A Consultancy Report

on

Evidence based research on salinity management, technologies, and management strategies in context to salinity in Egypt

Submitted by

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1. Introduction

Soil salinity is a major challenge in arid and semi-arid regions that severely affects agricultural production. Increasing global population, anthropogenic activities, unscientific management practices, and climate change exacerbate the problem. Salt-affected soils are present in over 100 countries worldwide and are more common in arid and semi-arid climates. About 932 million hectares are affected by salinization and alkalinization worldwide, with 581 and 351 million hectares affected by sodicity and salinity, respectively (Table 1). Soil salinity already covers 20% of total cultivated lands and 33% of irrigated agricultural lands worldwide. About 40-60% of the world's salt-affected lands are saline and sodic in nature. The Asia Pacific region, which includes Australia, has the highest extent of salt-affected soils. Countries predominantly affected by land salinization include Argentina, Australia, China, Egypt, India, Iran, Iraq, Pakistan, Thailand, the former Soviet Union, and the USA.

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

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

Soil Salinity: Egyptian context

Egypt is situated in the northeastern region of Africa, between latitudes 22° and 32° N and longitudes 25° and 34° E. The country has a long history of irrigation, spanning over 5000 years. Egypt's climate is considered arid in the north (Alexandria) and highly dry in the south (Aswan). The aridity of the environment is characterized by a negligible amount of rainfall, which ranges from 190 mm along the Mediterranean coast to 20-50 mm in the south (from October to May). Annual potential evapotranspiration is about 1400 mm in the coastal zones and increases towards the south. Rainfall is not a significant water source for agriculture, except for a small area along the Mediterranean Coast in the Western Desert and the Sinai. Daily evaporation ranges from 1.5 to 8.5 mm, with a mean daily reference evapotranspiration from approximately 2.0 to 10.0.

Egypt's total land area is around 100 million ha. The country is heavily populated, with 60 million people living on less than 4% of the land, primarily in the Nile Valley, Nile Delta, and sparse cities along the northern coastal periphery. The total cultivated area in Egypt is 3.36 Mha. Egypt relies entirely on water from the River Nile, which provides 95% of the country's total water supply.

An early soil survey revealed that the percentages of salt-affected soils relative to the total cultivated lands were 60% in the Lower Delta, 25% in the Middle Delta, 20% in the Upper Delta and Middle Egypt, and 25% in Upper Egypt (Aboukhaled et al., 1975). A recent inventory concluded that almost 35% of Egypt's agricultural lands (approximately 1 Mha) suffer from salinity, wherein the electrical conductivity of the extract from saturated soil is higher than 4 dS/m (GARE, 1992).

The main reason for soil salinity in agriculture regions is the poor management of soil and water resources. Soil salinization processes are active in arid and semi-arid areas, considered the most important factors affecting crop productivity. Agriculture in Egypt depends on irrigation mainly from the river Nile and, in some places, from underground water. The principal irrigation water resources are the Nile and the water gathered in its dams, notably the Aswan High Dam. Croplands in Egypt are 100% irrigated since precipitation is very scarce and evaporation is very high. According to Mohamed (2016), three main factors cause salinization in the Nile Delta in Egypt: irrigation water, shallow groundwater (and waterlogging), and seawater intrusion. One of the problems of the Nile Delta was salinity affecting its clay-textured alluvial soils. This implies that leaching may be difficult, but the extent of the drainage canals does show that it is possible to drain this soil type. Generally, the soils are more sandy on the edges of the delta and in the desert. This could imply that the ideal soil type for using saline irrigation water is more on the edges of the delta, where there is more sandy, loamy soil inside the delta or in the desert. So, the overall soil type in the delta can be suitable for irrigation with moderately saline water, in combination with drainage and leaching. However, the soil type (heavy clayey to clay) can be problematic in combination with salts. The problem of salts and clay soils consists of the fact that sodium can replace calcium in the cation clay-humus complex, and when this happens, the soil structure “collapses”. The clay particles become more mobile and can block the pores in the soils, resulting in compact and potentially waterlogged soils (among others). Intensive cropland irrigation under an arid climate is the main reason for secondary soil salinization in Egypt. Unsuitable irrigation management, especially using salty sea and lake water, is a primary reason for increasing soil salinity in which sodium chloride (NaCl) is the dominant salt (EL-Assioti, 1992). Soil salinity is one of the significant problems for agriculture in semi-arid regions. In Egypt, plants are subjected to extreme climatic factors such as high temperatures and drought. Under these conditions, dissolved salts may accumulate in soils because of the insufficient leaching of ions (Mohamed et al., 2007). An accumulation of salt in upper soil layers may also be due to unsuitable irrigation management. Challenges faced by crop plants cultivated in the presence of excess salt are a disturbance of osmotic regulation, ion imbalance, and oxidative stress, which impair plant metabolism and growth.

2. Salt affected soils: Classification

Internationally, soil salinity is classified based on the pH of saturated soil paste, EC of saturated paste extract (EC_e), and exchangeable sodium percentage (ESP). Salt-affected soil includes saline soil, sodic soil, and saline-sodic soil. Sodic soils are characterized by high pH (>8.5), high ESP (>15%), and low salt concentration EC (<4.0 dS m^{-1}) (Table 2). However, saline soils are characterized by high pH (<8.5), high ESP (<15%), and low salt concentration EC (>4.0 dS m^{-1}). The saline-sodic soils are characterized by high pH (<8.5), high ESP (>15%), and low salt concentration EC (>4.0 dS m^{-1}). The characteristics are as follows:

Table 2. Classification of saline, sodic and saline-sodic soils

Type of soil	EC_e (dS/m)	ESP	pH_s
Saline	>4.0	<15	<8.5
Sodic	<4.0	>15	>8.5
Saline-sodic	>4.0	>15	<8.5

Major causes of salt-affected soils and their reclamation approaches are listed in Fig. 1.

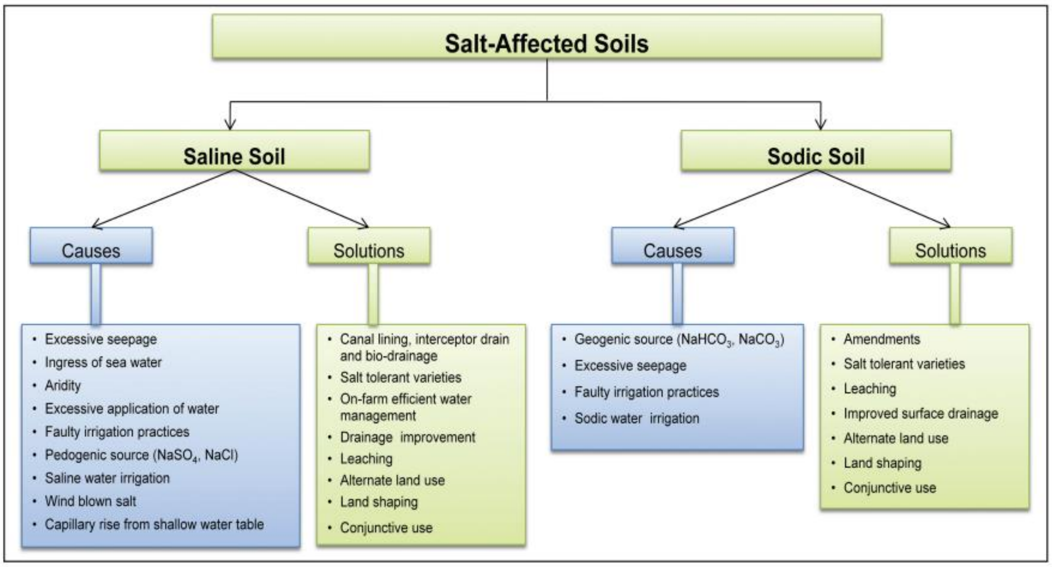

Fig. 1 Salt-affected soils and their reclamation approaches

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

Climate change refers to long-term changes in weather conditions and climate systems. Due to climate change, the following drastic changes have been observed, which greatly influence the development of soil salinity:

- ❖ Increase in the frequency of extreme weather conditions such as rise in air temperature, evaporation rate, excessive rainfall, and heat stress.
- ❖ Global warming due to increased concentration of greenhouse gases (e.g., CO_2, N_2O, CH_4) which trap the heat within the atmosphere.
- ❖ Variability in rainfall distribution leads to changes in soil moisture contents.
- ❖ 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.
- ❖ Rise in sea-level and sea water intrusion in the coastal areas limits their application for irrigation.

Countries and populations that are already vulnerable and impacted are at the greatest risk from the effects of climate change. This includes regions that are arid, semi-arid, landlocked, or small island developing states. Climate change will also affect global trade, food markets, and price stability, which could pose new threats to human health. Urgent and extensive efforts are required to address climate change and protect the capacity of food systems to ensure global food security.

Egypt is particularly susceptible to the effects of climate change, and is currently facing a variety of challenges, including rising temperatures, extreme weather patterns, water scarcity, and sea level rise. These impacts are already being felt throughout the country and are predicted to become more severe in the following decades. Some of the key impacts of climate change in Egypt are listed here:

- Rising Temperatures: Egypt is currently undergoing a warming trend, and it is projected that the average temperatures will increase by 2.1°C by mid-century and 4.4°C by the end of the century, if high emissions continue. This increase in temperature will result in more frequent and intense heatwaves, which can have a severe impact on the health of vulnerable populations.
- Extreme Weather Events: Egypt is experiencing a rise in extreme weather such as heatwaves, dust storms, floods, and droughts, which can cause widespread damage to infrastructure, agriculture, and ecosystems.
- Water Scarcity: Egypt, with its arid climate and growing population, is already facing water scarcity. This problem is expected to worsen due to climate change, leading to reduced rainfall and increased evaporation.
- Sea Level Rise: Sea level rise is a major threat to Egypt's low-lying coastal areas, including the Nile Delta. Rising seas could inundate homes, farms, and infrastructure, and displace millions of people.

Climate change is expected to have negative impacts on Egypt's agriculture. Irregular rainfall, rising temperatures, and water scarcity will lead to reduced crop yields and livestock productivity. In Egypt, irrigation is crucial for agriculture, but water scarcity will limit the irrigation process, which heavily relies on the Nile River. However, climate change is expected to alter the Nile's flow patterns, thus reducing available water for agriculture. Farmers in Egypt are already struggling with various challenges, and the reduction in water resources will only worsen their situation. Extreme weather events like floods and storms can disrupt transportation networks and damage storage facilities, hindering the movement and distribution of food. This can cause food shortages and price spikes, especially in vulnerable areas. Moreover, high humidity and warm temperatures favor the growth and spread of foodborne pathogens, leading to an increase in foodborne illnesses, which can pose a significant health risk to the population. Needless to mention that soil salinity adds to the more adversity and will have stronger impact on country’s food supply.

5. Soil salinity mitigation approaches for sustainable agriculture and food security (Potential technologies for Egypt)

Useful techniques for reclaiming salt-affected soils in affected countries along with their major cropping systems are given in Table 3. In addition to various organic and inorganic amendments, applications of microorganisms, halophytes, tree species, land use pattern change, CSA, and innovative irrigation and drainage strategies have been employed to reclaim salt-affected soils worldwide.

Table 3. Country-wise salt reclamation strategies with major cropping systems in the world

Types of salt-affected problems	Countries	Popular methods of reclamation	Major cropping system
Sodicity	Australia	Gypsum application	Wheat-pulses
Salinity and sodicity	India	Sub surface drainage, salt tolerant genotypes and gypsum application	Rice-wheat
Salinity and sodicity	China	Sub surface drainage, scraping out of salts and gypsum application	Rice-rice
Salinity and sodicity	United States & Mexico	Salt flushing, drainage, gypsum and organic amendment applications	Corn-wheat
Salinity and sodicity	Pakistan	Sub surface drainage, amendments, salt-tolerant genotypes and gypsum application	Rice-wheat
Salinity	Egypt	Sub surface drainage	Wheat-vegetables
Salinity	Iraq	Sub surface drainage	Wheat-oil seeds/legume
Salinity	Iran	Drainage	Wheat-vegetables
Salinity	Israel	Drip irrigation	Wheat-vegetables

There are number of amendments as well as management practices available throughout the globe and some of the promising technologies which can be adopted in Egyptian agrarian system are briefly described below.

5.1. Amendments

Various types of amendments can be used to reclaim sodic soils with variable impacts on soil properties (Fig. 2). Organic amendments, including biochar and compost of municipal solid wastes (MSW), and inorganic amendments that are rich in calcium, such as fly ash, gypsum, phosphogypsum (Fig. 3), and marine gypsum, as well as zeolites, have been found to be effective. These amendments improve the soil bulk density, aggregate stability, and hydraulic conductivity, while reducing the pH, electrical conductivity (EC), and exchangeable sodium percentage (ESP) of salt-affected soils. Additionally, amendments have a positive effect on soil biological properties, such as soil enzymatic activities, microbial population, and microbial biomass nitrogen and phosphorus contents.

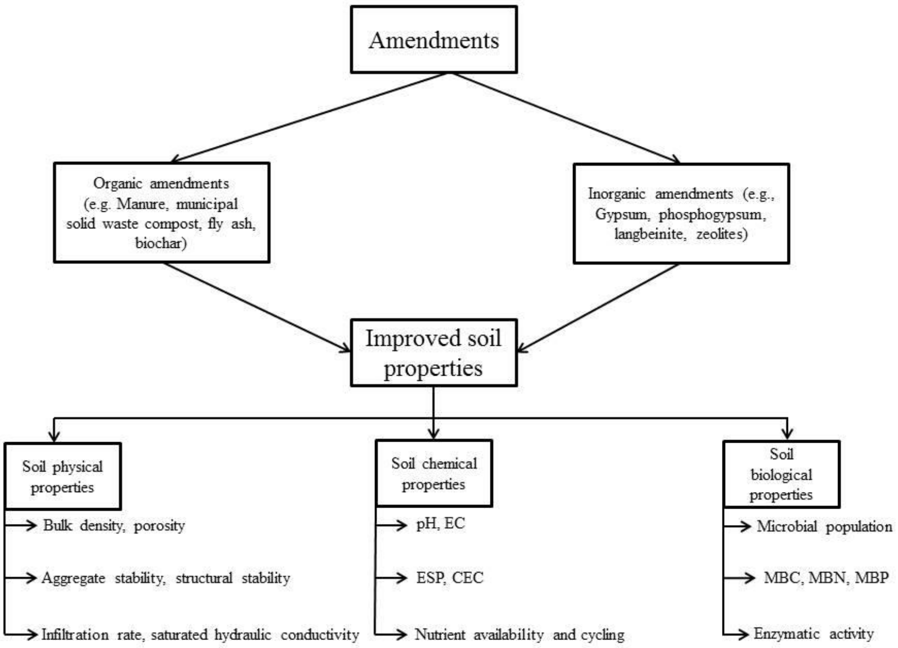

Figure 2. Beneficial effects of different types of amendments on soil properties in salt-affected soils.

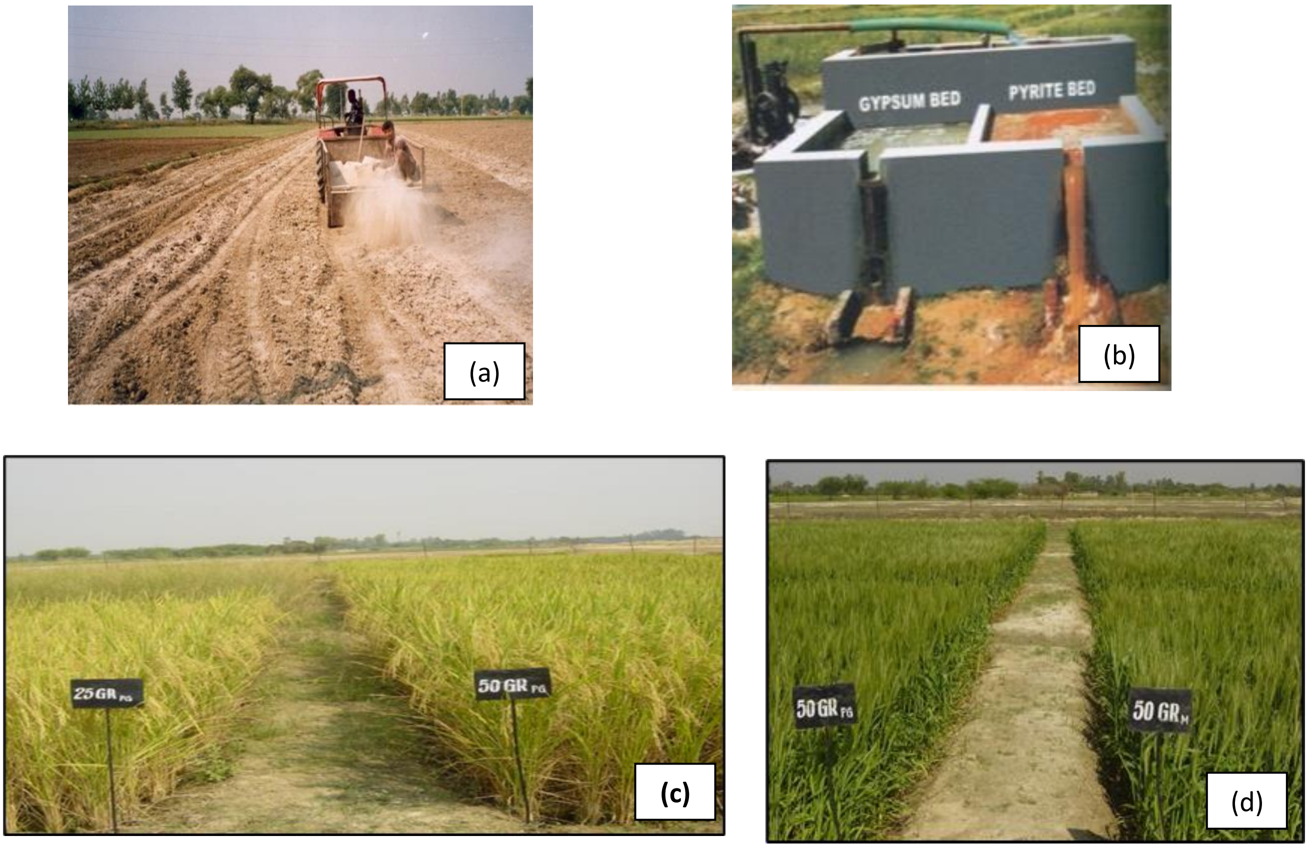

Figure 3. Gypsum application to soil (a), Gypsum bed technology for poor quality water management; Crop performance under different doses of gypsum (c & d) [Source: ICAR-CSSRI reports]

Flue Gas Desulfurization (FGD) Gypsum

Flue Gas Desulfurization (FGD) gypsum can serve as an alternative to regular gypsum for the reclamation of sodic soils (Fig. 4). The use of FGD gypsum led to a 50-60% increase in wheat yield compared to the control group in sodic soil with a pH greater than 9.0 in India. At farmers' fields, the use of FGD gypsum resulted in a pH reduction of 0.43-2.16 units.

Figure 4. Reclamation of sodic soils through FSD technology [Source: ICAR-CSSRI reports]

Other amendments include (i) Sulphur based formulations as an alternate to gypsum, (ii) municipal solid waste compost, (iii) biochar, (iv) fly ash, (v) zeolites,

5.2. 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. The salt tolerant varieties developed by ICAR-CSSRI are given in Table 3.

Table 4 Salt-tolerant varieties developed by ICAR-CSSRI

Name of crop	Salt tolerant varieties
Rice	CSR 10, CSR 13, CSR 23, CSR 27, CSR 30, CSR 36, CSR 43, CSR 46, CSR 56, CSR 60, CSR 76
Wheat	KRL 1-4, KRL 19, KRL 210, KRL 213, KRL 283
Mustard	CS 52, CS 54, CS 56, CS 58, CS 60, CS 61, CS 62
Chickpea	Karnal Chana-1
Lentil	PDL-1, PSL-9

5.3. Drainage strategies

Sub surface Drainage technology for waterlogged saline soil

Agricultural drainage is crucial to eliminate excess water caused by high precipitation, remove dissolved soluble salts from the soil profile, and maintain the groundwater table. However, due to a lack of attention, waterlogged salinity remains a severe issue in many productive areas across Australia, the Middle East, the United States, and Asia. The most effective technique for removing salts from a depth of 1.5 meters is sub-surface drainage

(SSD). Two types of SSD can be used for the reclamation of saline soils: (i) horizontal sub-surface drainage, which operates up to a depth of 1.5-2.0 meters in the root zone and comprises a network of drains consisting of the main drain, lateral drains, and collectors, and (ii) vertical sub-surface drainage, which involves the pumping of excess water by tube well. SSD installation increases yields by 50-100% in most crops, making it a profitable solution for farmers in salt-affected areas. Investment in surface drainage is also 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.

Figure 5. Subsurface drainage system installation in a field of Haryana, India [Source: ICAR-CSSRI reports]

Individual farmer-based groundwater recharge structures use gravity to pass excess rain and canal water through a bore well into subsurface sandy zones, which then flows through a recharge filter made up of coarse sand, gravel, and boulders. The filter is located inside a small brick masonry chamber and can be installed in any low-lying area prone to surface water flooding. These structures are easy to maintain and clean, making them more likely to be successful.

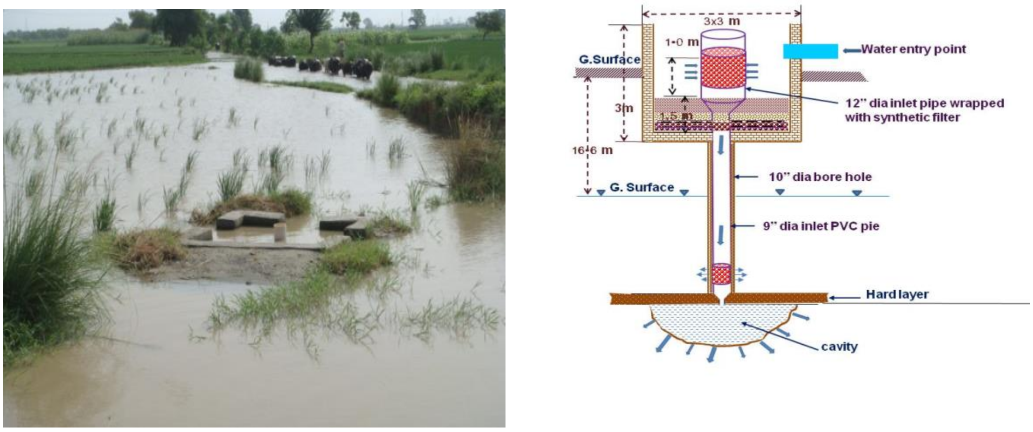

Figure 6. Groundwater recharge structures in Farmers' fields [Source: ICAR-CSSRI reports]

5.4. Bioremediation

The process of bioremediation involves the use of microorganisms or microbial consortium for the restoration of salt-affected soil. The soil microbes comprise plant growth-promoting rhizobacteria (PGPR), bacteria, mycorrhiza, and cyanobacteria which produce various hormones and beneficial substances that improve soil quality and promote plant growth. Phytoremediation is another method that involves using plant species to reduce the concentration of salts in cultivated soil. There are mainly three approaches for phytoremediation, namely agroforestry, bio drainage, and halophytic plants.

Halophytes are plants that can grow and adapt under saline conditions. There are several genera of halophytes, such as *Pandanus*, *Pongamia*, *Panicum*, *Plantago*, *Porterasia*, *Prosopis*, *Rhizophora*, *Salicornia*, and *Salvadora*, which are commonly used for the reclamation of salt-affected soils. Halophytes are classified based on their salt tolerance or exclusion, as shown in Table 5.

Table 5. Classification of halophyte plants used for the reclamation of salt-affected soils

Classes	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	*Salicornia europaea*, *S. maritima*, *Salosa soda* and *Halocnemum strobilaceum*

	accumulation of salts and high osmotic potential.	
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*.

5.5. Agronomic approaches

Nutrient management

Management of nutrients is one of the most vital factors for sustaining crop production on sodic soils or soils irrigated with sodic water. Optimum supply of nutrients to plants provides essential elements and help in overcoming the adverse effects of salts and specific ions stress.

Alkali soils have low organic matter and nitrogen, causing most crops to lack nitrogen. High pH and sodicity negatively affect nitrogen transformations. Applying nitrogen fertilizer correctly is essential for maximum benefit. Aside from nitrogen, phosphorus is critical for crop production. Sodic soils contain soluble phosphorus, but research shows varying responses to phosphorus fertilizer. Using amendments and growing rice under submerged conditions can decrease phosphorus levels in surface soil. Applying potassium fertilizer has no effect on rice and wheat yields. Studies suggest that application of potassium can be avoided without reducing crop productivity.

Irrigation water management

Saline groundwater challenges water management in arid and semi-arid regions. Sub-surface drip irrigation, controlled atmosphere storage, sprinkler irrigation, and low energy water application devices can save up to 53% of irrigation water and 40% of water compared to surface irrigation. Using saline water in conjunction with fresh water, sub-surface drip irrigation can effectively reduce the salinity effects and tackle water scarcity in semi-arid and arid regions.

5.6. 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. A short description of CSCA based agroecosystem is presented in Figure 3. The CSCA is a wonderful mitigation strategy for soil salinity under climate change, especially in global drylands.

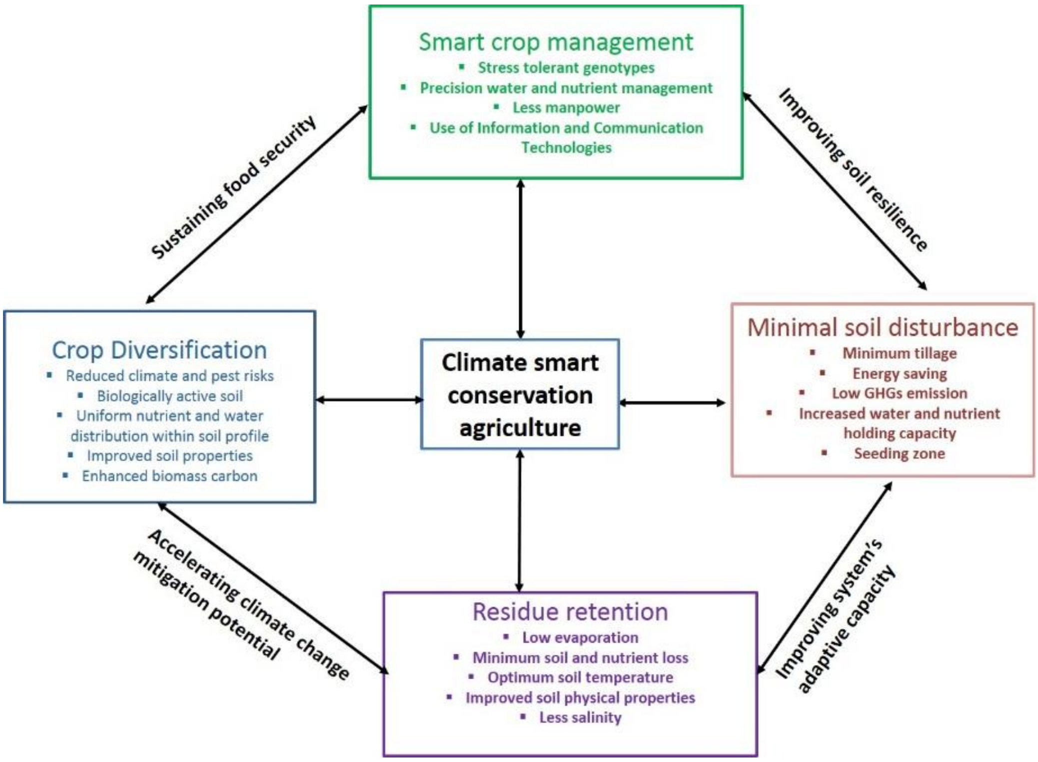

Figure 7. Conceptual framework of agroecosystems based on climate smart conservation agriculture.

CA and salt affected soils

Conservation agriculture (CA) practices are gaining global attention as a solution to the emerging challenges of declining system productivity, low input efficiency, deteriorating soil health, and farm profitability. One of the major and widespread challenges facing the world today is soil salinity, which adversely affects global food security and environmental sustainability in the arid and semi-arid regions of the world and has a negative impact on global agricultural production and biodiversity. Salinity is a particular problem in waterlogged and coastal areas, which are vulnerable to seawater intrusion and inundation, often due to climate change. Soil salinity impairs crop production globally, and conservation agriculture (CA) has been identified as a possible solution for maintaining the sustainability of soil production systems on degraded lands, as evidenced by normal/reclaimed sodic soils. The three principles of minimum soil disturbance, crop rotation, and soil cover that underlie CA practices make it an ideal practice for sustainable crop production that conserves soil and water resources while reducing input costs. The application of CA practices enhances soil quality by reducing the breakdown of soil aggregates, enhancing the infiltration rate, nutrient cycling, and soil organic carbon (SOC), which improves soil physical and biochemical properties while reducing soil erosion. CA practices also have higher energy-use efficiency compared to conventional tillage (CT). The increase in SOC and aggregate stability under CA plays an important role in regulating the movement of water and gas and nutrient cycling. CA practices may also help to mediate soil sodicity through zero tillage (ZT) and crop residue recycling. It is speculated that higher crop residues have the potential to reduce soil pH in the long term by producing organic acids during decomposition, which subsequently produce H+ ions and reduce soil pH. Another possible hypothesis is that acids produced during crop residue decomposition dissolve CaCO3 and thereby reduce soil pH.

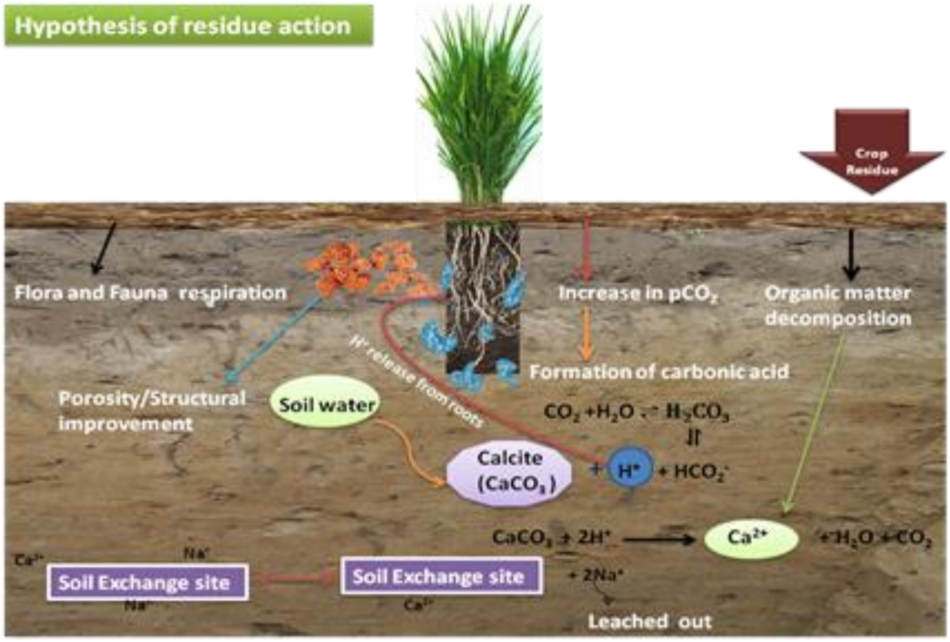

Figure 8. Hypothesis of crop residue action in soil

CA and cycling of irrigation water

Agriculture is facing multiple challenges worldwide, such as meeting the food demands of a growing population with limited land resources, combating salinity, and making productive use of saline soils. The dominant agricultural system is rainfed crops during the monsoon season, followed by fallow during the winter season, which faces long dry spells in the succeeding winter season. Therefore, adopting suitable water conservation measures and water reuse is considered a potential solution to supplement the freshwater needs of agriculture. The strategic use of available saline groundwater for irrigation, adoption of drought and salt-tolerant crops with matching agronomic practices, and other important strategies can help overcome the barriers in transitioning to an intensified system. Experiments have demonstrated that combining conservation tillage, mulching, and deficit irrigation with intensive cropping systems beyond rainfed monocropping, such as adding other salt-tolerant crops like wheat, mustard, and other seed spices into the rotation, can increase profitability, improve soil health, and increase overall food production. The combined practice of deficit irrigation and mulching appears promising because it reduces salt loading through irrigation water and reduces upward salt flux. These strategies can be a nature-based solution, working within the boundaries of available natural resources and synergized with the climate and soil type of geographical unit. In California, crop residue mulching and efficient water management can also increase water use efficiency with a lower risk of root zone salinity because of reduced salt loading, evaporation, improved water distribution, and efficient salt leaching from surface soil. However, the long-term use of saline water may result in soil salinization with associated crop losses. Therefore, it is necessary to develop alternative cropping systems with matching agronomic practices having a net effect of salt leaching for sustained productivity under saline water irrigated agriculture. In semi-arid regions with monsoonal climate, soil salinity and limited freshwater availability pose challenges to intensifying the cropping system. Under zero tillage (ZT) conditions, augmenting freshwater with saline groundwater along with crop residue retention could be an alternative strategy for increasing cropping intensity under saline soils. Results in the saline soils of Haryana, India showed that integration of ZT, deficit irrigation, and mulching is effective in intensifying the cropping system and can be a candidate crop in rotation with saline water irrigated wheat in a semi-arid region.

CA and bed plating system

Agriculture faces several challenges worldwide, including meeting food demand while handling limited land resources and saline soils. Adopting water conservation measures and using available saline groundwater for irrigation can supplement freshwater needs. Saline groundwater management, drought and salt-tolerant crops with matching agronomic practices can overcome barriers to intensifying the system. Adding salt-tolerant crops with conservation tillage, mulching, and deficit irrigation can increase profitability, soil health, and food production. The combined practice of deficit irrigation and mulching is promising. In California, crop residue mulching and efficient water management can increase water use efficiency. Alternative cropping systems with matching agronomic practices are necessary for sustained productivity under saline water irrigated agriculture. In zero-tillage conditions, augmenting freshwater with saline groundwater and retaining crop residue can increase cropping intensity under saline soils. Integration of zero-tillage, deficit irrigation, and mulching is effective and a candidate crop in rotation with saline water irrigated wheat in Haryana, India.

Figure 9. Conservation agriculture for salt-affected soils [Source: ICAR-CSSRI reports]

Future directions

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

1) 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.
2) Sub-surface drainage integrated with inland saline aquaculture is a new area of research to achieve sustainable management of salt-affected soils. Experiments should be conducted globally on the basis of salt-load, soil nutrients and carbon loss, and their environmental impacts over long period should be assessed.
3) Halophytes have worldwide potential for salt tolerance. 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.
4) Naturally available gypsum is scarce and of poor quality. Therefore, development of suitable alternative amendments to gypsum is the need of the hour.
5) Functionalized biochar has enormous potential to manage sodic soils. Investigations on the impact of functionalized biochar on $CaCO_3$ dissolution in sodic soils, and associated soil properties should be pursued in the near future.

6) Salt-tolerant plant genotypes can cope up with soil salinity. Microbiological interventions with cyanobacteria at salt-tolerant crop rhizosphere and their integration with various organic amendments are a potential area of salt remediation warranting further research development.
7) 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.

Conclusions

Climate change is increasing the rate of soil salinity development especially in arid and semi-arid regions across the globe. However, various mitigation technologies such as amendments (such as gypsum, biochar, MSW, and zeolites), salt-tolerant genotypes, sub-surface drainage in waterlogged saline areas, micro-irrigation techniques (such as drip system), climate-smart conservation agriculture, land shaping techniques, agroforestry, and microorganisms can reclaim salt-affected soils. These technologies have the potential to improve the physicochemical (pH, EC, bulk density, available soil nutrients) and biological properties (enzyme activities, MBC) of salt-affected soils worldwide, leading to improved soil health and productivity. The mitigation approaches are environmentally friendly and economically sustainable for farmers in various agro-ecological regions and can be adopted based on the bio-physical and socio-economic conditions of farming communities. Continuous research in this area, along with the global practice of these technologies, could enhance global agricultural sustainability and food security in salt-affected regions.

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