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REVIEW

Saline-alkali soil reclamation and utilization in China: progress and prospects

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KEYWORDS

Food security, land reserve, reclamation, saline-alkali soil, utilization

HIGHLIGHTS

- Saline-alkali land is an important underutilized resource in China that could complement arable land and maintain the food security.
- China has made great progress in saline-alkali soil reclamation and utilization, and developed customized technologies for these soils.
- In the future, comprehensive management strategies should be implemented by integrating traditional saline-alkali soil management practices and new technologies to increase crop tolerance.

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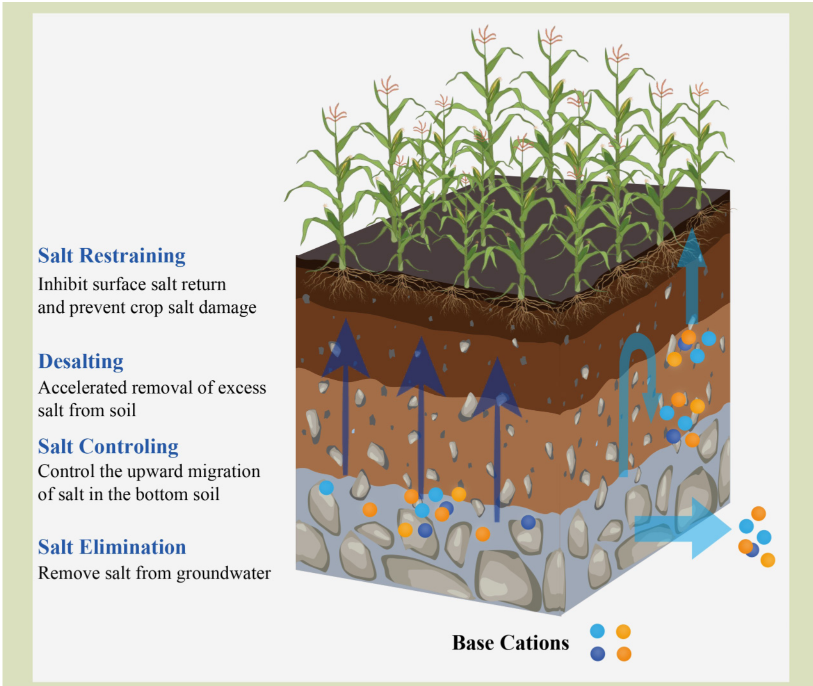
GRAPHICAL ABSTRACT



ABSTRACT

Soil salinity is a global threat to the productivity of arable land. With the impact of population growth and development of social economy in China, the area of arable land has been shrinking in recent decades and is approaching a critical threshold of 120 Mha, the minimum area for maintaining the national food security. Saline-alkaline land, as important backup reserve, has been receiving increased attention as an opportunity to expand land resources. This review first summarizes the general principles and technologies of saline soil reclamation to support plant growth, including leaching salts or blocking the rise of salts, and soil fertility enhancement to improve the buffering capacity. Then the progress in this area in China is described including the customization of technologies and practices used in different saline-alkali regions. Following the soil management strategies, the concept of selecting crops for saline soil is proposed. This encompasses halophyte planting, salt-tolerant crop breeding and the application of saline-adapted functional microorganisms to improve the adaptation of crops. Finally, the current problems and challenges are evaluate, and future research directions and prospects proposed for managing this major soil constraint.

1 Introduction

Soil salinization threatens agricultural production, food security and sustainable development worldwide. The area of saline soil in the world is about 932 Mha, occurring more than 100 countries on all continents except Antarctica[1]. Countries affected by salinization are mainly located in arid and semiarid climate zones, where rainfall is low and evaporation is high, which can easily lead to soil salinization. Salinization destroys soil structure and leads to soil degradation. It is reported that about 10 Mha of irrigated land is abandoned every year due to salinization[2]. With climate change, soil salinization is projected to intensify due to the impact of rising sea levels on coastal areas and increased evaporation due to global warming.

China has about 36.7 Mha of saline-alkali land, of which the total area with agricultural potential of about 12.3 Mha, 2.1 Mha of which is currently cultivated salt-affected land that is not effectively used, as well as 10.2 Mha of newly formed uncultivated land[3]. Among these saline lands, about 6.67 Mha has the potential to be used as arable land, 2.33 Mha is suitable for crop production after reclamation and the remaining 4.34 Mha is used for other agricultural practices. This arable land is dispersed in the northeast, northwest, central north, north and coastal regions[4], with 2 Mha each in the northeast and northwest, 1 Mha each in the north-central and coastal area and 0.67 Mha in the north[3].

Cultivated saline-alkali land is an important land resource in China, and reclamation and quality improvement of saline-alkaline soil can effectively expand land use and relieve food security pressures, and contribute to increasing food production and ensuring national food security. The Food and Agriculture Organization of the United Nations set the theme of World Soil Day 2021 as, “halt soil salinization, boost soil productivity,” suggesting the importance and necessity of efficient utilization of saline soil. In the past, much attention has been on saline soil reclamation to support plant growth by reducing the salt content, while recent progress in plant and microbial genomics offer solutions to increase crop tolerance in saline soils. Here, we comprehensively review the basic principles and strategies of saline-alkali land reclamation and utilization, feature the technologies used in different salt-affected regions, introduce the concept of selecting crops for saline soil and its progresses and development, and analyze the current challenges of saline land management, suggesting future research needed to address this major soil limitation.

2 Saline soil reclamation to support plant growth

2.1 Irrigation and drainage engineering

Soil base ions (e.g., Na^+, Mg^{2+}, Cl^- and SO_4^{2-}) reach the soil surface as water evaporates, forming saline-alkali soil. Salt-affected soil reclamation has two core approaches (Fig. 1): leaching salt from the soil by irrigating with fresh water, and inhibiting upward movement of the underground water table. In areas with high rainfall and sufficient irrigation, engineering measures like deep ditching, subsurface pipe drainage and wells are used to drain off salt ions. The ditching method can improve the drainage efficiency of irrigation or rainfall, and prevent the water table from rising to the threshold depth. Ditching is also an effective salt removal method on the surface and deep soil (< 80 cm), with average desalination rate reaching 32.6%[5], but the desalination effect may not be ideal for deeper soil layers. The underground pipe drainage technology uses buried pipes with holes at a soil depth of 1 to 2 m, then uses rainfall and irrigation to leach the salt from the soil[3]. The distance between underground pipes and burial depth are the most important factors affecting the efficiency of salt removal, as when the distance between pipes decreases, the efficiency of salt removal increases[5]. The establishment of a combined system of ditching and underground pipe drainage can significantly promote soil desalination as in combination they benefit salt drainage both vertically and horizontally, respectively. However, a major disadvantage of this approach is that a large amount of precipitation or irrigation water is required. Additionally, the leached salt should preferably flow into lake or oceans, and in areas with underdeveloped drainage systems, the discharged salt will accumulate, risking land degradation and desertification in downstream districts.

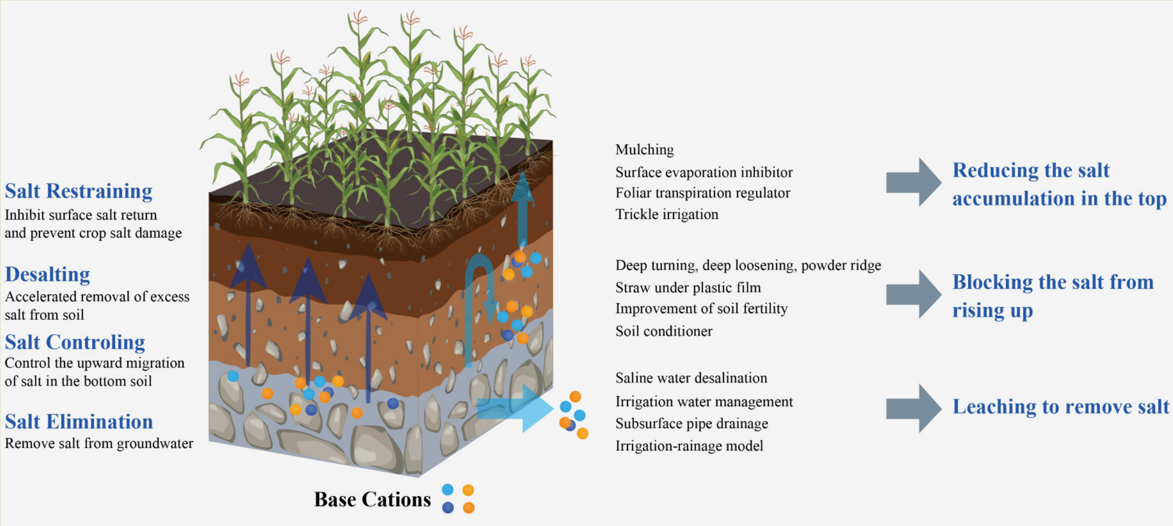


Fig. 1 Basic principles and techniques of saline-alkali land reclamation and management.

2.2 Land coverage and soil isolation layer to block the salt moving up

In areas without sufficient water, surface coverage and deep isolation layers can reduce water evaporation, as well as the amount of salt movement and accumulation in the topsoil. Surface coverage and deep isolation can create a desalinated plow layer and control the upward movement of salt by reducing evaporation and breaking soil capillary to reduce salt accumulation, respectively. The materials used for surface coverage include plastic film, straw, cover crop and liquid mulch. Straw or sand interlayers are installed at a depth of 40 cm to cut off the continuity of soil capillaries, blocking the upward movement of water and salt, so that the surface coverage further prevents water evaporation and surface accumulation of salt[3]. As a bonus, the straw returning into the deep layer also acts as soil fertilizer. The surface coverage and deeper isolation layer can be jointly utilized to improve the effectiveness of salt blocking, technology known as top-coverage and bottom-isolation, and are widely used in many saline-alkaline areas.

2.3 Balance the nutrient elements and salt ions by fertilization

Enhancement of soil fertility can further improve the buffering capacity and release of soil nutrients, thus promoting crop growth and salt tolerance. Additional application of organic fertilizer can also improve the soil structure by increasing soil aggregates, porosity and permeability, which is beneficial to salt leaching, as well as fertilizer and water retention. In addition to organic fertilizers, the application of chemical fertilizers or ameliorants is also important in reducing alkali and controlling salt. Nitrogen has both nutritional and osmotic benefits under saline conditions[6], and nitrogen application can improve salt tolerance and yield of crops[7,8]. Phosphorus is easily fixed in the soil, though soil salinity and alkalinity could further reduce phosphorus availability by affecting soil structure and permeability[9], soil microbial activities and alkaline phosphatase[10,11]. In turn, phosphorus fertilizer application could increase the uptake of P, K, Ca and Mg, which improves crop salt tolerance and productivity[12].

Acidic fertilizers are also widely used in saline and sodic soils. For example, ammonium sulfate as acidic fertilizer, contains many protons and also stimulate crops to release H^+ from roots when taking up NH_4^+, which reduces the pH of the rhizosphere soil and activates insoluble soil ions like Ca^{2+} and Mg^{2+}, leading to replacement of Na^+ and reduction of rhizosphere soil salinity[13]. In sodic saline-alkali soils, functional groups such as carboxyl released by organic fertilizer or other organic materials, or H^+ formed by hydrolysis of Fe^{2+} and Al^{3+} can neutralize OH^- released by CO_3^{2-} and HCO_3^- in soil solution, which reduces the degree of soil alkalization and pH[14]. The application of gypsum can help eliminate alkalinity as Ca^{2+} replaces Na^+ bound to soil colloids, combining with rainfall or irrigation to wash Na^+ from the soil[15]. Compared with one ameliorant, a combination of multiple materials could be more effective in saline soil reclamation and fertility improvement. For instance, compared with humic acid alone, the combination of gypsum and humic acid can significantly reduce soil pH and sodium adsorption ratio[16].

2.4 Cultivation practices

As an important part of agricultural production, vertical or horizontal cultivation practices have received increasing attention for saline soil reclamation. The plow pan is common in saline-alkali soil and the hardened impermeable layer hinders the process of salt leaching by rainfall and irrigation. Therefore, it is necessary to combine mechanical deep tillage to loosen the plow pan to promote rapid infiltration of water and improve the efficiency of salt leaching vertically. Compared with standard tillage, long-term deep tillage can reduce soil bulk density, accelerate salt leaching, and increase air and water permeability. With increased depth of tillage, the salt content gradually decreases, which is conducive to root growth[17]. Smashing ridge tillage at depths of 20, 40 and 60 cm of during cotton production has been shown to reduce soil salinity by 5.5%, 24.3% and 54.1%, respectively, and the increase yield of the 60 cm treatment by 84.1% compared with the standard tillage[18].

Furrow planting and irrigation is an alternative option to change the horizontal distribution of salt and protects crops from salt stress. There are various bed shape options to reduce salinity effects of plants[19]. If a sloping bed is chosen, due to water evaporation and the bed shape, the maximum salt accumulation will be either on the sides (Fig. 2(a)) or in the center of the bed (Fig. 2(b)). Thus, reduced salinity accumulation favors planting crops in the furrow, thus achieving a higher yield. If chosen to plant crops in the flatbed and both furrows are irrigated, it is proper to place the seeds on both sides of the flatbed as the maximum salt accumulation will be in the center (Fig. 2(c)). If crops are planted in the center area, they are less likely to germinate or seedlings will die over time (Fig. 2(d)). The furrow could also be irrigated alternatively, where one furrow is irrigated while the one next to it keeps unirrigated, so that the salt will accumulate on the ridges of the unirrigated side. In this situation, the crops should be planted close to the irrigated furrow (Fig. 2(e)). It is notable that furrow irrigation is more effective in areas with fine soil texture rather than a sandy soil as salt movement in the latter is prevented with high soil porosity and low granular structure.

3 Featured reclamation technology in different region

Soil salinization is a common problem worldwide, and much research and development on the topic has been conducted in different regions. Since the 1960s, China has made great advances in utilization of saline-alkali land according to the regional causes of salinization, climate characteristics and cropping systems (Table 1), which makes significant contributions to food security.

3.1 Mulched drip irrigation in Northwest China

In the arid and water-scarce regions of Northwest China, the limited rainfall (about 50–250 $mm \cdot yr^{-1}$) and large potential evaporation (> 1000 $mm \cdot yr^{-1}$) easily cause soil salinization[22].

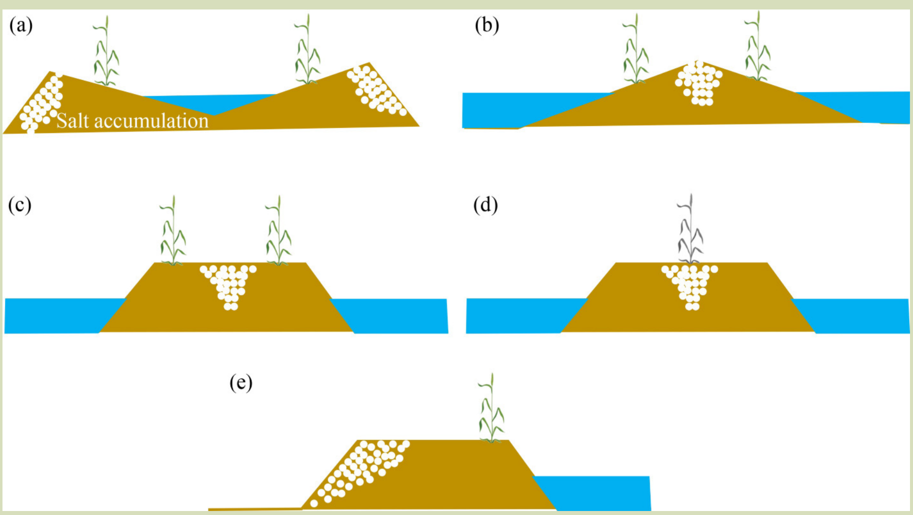


Fig. 2 Pattern of soil accumulation and safe zone for crop planting in different furrow irrigation systems: (a) sloping bed when furrow irrigation in the middle; (b) sloping bed when furrow irrigation on both sides; (c) and (d) flatbed when furrow irrigation on both sides; (e) flatbed when furrow irrigation on either side.

Table 1 The soil type, typical problem, climate characteristics and provinces affected in different saline-alkali regions

Region	Saline-alkali soil type	Typical problem	Precipitation (mm)	Evaporation (mm)	Major cropping system	Reference
North-west						
Xinjiang, Gansu, Ningxia	Sulfate or chlorinate-sulfate	Low precipitation, high evaporation	50–250	1500–3000	Cotton	[20–22]
North-east						
Liaoning, Jilin, Heilongjiang	Carbonate or bicarbonate	High soil pH and sodium content	300–600	1200–1800	Rice	[23–25]
Mid-north						
Inner Mongolia, Shaanxi	Chlorinate or sulfate	Secondary salinization due to irrigation	200–400	2000–2500	Maize	[26,27]
North China Plain						
Hebei, Tianjin, Shandong, Jiangsu, etc.	Chlorinate-sulfate	Fresh water shortage	400–1400	800–1200	Wheat, maize	[28–30]
Coastal area						
Hebei, Tianjin, Shandong, Jiangsu	Chlorinate-sulfate or sulfate	Sea water encroachment, high groundwater level	400–1000	1400–2400	Wheat, maize	[31,32]

To improve irrigation water use efficiency and control soil salinization, mulched drip irrigation is widely used (Fig. 3(a)). This technique has been practiced across Xinjiang since the early 1990s, and the area increase markedly from 50 kha in the early 2000s to 2 Mha in 2014[33]. Compared to flood irrigation, drip irrigation is one of the most efficient technologies because it drips water more uniformly and avoids deep percolation. Also, mulch reduces evaporation and keeps the salt ions from rising up to the soil surface[34]. During the irrigation period, the soil moisture is higher in the root zone than the bulk soil, thus, soil in the root zone is in a state of desalination, but with salt accumulation away from the drip irrigation[33]. Currently, this technology has been widely adopted and practiced in other places such as Gansu, Inner Mongolia and Jilin.

One important issue is that with the shift from flood irrigation to drip irrigation, deep layers of soils below the root zone cannot obtain enough water, which easily causes secondary salinization[35]. In addition, with the increase in drip irrigation, irrigation water consumption continues to increase, resulting in a decrease of water in the downstream area. This results in exacerbating the salinization and desertification of the soil, ultimately causing serious damage to the ecosystem. For example, from 1959 to 2006, the irrigated arable land in Xinjiang increased from 2.37 to 3.46 Mha[36]. Consequently, salt accumulation increased by 40% from 1983 to 2005, and over one-third (1.23 Mha) of the total irrigated land is now affected by secondary salinization induced by irrigation[37], which poses a major threat to agriculture sustainability.

3.2 Rice planting and alkalinity reduction in Northeast China

The area of salt-affected soil in Northeast China is 3.42 Mha, accounting for 19% of the total area[38]. The main characteristic of salt-affected soils in this region is sodic, as sodium accounts for more than 80% of the total dissolved cation concentration[23,24]. Rice has been planted since the 1950s on the Western Songnen Plain, with the planting area of saline-sodic paddy fields reaching 0.8 Mha by the beginning of the 21st century, accounting for 49% of the total area of paddy fields in the region[39]. Nevertheless, paddy rice can be effectively produced probably because the water dilutes salt in soil and the shallow root system of rice makes it less sensitive to high contents of Na^+ in the subsoil[40].

Sodic soil reclamation requires removal of as much of the exchangeable Na with other cations, improvement of the soil physical structure, and lowering of soil pH. Considering certain technical and/or economic reasons, most sodic soil research and practices focus on the use of chemical amendments, cropping and tillage. In consideration of effectiveness and cost, Ca^{2+} is an important ion to replace Na^+ (Fig. 3(b)). Of all the chemical amendments including Ca^{2+}, gypsum is the most common chemical amendment for sodic soil reclamation because it is comparatively cheap, generally available and easy to apply[41]. The exchange efficiency between Ca^{2+} and Na^+ depends on the contact of gypsum with soil particles and removal rate of Na^+ from the soil solution. Therefore, in most cases, fine gypsum is more effective because they dissolve more rapidly in water[42]. For the best results, after gypsum

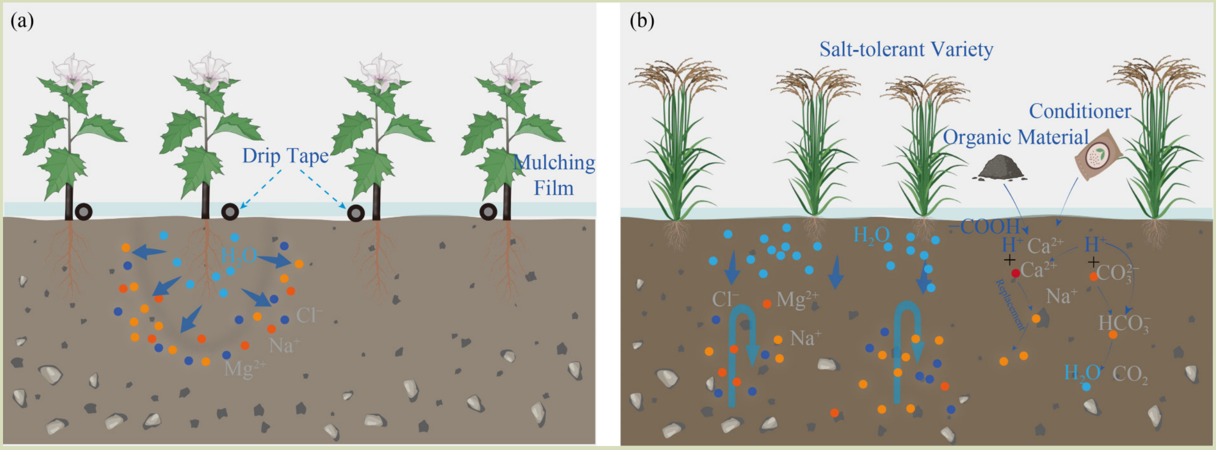


Fig. 3 Mulched drip irrigation technology (a) and paddy rice planting technology (b).

application, soluble Na^+ should be leached from the root zone using fresh water[43]. Chemical amelioration in some areas is still costly, thus, phytoremediation with low investment could be a viable substitution. Studies found that phytoremediation planting with Kallar grass and sesbania, along with chemical treatments and application of gypsum, resulted in similar decreases in soil salinity and sodicity, indicating that phytoremediation can replace or supplement the more costly chemical approach in less developed areas[44]. Sodic soil is characterized by a dense, sodic clay pan or a natric horizon with poor water penetration and high bulk density and degree of soil alkalization. Long-term amelioration for improving the structure requires the increase of macroporosity by tillage options such deep plowing, subsoiling, sanding (incorporating sand to the fine-textured soil) and hauling (replace the sodic surface soil with a good soil)[45].

3.3 Saline water utilization in the North China Plain

Home to 20% of the global population, China has only 6% of global freshwater resources, and the per capita water availability is about 2200 $m^3 \cdot yr^{-1}$, less than one-fourth that for the United States[46]. A typical example is the North China Plain, where the amount of water per capita is less than 500 $m^3 \cdot yr^{-1}$, reaching the absolute water scarcity level according to the widely used Falkenmark indicator[28], and serious groundwater overexploitation further results in a freshwater crisis. Constrained by the shortage of freshwater resources, water-saving irrigation and alternative water resources are currently important ways for saline-alkali land restoration and agricultural production. China is rich in saline and brackish water (2–5 $g \cdot L^{-1}$), with an available volume of about 20 billion $m^3 \cdot yr^{-1}$, of which 13 billion m^3 can be exploited. On North China Plain, there is more than 3.5 billion $m^3 \cdot yr^{-1}$ of exploitable saline and brackish water[47]. If these brackish water resources are fully utilized for agricultural irrigation, the problem of insufficient freshwater resources in irrigation areas in China can be effectively alleviated.

China started using brackish water in the 1960s and 1970s. Since then, we have seen that the exploitation of saline and brackish water resources not only helps to alleviate the water scarcity, but also supports groundwater resource renewal[48]. The comprehensive utilization of brackish water and limited fresh water requires a reasonable irrigation regime based on the salt-tolerance of different crops. Supplementary irrigation with brackish water at the crop tolerant stage can replace fresh water resources to support crop growth. For example, winter wheat can be irrigated with brackish water with a salt content of less than 4 $g \cdot L^{-1}$ at the jointing stage, and the yield is the same as that of freshwater irrigation[49]. Guo and Liu[50] proposed a technology to improve saline-alkali land by irrigating freezing salt water in winter based on the different freezing and melting points of salty and fresh water. When the temperature is below −5 °C from December to January of the next year, after irrigation the salty water freezes in the topsoil. Since the freezing point of saline water is lower than that of fresh water, when the temperature rises in spring, salty and fresh water will melt and infiltrate separately, with frozen saline water with higher salinity water melting first, and frozen fresh water with lower salinity melting later. The melting of frozen fresh water will also wash the early dissolved salt into the deep soil or from the upper soil layer, effectively reducing the soil salinity. A study using maize showed that using frozen saline water irrigation, the soil salinity in the 0–40 cm soil layer reduced by about 50%, and in the 80 cm decreased by about 43.6%[51]. In addition, salty water ice is rich in Mg^{2+}, Ca^{2+} and other cations with relatively small hydration radius that can replace excess Na^+. This technology facilitates the cultivation of many crops including wheat, cotton, oil-sunflower and sugar beet in saline coastal regions of the North China Plain[52].

3.4 Fertile layer construction

Low soil quality is a major problem plaguing the development of salty-soil agriculture across all the regions. Various measures have been taken to improve soil quality and build a fertile arable layer in different regions. In areas with heavy salinity, engineering measures are prioritized to wash salt out by flooding irrigation, open ditches, underground pipe drainage[53]. With the decline of soil salinity, agronomic measures such as land leveling, deep tillage, sand mixing and straw return can be conducted to deepen the plow layer and optimize soil structure[54]. The application of organic and chemical fertilizer, soil amendment and conditioner would further improve soil fertility and the buffer capacity to salinity[55]. Although multiple measures have been applied, there is still a lack of a standard indicator portfolio and thresholds to assess the fertile soil layer. In different regions the most optimal indicators for the establishment of fertile layer, such as salt content, fertility properties and plow layer depth, should be screened and verified. Future work needs to elucidate the mechanisms on the evolution dynamics of land salinization, the driving factors and principles of soil fertilization; although technically, regionally oriented governance and restoration are the priority as to optimize and improve soil conditioning.

4 Improvement of plant tolerance to saline soil

4.1 Halophytes to remove salts

Biological reclamation technology for saline-alkali land focuses on the salt tolerance of plants/crops. China has more than 400 kinds of halophytes and most these, including seepweed (*Suaeda salsa*), frog grass (*Salicornia europaea*), sesbania (*Sesbania cannabina*) and reed (*Phragmites australis*), have special osmotic adjustments or salt secretion mechanisms which allows them to grow in high salt soil[56,57]. In saline-alkali lands lacking fresh water resources, halophytes have been widely cultivated to reduce soil salinity content and improve soil physical and chemical properties. For example, when seepweed is planted in the arid saline-alkali area of Northwest China, there can be a reduction of about 3749–3911 $kg \cdot ha^{-1}$ of salt aboveground from soil every year, while salt content in the soil decreases overtime, particularly in the topsoil (0–40 cm)[58]. Halophytes can be grown in monoculture or via intercropping, used as nutritive and productive forage, biofuel and gourmet vegetables after harvesting[59]. In moderately saline soils, intercropping is generally adopted, while in severely saline soils, halophytes are usually planted continuously for several years in monoculture until the soil salinity drops to the salt-tolerant level of common crops. For example, the cotton/seepweed intercropping system can significantly reduce soil salinity and soil bulk density, as well as improve soil physical and chemical properties compared to standard cotton monocropping systems and cotton/alfalfa intercropping systems, with the salt removal capacity of 453 $kg \cdot ha^{-1} \cdot yr^{-1}$[60]. A three-year experiment showed that seepweed can extract as much as 3839 $kg \cdot ha^{-1} \cdot yr^{-1}$, removing the salt brought by irrigation[61]. This technique is a promising technology due to the advantages of water conservation, low investment, ecological sustainability and potential economic value. Further explorations on the combination of this measure with other soil improvement practices are necessary in future studies.

4.2 Crop breeding for salt tolerance

Apart from soil reclamation, another important aspect is to enhance crop salinity tolerance by conventional breeding and plant omics technologies[62]. Salt tolerance processes are complex with various mechanisms, which genomic approaches and crop physiology provide new insights to breeders to overcome salinity stress using new emerging tools for crop improvement (Fig. 4). Ion (Na^+ exclusion, K^+ influx, Ca^{2+} pump and Na^+/H^+ exchange), osmotic (polyols, proline and sugar accumulators) and oxidative (superoxide dismutase, catalase, glutathione peroxidase and other activators; and glutathione, ascorbic acid, flavonoids and other accumulators) homeostasis are important properties to improve salinity tolerance in stressful environmental conditions[63]. Therefore, halophytes and salt-tolerant crops are important germplasm resources encoded with abundant salt-tolerance genes with potential use in crop breeding. A recent study identified that the *Alkali Tolerance 1* locus in sorghum regulates the phosphorylation of aquaporins, which can transport hydrogen peroxide to alleviate oxidative stress, and the loss-of-function of this gene in sorghum, millet, rice and maize improves the field performance of crops in sodic land[64]. The novel approaches of plant breeding and biotechnologies like CRISPR/Cas gene editing, marker-assisted breeding, double

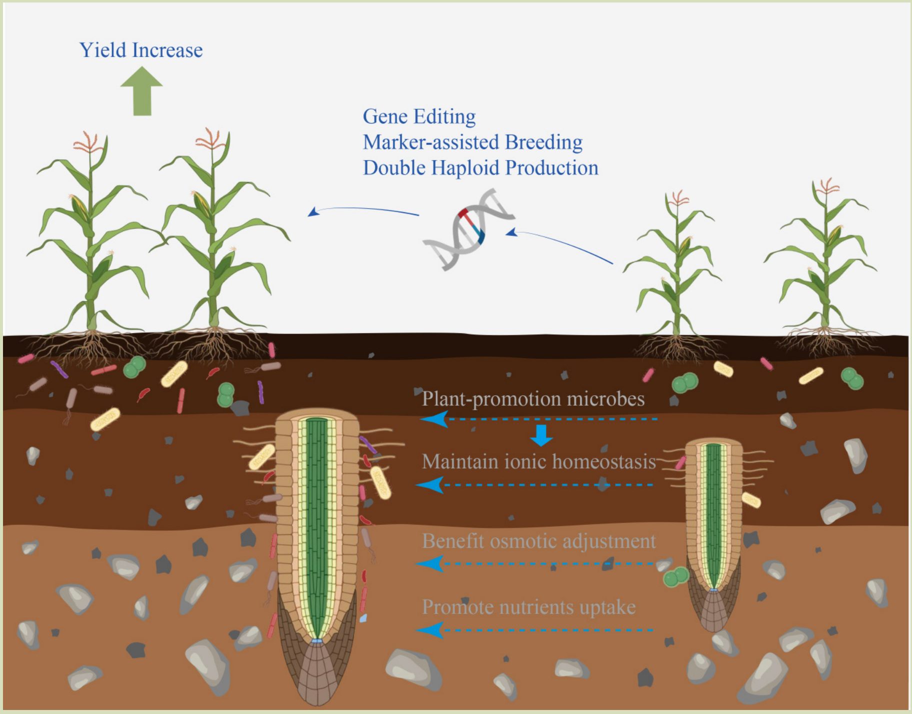


Fig. 4 Crop breeding and associated plant-promotion microbes to improve the adaptation of crop to saline-alkali stress.

haploid production hold great potential to accelerate the breeding process and cultivate the crops to be more salt tolerance[65]. The mechanisms of salinity tolerance are complex as multiple genes and pathways are involved; although considerable progress has been achieved, there still remain obstacles in transferring the current molecular knowledge into plant breeding activities. Advances in tools and methods of genetics- and genomics-related information and technology provide insights into dissecting the salinity tolerance mechanisms and manipulating plant genomics for accomplishing the breeding goals.

4.3 Salt-tolerant microorganisms for salinity management

Under salt stress, plants can recruit specific functional microorganisms by secreting volatile organic compounds, secondary metabolites, organic acids and other substances in their rhizosphere. These microorganisms in turn enhance the adaptability of plants to a saline environment and promote plant growth[66,67]. Microbes can maintain the ion balance by secreting osmotic adjustment substances such as exopolysaccharides to improve salt tolerance. Such compounds released by plant growth promotion microbes can bind excess Na^+ in the soil, thereby limiting its access to plant roots[68]. In addition, those beneficial microorganisms can (1) maintain ionic homeostasis via increasing Na^+ exclusion in roots or preventing the accumulation of Na^+ in leaves, (2) favor osmotic adjustment and enhance water uptake in plants, and (3) promote the nutrient uptake by plants (Fig. 4)[69–71]. The organic acids secreted by plant roots induced by microbes or by microorganisms themselves can also reduce soil pH, acidify the root layer and facilitate plant growth in saline soil. In addition to single-strain inoculation, synthetic communities may have a more significant regulatory effect due to the mutual promotion of each strain. Studies have shown that inoculation of a synthetic community composed of four species of *Paenibacillus amylolyticus*, *Stenotrophomonas rhizophila*, *Xanthomonas retroflexus*, and *Microbacterium oxydans* could better promote crop growth compared with a single species[72]. In order for exogenously inoculated microorganisms to survive in the soil and function more efficiently, it is necessary to combine organic materials, biochar and nanomaterials as substrates or carriers in agricultural practices. For example, the advanced formulation technologies, encapsulating microbes in a polymer matrix such as alginate beads promotes the slow release of microbes and protects them from the soil environment as well as other competing soil microbes[73–75], showing potential for improving inoculation efficiency.

5 Challenges and prospects

Although the saline-alkaline soil reclamation and utilization in China has made important contributions to grain production, there are still many deficiencies. First, there remain many duplicative and low efficacy technologies which are not suitable in agricultural practice. Second, as irrigation is the fundamental approach to leach the salt from soil, there is a conflict between saline-alkali land reclamation and water resource shortage. Third, the current saline soil treatment technology is too complicated to use with high cost and complex procedures, which makes it difficult for farmers to adopt and apply. Based on these shortages, we propose four aspects that need to be strengthened (Fig. 5).

(1) Develop restoration technologies specific for different regions. Factors such as climate characteristics, salinity type and salinity level in different regions of the country should be fully considered to maximize the efficiency of research technology, development and application, to avoid excessive repetitive work and build region-specific technical systems. Under such circumstances as fresh water shortage, collaborative innovation from multiple perspectives such as effective water management, soil fertility and structure improvement, and the salt tolerant crop breeding should be integrated into standard practices.

(2) Precise regulation and management in the crop rhizosphere. The rhizosphere is the hub that controls material, energy flow and information exchange in the plant–soil system, and thus is the most active hotspot for plant–soil and plant-microorganism interactions. Therefore, under the concept of selecting crops for saline soil, it is necessary to construct precise regulation and management in the rhizosphere to improve efficiency without wasting unnecessary fresh water. Recommended regulation techniques include drip irrigation to create a desalination root area, acidic fertilizer application to acidify rhizosphere and microbial inoculation to improve the tolerance and adaptability of crops. These comprehensive measures could strengthen the salt tolerance of crops and

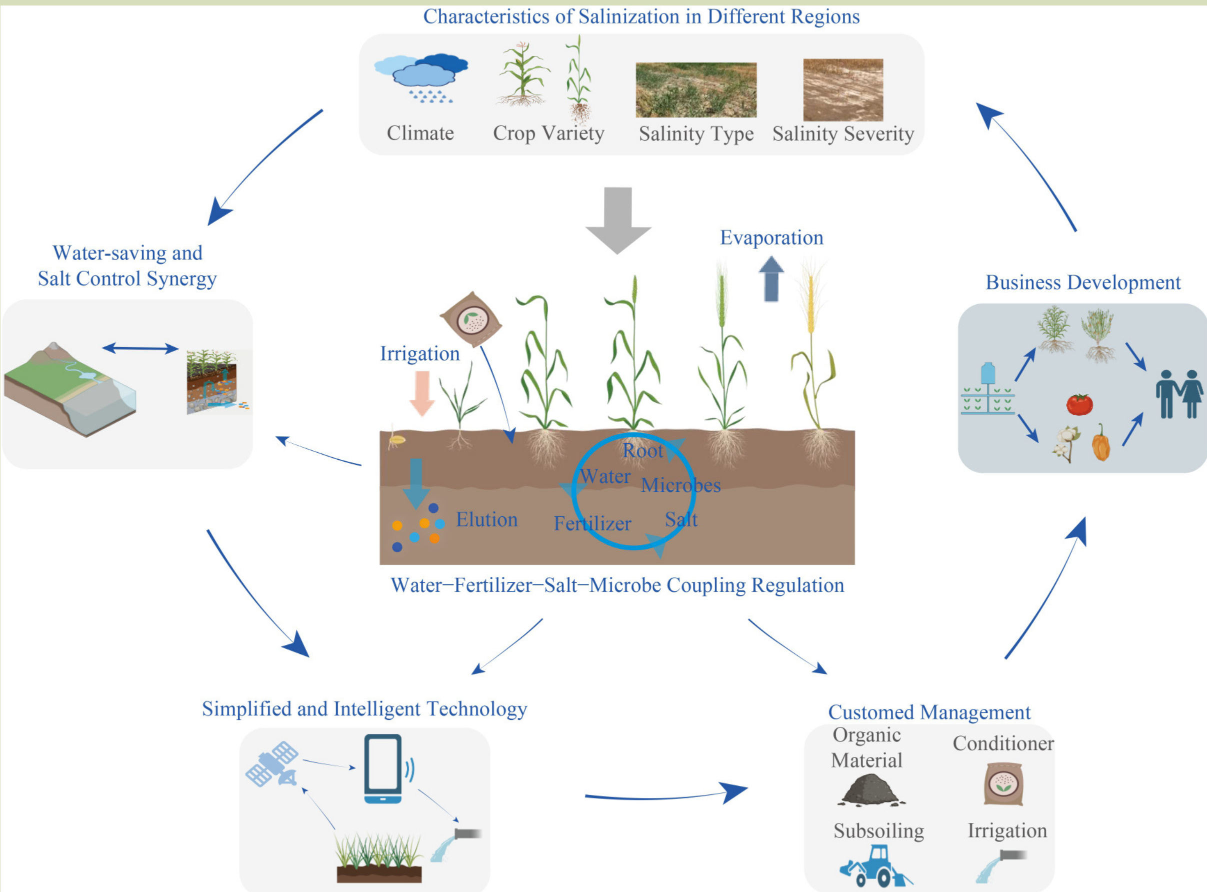


Fig. 5 Prospects of future saline-alkali land utilization and management.

promote saline-alkali agriculture in a more sustainable way.

(3) Comprehensive utilization of brackish water resources based on local conditions. Due to the limitation of fresh water, brackish water irrigation should be considered. A suitable irrigation regime, namely irrigation rate, frequency and time of applications to crops should be designed depending on the biological characteristics of plants as well as regional climatic, soil and hydrologic conditions of irrigated lands. In addition, it is necessary to adhere to the principle of using water as its capacity permits, and clarify the relationship between the protection and utilization of freshwater resources and marginal water resources in each region. Therefore, at the regional scale, analysis of spatial distribution characteristics of water resources and rational resource allocation are required to develop the most suitable method of water use.

(4) Research and development of simplified and intelligent technology. To improve the technology acceptance and application rate, in particular to reach smallholders, simple technologies and products need to be accessible. Specifically, precise diagnosis and monitoring of saline-alkali land need to be strengthened, followed up by the precise treatment of saline-alkali plaques due to the spatial heterogeneity. The new agricultural machinery could improve operation efficiency to save on labor, which will aid in modernized management of saline-alkali land. Digital technologies from different disciplines[76], including information science, computer and software engineering, remote sensing, combined with artificial intelligence, big data and machine learning, can all contribute to precise agriculture management, higher productivity and profitability.

(5) Commercial investment and business development of saline-alkali land. The cost of saline-alkali land reclamation and development is relatively high, and intervention of agricultural companies and capital will increase input, solving the problem of capital shortage. The entry of agriculture enterprises could introduce more efficient and advanced planting technologies, salt-tolerant cultivars and more readily hatch featured products. The improvement of planting or management scale will connect with the market more efficiently as it is better fitted with the market demand. Also, the production, marketing and sales of saline-alkali featured products could boost local employment and accelerate economic development.

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Compliance with ethics guidelines

Guangzhou Wang, Gang Ni, Gu Feng, Haley M. Burrill, Jianfang Li, Junling Zhang, and Fusuo Zhang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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