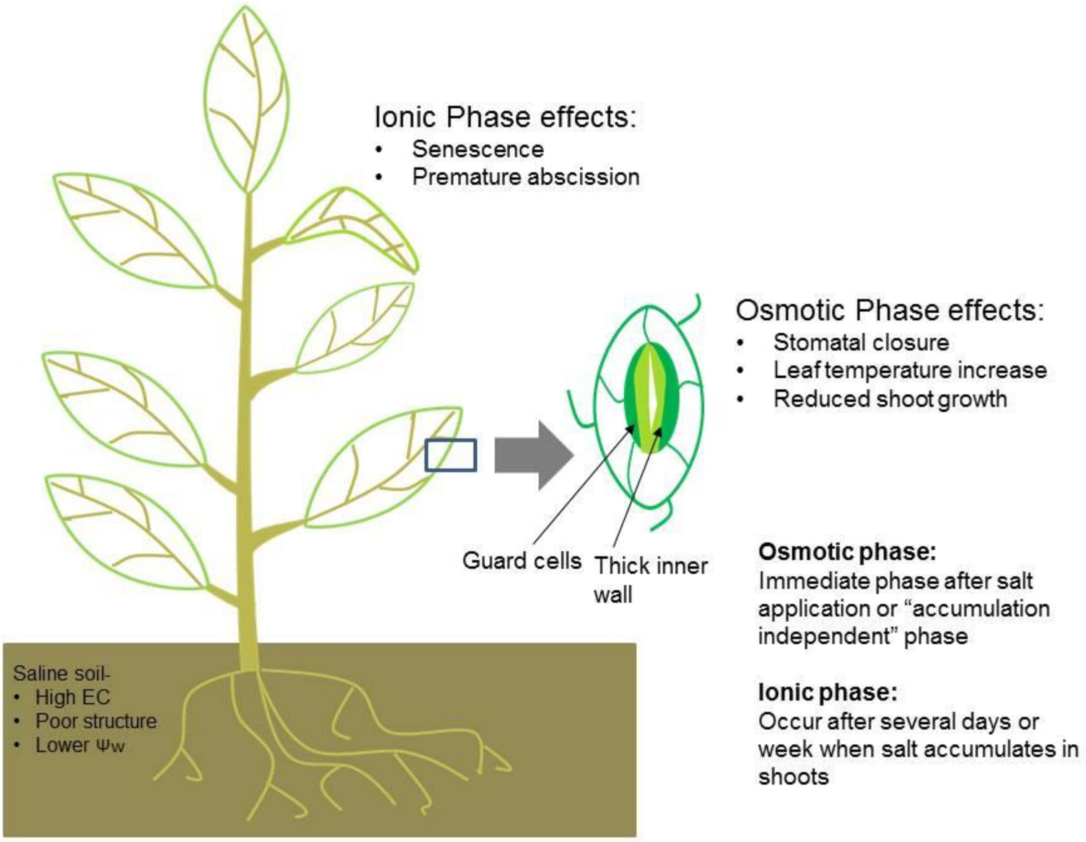

Figure 1.

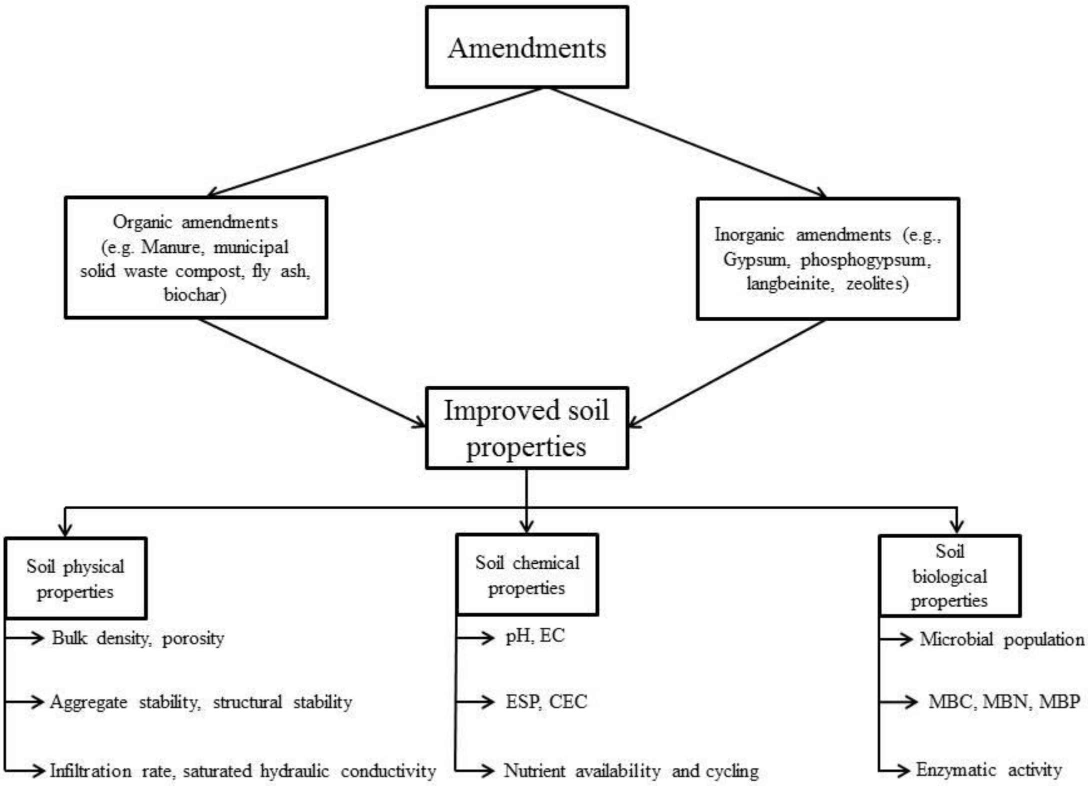
Amendments
Organic amendments (e.g. Manure, municipal solid waste compost, fly ash, biochar)
Inorganic amendments (e.g., Gypsum, phosphogypsum, langbeinite, zeolites)
Improved soil properties
Soil physical properties
Bulk density, porosity
Aggregate stability, structural stability
Infiltration rate, saturated hydraulic conductivity
Soil chemical properties
pH, EC
ESP, CEC
Nutrient availability and cycling
Soil biological properties
Microbial population
MBC, MBN, MBP
Enzymatic activity

Figure 2.

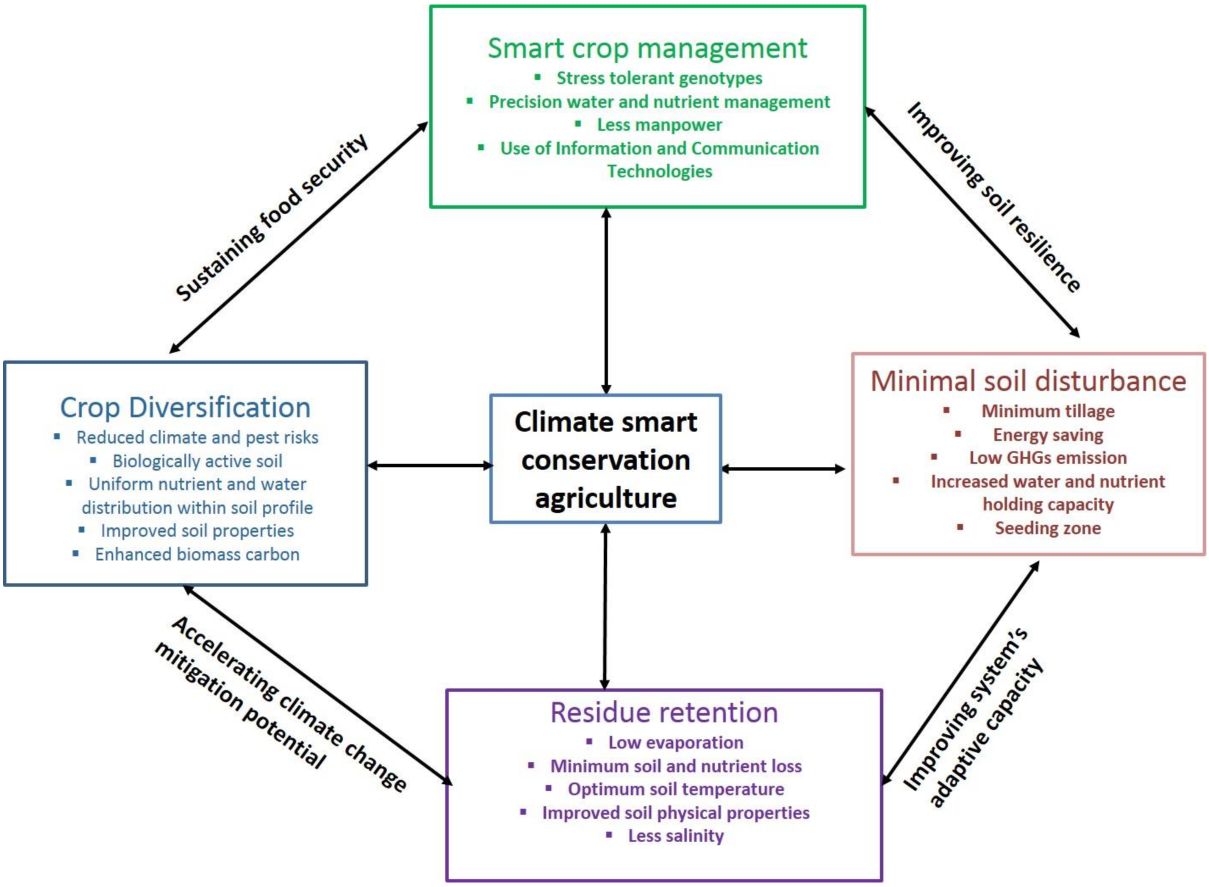

Figure 3.

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Figure 1. Plant's response to salinity stress (Munns and Tester, 2008; Sirault et al., 2009).

Figure 2. Beneficial effects of different types of amendments on soil properties in salt-affected soils.

Figure 3. Conceptual framework of agro-ecosystems based on climate smart conservation agriculture (adapted from Lal, 2015).