Postprint: Research Progress on Farmland Regulation and Control Techniques for Safe Utilization of Saline Water

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Abstract

Freshwater resource scarcity has become a global issue, and the development and utilization of underground saline water resources for agricultural irrigation has become a focal concern for various countries. Using brackish or saline water to replace partial freshwater for agricultural irrigation can alleviate freshwater shortages to a certain extent; however, problems such as soil salt accumulation and crop yield reduction caused by saline and brackish water irrigation remain key focuses and challenges in research. This paper addresses the potential soil salinization hazards caused by saline or brackish water irrigation, and in response to the secondary salinization issues arising from such practices, analyzes various approaches to mitigate soil salinization damage to crops by summarizing extensive previous research findings. The paper provides an overview of optimized agronomic measures, biological measures, and water engineering measures for farmland management from both brackish and saline water irrigation perspectives. The paper focuses on the effects of saline or brackish water irrigation on the soil microenvironment, optimized field management agronomic measures (such as rational irrigation scheduling and methods, mulching, deep tillage, etc.), application of organic materials (such as crop straw, organic fertilizer, green manure, biochar, etc.) and inorganic soil amendments (such as gypsum, zeolite, etc.) to soil, application of plant growth-promoting rhizobacterial fertilizers, cultivation of salt-tolerant plants and crop varieties, as well as water engineering measures such as saline water freezing irrigation and subsurface pipe drainage for salt removal. These are all effective methods for reducing soil salt damage from saline water irrigation. Centered on supplementary irrigation with brackish or saline water, combined with rainwater resource utilization, measures such as planting salt-tolerant crop varieties, increasing application of soil microbial fertilizer, and soil conditioners can enhance soil buffering capacity. Supporting measures like ridge tillage and plastic film mulching reduce soil evaporation and suppress surface salt accumulation, while straw return to field

and soil tillage techniques improve rainwater storage for salt leaching and rapid nutrient enhancement. Integrating safe and efficient brackish water irrigation technical models and establishing standardized technical application protocols, combined organically with various improvement measures, can effectively control soil secondary salinization in saline and brackish water irrigation districts, achieve efficient, safe, and sustainable utilization of saline water resources, and enhance water resource security capacity.

Full Text

Advances in Agricultural Practices for Attenuating Salt Stress Under Saline Water Irrigation

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Abstract

The shortage of freshwater resources has become a global issue, particularly in arid and semi-arid regions. The rational development and utilization of saline groundwater for agricultural irrigation has emerged as a focal concern worldwide. Many studies on agricultural saline water irrigation have demonstrated that reasonable utilization of brackish water does not cause crop yield reduction [1-5], making saline water irrigation an effective solution to severe freshwater scarcity [6]. Countries have employed saline and brackish water for farmland irrigation for nearly a century. In China, research on brackish water utilization began in the 1960s-1970s, with successful high-yield applications in Ningxia, Gansu, Inner Mongolia, Shanxi, Henan, Hebei, Shandong, and other provinces.

Using shallow brackish water to replace partial freshwater for agricultural irrigation can alleviate freshwater shortages to some extent, but soil salt accumulation and crop yield reduction resulting from saline water irrigation remain key research challenges. Saline water irrigation increases the risk of soil secondary salinization [7]. Excess salts in soil solution, primarily sodium salts, cause multiple negative effects: destruction of soil structural stability, deterioration of soil hydraulic properties, crop yield decline, and reduction in microbial biomass and soil enzyme activity [8-10]. Unsuitable long-term saline water irrigation leads to permanent soil degradation, destroys soil productivity, and causes serious environmental problems [11-12]. Soil health is crucial for sustainable agricultural and environmental development and is a prerequisite for crop production [13].

Without any ameliorative measures, long-term saline water irrigation will significantly reduce crop yields [11]. Therefore, developing effective management measures to achieve high crop yields and efficient saline water utilization under saline irrigation conditions, ultimately achieving coordinated and sustainable resource and environmental development, is imperative. Experts have attempted numerous methods to mitigate soil salt damage under saline water irrigation, achieving many successful experiences [14].

This paper analyzes and summarizes farmland regulation techniques under saline water irrigation, addressing the potential hazards and secondary salinization issues. The review examines measures from both brackish water irrigation (1-5 g·L^{1}) and saline water irrigation (>5 g·L^{1}) perspectives, aiming to provide guidance for future saline/brackish water irrigation agriculture.

Keywords: Brackish water irrigation; Saline water irrigation; Agricultural regulation practice; Biological practice; Soil environment; Secondary soil salinization

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1. Deterioration of Soil Microenvironment by Saline Water Irrigation

Saline water irrigation rapidly alters the concentrations of Na , Ca^{2} , and Cl in soil solution, with salt concentration depending on both irrigation water salinity and the frequency of saline water use during irrigation cycles [11]. Long-term brackish water irrigation increases soil pH and exchangeable sodium percentage (ESP), destroys soil physical structure, and leads to crop yield reduction [15-16]. In arid and semi-arid regions where soil evaporation greatly exceeds precipitation, salts from groundwater accumulate in the surface soil through capillary movement. Na can replace Ca^{2} and Mg^{2} —soil binding agents adsorbed on clay mineral surfaces or between soil aggregates—thereby destroying secondary clay minerals. As irrigation water salinity increases, soil total porosity and aggregate stability coefficient decrease, soil structure is destroyed, soil porosity declines, surface soil bulk density and saturated hydraulic conductivity increase, soil water permeability decreases, and soil water holding capacity increases [17], resulting in soil compaction [18].

Saline water irrigation-induced soil salinization not only negatively impacts soil physicochemical properties and crop growth but also significantly affects soil microbial quantity, activity, and biochemical processes that maintain soil quality [10]. Soil microorganisms are key factors in soil aggregate formation and stability; increased soil salinity reduces microbial respiration and population [19], leading to aggregate decomposition and soil structure destruction [10]. Soil Na primarily affects rhizosphere microbial structure indirectly through root exudate quantity and/or quality rather than through direct toxicity to microorganisms [20].

Reduced soil nutrient availability is another limiting factor for crop yield in saline soils. Brackish water irrigation significantly inhibits soil enzyme activity, decreases soil microbial biomass and CO flux, reduces soil organic matter degradation rate, and deteriorates farmland soil biological properties [21]. High-salinity saline water irrigation slows soil organic matter decomposition and mineralization of soil carbon, nitrogen, and phosphorus, thereby reducing soil nutrient availability and causing crop yield reduction [22]. Long-term brackish water irrigation decreases soil organic carbon and total nitrogen content [23]. Micro-brackish water with electrical conductivity less than 4.61 dS · m ^{1} has no effect on cotton growth and water-nitrogen use efficiency, while drip irrigation with saline water greater than 8 dS · m ^{1} inhibits cotton growth and reduces water-nitrogen use efficiency [24]. Na , Ca^{2} , and Mg^{2} in poor-quality irrigation water participate in soil ion exchange processes, causing K displacement from soil mica minerals and leaching into solution, thereby increasing groundwater K concentration. Under saline water irrigation, especially with water high in Mg^{2} , soil K release increases, which benefits crop absorption, but in the long term, this potassium is leached below the root zone [25–26]. Without sufficient potassium fertilizer input, long-term saline water irrigation leads to crop yield reduction [27]. Saline water irrigation on sandy loam soil causes leaching of Ca^{2} , Mg^{2} , K , and phosphorus while increasing the risk of shallow groundwater salinization [28].

2.1 Optimized Field Management Agronomic Practices

Field management agronomic practices are primarily physical amelioration methods and represent the most direct approach for improving saline-irrigated soils. These mainly include optimizing irrigation methods and scheduling (such as adopting water-saving drip irrigation, leaching salts through irrigation, rotational or mixed irrigation, and optimizing the sequence of fresh and saline water irrigation), deep tillage, subsoiling, soil turning, and mulching with inorganic materials (plastic film) and organic materials (crop straw).

2.1.1 Optimized Irrigation Scheduling

Brackish water irrigation methods mainly include flood irrigation, furrow irrigation, sprinkler irrigation, and drip irrigation. Flood and furrow irrigation have large water quotas, while sprinkler and drip irrigation offer clear water-saving advantages. The introduction of drip irrigation technology into brackish water utilization represents a revolutionary advancement. Drip irrigation with brackish water offers two key advantages: first, it avoids leaf damage, and second, due to the leaching effect of drip irrigation, salts accumulate near the wetting front, resulting in relatively low salt content in the soil beneath the emitter, which benefits crop growth while maintaining high matrix potential. Under drip irrigation, soil water content distribution is opposite to salt distribution, facilitating crop root development and water-nutrient absorption [29]. Compared with furrow irrigation, drip irrigation maintains ideal soil water content, reduces salt content in the root zone, and significantly improves soil physical properties and nutrient status while enhancing soil microbial biomass and enzyme activity. Water use efficiency under drip irrigation is on average one-third higher than under furrow irrigation, enabling efficient brackish water resource utilization without yield reduction and alleviating severe freshwater scarcity [30].

The combination of mulching and drip irrigation—mulched drip irrigation with brackish water—provides a reference for effective brackish water resource utilization and saline-alkali land development in arid and semi-arid regions. Mulched drip irrigation combines the benefits of drip irrigation (preventing deep percolation, reducing inter-plant evaporation, saving water and fertilizer) with plastic film cultivation (increasing temperature, preserving moisture). Drip irrigation creates a desalinated zone in the root area, while mulching inhibits soil evaporation beneath the film, promotes lateral salt movement, reduces deep percolation, and decreases the possibility of secondary salinization. Therefore, mulched drip irrigation is also used to prevent soil secondary salinization. Compared with conventional surface drip irrigation, subsurface drip irrigation with brackish water effectively prevents salt accumulation in the cultivated soil layer and has been widely applied in freshwater-scarce arid and semi-arid regions [31-32].

The characteristics of soil salt accumulation under long-term drip irrigation are crucial for determining the sustainability of this irrigation method. The timing sequence of fresh and saline water rotation under mulched drip irrigation significantly affects both crop yield and soil salt accumulation [33]. However, several issues remain requiring further research regarding brackish water irrigation using mulched drip irrigation [34-35].

The key technology for saline water irrigation is ensuring soil salt accumulation does not exceed crop salt tolerance. Therefore, rational saline water irrigation scheduling must be developed through experimentation, including irrigation amount, frequency, timing, and water salinity concentration. Optimizing irrigation methods combined with root zone soil salt management requires consideration of the interactions among evapotranspiration, salt content, soil type, precipitation, groundwater level, crop type, and water management. Irrigation scheduling should be tailored to local conditions based on salt accumulation patterns under brackish or saline water irrigation. Currently, mixed and rotational fresh-saline water irrigation has been widely utilized. This technology not only enables efficient brackish water resource utilization but also effectively controls surface salt accumulation in the root zone, maintains water-salt balance in the crop root zone, and ensures crop production safety. Crops exhibit different responses to water and salt stress during different growth stages. Post-harvest flood irrigation measures can be developed according to local conditions to leach accumulated soil salts. A single large flood irrigation after crop harvest effectively reduces soil salt accumulation and is more effective for salt control than applying the same amount of water during the growing season [36]. However, due to freshwater scarcity, salt leaching measures can only be implemented in regions with adequate water resources.

2.1.2 Mulching and Deep Tillage Practices

Salt accumulation in surface soil can be controlled by reducing soil evaporation. Compared with bare land, plastic film mulching—particularly crop straw mulching—more effectively reduces soil water evaporation loss and controls salt accumulation [37]. Straw mulching can reduce surface soil salt accumulation and sodium adsorption ratio (SAR) increase caused by brackish water irrigation [38-39], while simultaneously improving the vertical distribution of salts in the soil profile and maintaining lower salt levels in the dense root distribution layer, alleviating salt damage to crops and achieving significant yield increases [40-41].

Deep tillage and straw mulching treatments reduce soil bulk density in the 0-30 cm layer, increase soil porosity, and improve the distribution of water-stable aggregates. Compared with conventional tillage and straw removal, deep tillage and straw mulching reduce soil salt content by 20.3%-73.4% due to improved soil structure and permeability [42].

2.1.3 Ridge-Furrow Practices

Ridge formation artificially creates micro-topographic differences, leading to uneven surface evaporation and upward movement of water and salts from low to high positions. The micro-topographic changes produced by ridge-furrow practices alter the spatial distribution of local soil water and salts while improving soil physical conditions and optimizing soil physicochemical properties within furrows. Furrow irrigation under ridge-furrow systems shows better salt reduction effects than conventional border irrigation. Furrow-irrigated maize develops more robust root systems and achieves higher irrigation water use efficiency, making furrow irrigation a better method under low water conditions [43]. The ridge-furrow mulching planting method integrates two dryland cultivation techniques—micro-field water harvesting and plastic film mulching—based on three theories: mulched rainwater collection and superposition, rainwater infiltration in situ, and evaporation suppression by mulching. This approach combines "film surface rainwater collection, mulching evaporation suppression, and ridge planting" into one integrated technology, significantly improving soil temperature and physical properties while enhancing soil fertility [44]. Unlike ridge-furrow systems without mulching, the combined ridge-mulching method results in higher salt content at furrow bottoms than beneath ridges, helping crops avoid salt accumulation effects when planted on ridges under brackish water irrigation [45].

2.1.4 Application of Soil Amendments

The most effective method for ameliorating saline-sodic soils involves removing and exchanging soluble sodium salts by adding chemical amendments to alter soil ion composition while leaching Na out of the soil profile. Several methods have been recommended to reduce salt damage under saline water irrigation, including applying inorganic amendments such as gypsum, calcium chloride, and zeolite to reduce Na replacement in soils under saline water irrigation. Considering the cost and environmental impact of chemical amendments, finding cheaper natural amendments is more meaningful. Adding organic materials such as plant straw, organic fertilizer, green manure, animal manure, peat, lignite powder, and biochar are all effective methods for reducing soil salt damage under saline water irrigation.

1) Organic Amendments

Adding organic materials can accelerate sodium leaching, reduce ESP and electrical conductivity, and increase soil water holding capacity and aggregate stability [8,46]. Additionally, Walker and Bernal [47] demonstrated that organic amendments increase cation exchange capacity, with soil exchange sites being preferentially occupied by Ca^{2}, Mg^{2}, and K, thereby preventing Na from entering exchange sites. Long-term field experiments show that in wheat-rice rotation areas under brackish water irrigation, adding organic materials alone—such as wheat straw, green manure, and farm compost—can dissolve inherent Ca^{2} and Ca^{2} from CaCO precipitates in calcareous soils, increasing soil infiltration rates and achieving stable yields [16]. Applying livestock and farm manure improves soil fertility while reducing soil electrical conductivity and pH, preventing soil secondary salinization caused by brackish water irrigation and alleviating crop damage [48-49]. Humus application increases soil water and nutrient holding capacity, maintains good soil structure and high microbial activity, significantly reduces soil water evaporation, and improves crop water availability. Furthermore, humus promotes the transformation of various mineral elements into plant-available forms in soil [50-51], making it an effective measure for mitigating soil salt damage from saline water irrigation.

Increasing organic fertilizer application not only enhances soil humus content and favors soil aggregate formation but also improves aeration, water permeability, and nutrient status in saline soils. Nitrogen release in saline soils largely depends on the ratio of soluble carbon to total nitrogen in organic amendments [52]. Straw addition significantly increases soil nitrogen and phosphorus availability. Under salt stress, microbial carbon, nitrogen, and phosphorus are significantly affected by soil texture and straw amendments [53]. Although soil microbial respiration and biomass decrease with increasing soil salinity, straw addition increases soil microbial respiration and biomass, with greater effects in sandy loam than in clay soil and with alfalfa straw being superior to wheat straw [53]. After straw return to soil, the plow layer becomes loose with reduced bulk density and significantly increased non-capillary porosity, effectively inhibiting surface salt accumulation and maintaining lower salt levels in the main root activity layer without affecting normal crop growth [54]. Glucose addition increases microbial activity and growth in saline soils, alleviating the negative effects of soil salinity on microorganisms [19]. Therefore, organic amendments increase carbon sources, mitigating the impacts of saline water irrigation on soil microorganisms and nutrient availability while improving soil quality.

With mechanization in many agricultural regions, straw return to soil has been widely promoted. The deeply buried straw layer acts as a barrier to water and salt upward movement, preventing salt migration from deep soil and shallow groundwater and inhibiting salt return in the cultivated layer. Using crop straw and cow manure to fill soil, combined with film mulching and drip irrigation technology to create biological reactors for greenhouse vegetable production, effectively mitigates soil salt damage from saline water irrigation [55]. These biological reactors reduce soil salt concentration while increasing soil organic matter and nutrient content, improving soil environment and enhancing crop yield and quality [55].

Good water management combined with rational soil management is essential for sustainable crop production in drylands. Organic amendments contain substantial nutrients that can be released for crop uptake. However, irrigation with brackish water containing high Na and Ca^{2} concentrations can leach nutrients out of the root zone. Therefore, brackish water irrigation with organic amendments must be combined with technologies that prevent nutrient loss [48]. Some studies indicate that applying animal manure, such as poultry manure [56] and pig manure compost [57], can increase soil salinity and exacerbate crop damage from soil salt stress, suggesting that organic fertilizer application should be cautious in salt-sensitive soils.

2) Inorganic Amendments

Numerous studies have investigated adding inorganic amendments such as gypsum [23] and zeolite [67] to alleviate soil salinization under brackish water irrigation. Gypsum addition under saline water irrigation significantly improves soil physicochemical properties, increasing rice yield by 12.5% and wheat yield by 50% [16]. Long-term brackish water irrigation increases soil pH, SAR, and ESP while decreasing soil organic carbon and total nitrogen, whereas applying gypsum and organic amendments (such as green manure, farm compost, and rice straw) improves these soil properties [23]. The salinization hazard of brackish water irrigation varies with soil organic matter content [68]. After adding calcium sulfate and leaching, soils with high organic matter content maintain porosity unaffected by irrigation water salinity, while low organic matter soils show reduced porosity after saline water irrigation, possibly due to different iron-aluminum oxide contents affecting aggregate stability [18]. Gypsum and farm compost addition under brackish water irrigation also enhances soil nitrogen mineralization [23]. If appropriate measures such as fresh-saline water rotation or suitable soil amendments are applied, brackish water irrigation has no negative effects on crop yield and soil quality in wheat-cotton rotation areas [69]. In areas lacking freshwater resources where fresh-saline water rotation is impossible, gypsum must be used when irrigating with water containing high sodium ion concentrations [69-70].

2) Biochar
Biochar is a novel soil amendment that has received increasing attention in recent years. It refers to highly aromatic, refractory solid polymer products generated through relatively "low-temperature" (<700°C) pyrolysis carbonization of plant and animal residues or other biomass under complete or partial anoxic conditions [58]. Biochar application can increase crop yield by approximately 11% on average [59]. Biochar can alter soil physicochemical properties, improve soil fertility, and prevent soil biochemical property degradation [60]. Utilizing its high adsorption capacity, biochar application in saline-alkali soils can reduce soil bulk density, improve soil aeration, increase cation exchange capacity, and significantly improve soil physicochemical properties [61-62], while reducing soil salt content, sodium adsorption ratio (SAR), and ESP [63], enhancing carbon sequestration in saline-alkali soils, reducing greenhouse gas emissions, and increasing crop yield [64]. Under brackish water irrigation, biochar application promotes potato growth, reduces abscisic acid (ABA) content in stem base xylem sap and leaves, increases the K /Na ratio in stem base xylem sap, and mitigates potato damage from soil salt accumulation under saline water irrigation [65]. Biochar application under brackish water irrigation can also reduce soluble lead (Pb) content in soil and decrease Pb uptake by maize, thereby improving crop quality [66].

2.2.1 Application of Microbial Fertilizers

Under freshwater or limited freshwater irrigation conditions, high nitrogen fertilizer application rates achieve higher yields. However, under brackish water irrigation, optimal yields are obtained with low nitrogen application rates under both adequate and deficit irrigation [71]. Excessive nitrogen input under brackish water irrigation exacerbates crop salt damage [24]. If no other stresses exist, crops require less nitrogen fertilizer under brackish water irrigation conditions [72]. Microbial fertilizers can replace 23%-52% of nitrogen fertilizer without reducing yield but cannot replace phosphorus fertilizer [73].

Inoculation with plant growth-promoting rhizobacteria (PGPR) has proven to be an important measure for promoting wheat growth in saline-alkali soils. PGPR offers advantages including low cost, easy operation, and no side effects on soil. PGPR inoculation is an effective method for promoting crop growth and maximizing saline-alkali soil utilization under salt stress conditions [74]. Microbial fertilizer application replaces partial chemical fertilizer and improves fertilizer use efficiency. Recently developed microbial fertilizers with novel functions such as soil conditioning are significant for improving cultivated soil environmental quality [75]. Microbial communities play a crucial role in soil aggregate stability [76]. In arid and semi-arid regions, aggregate stability is an important property for promoting crop growth and preventing water and soil loss. Therefore, improving aggregate properties in degraded saline-alkali agricultural systems is particularly important. Microbial fertilizers possess multiple effects that other fertilizers cannot match, showing obvious advantages in enhancing soil salt damage buffering capacity under saline water irrigation.

Mycorrhizal fungi can significantly reduce plant Na and Cl uptake while promoting potassium and phosphorus absorption in horticultural crops. Mycorrhizal inoculation is a suitable method for improving horticultural crop salt tolerance under medium-to-high salinity brackish water irrigation [77]. Arbuscular mycorrhizal fungi inoculation can improve soil structure and increase soil organic carbon and available nutrient content [78]. Additionally, arbuscular mycorrhizal fungi improve photosynthesis and water use efficiency under salt stress [79]. Mycorrhizal fungi can improve crop carbon and nitrogen metabolism, increase relative water content, membrane stability, and leaf photosynthetic rate, promote protein synthesis and osmotic adjustment substance accumulation, and improve crop nutritional status, thereby reducing the impact of soil salt damage on crop yield [80].

Using nitrogen-fixing PGPR can promote maize K uptake, exclude Na uptake, increase the K /Na ratio, and enhance leaf chlorophyll content, thereby improving maize salt tolerance. PGPR application is an important biological method for reducing crop salt damage [81]. PGPR significantly promotes wheat growth and increases yield in field conditions [82]. PGPR-inoculated wheat exhibits low sodium content and high nitrogen, phosphorus, and potassium content [74]. PGPR promotes nutrient cycling in the rhizosphere [83], enhances crop nutrient absorption capacity, and plays an important role in maintaining nutrient balance in wheat. Under both saline and non-saline conditions, PGPR primarily promotes white clover growth by directly or indirectly regulating chlorophyll content, leaf osmotic potential, cell membrane stability, and ion accumulation [84].

Despite numerous advantages as an emerging technology for reducing salt damage effects on crops, microbial fertilizers have limitations: PGPR promotes crop growth under controlled conditions (laboratory or greenhouse), but field effects are uncertain due to variable natural conditions. Since PGPR cannot survive permanently in soil, annual or seasonal re-inoculation is required in the field [85], necessitating the screening and isolation of more advanced strains. The variable effectiveness of these strains results from PGPR population size and activity being affected by soil environmental conditions [86]. PGPR effectiveness depends on water salinity concentration and host crop growth stage [87]. The effectiveness of 45% of biofertilizers depends on crop nitrogen, phosphorus, and potassium fertilizer application rates and timing [73]. Farmers and agronomists must recognize the dual management of chemical and microbial fertilizers to achieve successful microbial fertilizer application.

2.2.2 Plant Improvement Techniques

Planting halophytes is an important pathway for saline-alkali land desalination. Halophytes can serve as a drought-resistant emergency measure in saline fields with severe freshwater shortage. Field and greenhouse experiments show that planting halophytes significantly reduces soil electrical conductivity, with *Suaeda* capable of removing 1–6 t · hm ^{2} · a ^{1} of sodium chloride [88]. These results are consistent with NaCl removal calculations based on Na and Cl concentrations in dry matter and total biomass under brackish water irrigation conditions [88]. Planting green manure crops such as sesbania can improve physicochemical properties under brackish water irrigation and increase wheat and rice yields, with the best improvement achieved when combined with gypsum application [89]. Additionally, planting transgenic salt-tolerant plants can increase yields [90–91].

Compared with bulk soil, rhizosphere soil in saline-alkali soils has lower salt content, higher water content, and greater microbial populations. Abundant rhizosphere microorganisms indicate that roots can reduce soil salt damage and provide a favorable environment for microbial survival. The increased microbial abundance and diversity in rhizosphere soil enhance the ability of microorganisms to maintain normal operation of degraded soil systems [92]. Soil Na primarily affects rhizosphere microbial structure indirectly through root exudate quantity and/or quality rather than through direct microbial toxicity [20]. Root exudates are proportional to aboveground [93] and root [94] biomass. Host plant salt tolerance determines the successful establishment of rhizobia-soybean symbiosis under high salinity conditions [95]. Plant health is the main determinant of rhizosphere microbial structure and nitrogen cycling [53]. Planting salt-tolerant crops indirectly improves rhizosphere microbial structure and nutrient status under saline water irrigation conditions, enhancing soil salt damage buffering capacity. Significant variation exists in salt tolerance among crop varieties, and planting salt-tolerant varieties directly affects final yield under brackish water irrigation [96].

In addition to the above farmland regulation measures, brackish water ice irrigation can effectively control salt accumulation in the plow layer under brackish water irrigation, with more pronounced effects when combined with straw mulching [97].

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3. Farmland Regulation Measures Under High-Salinity Water Irrigation

Numerous studies have examined the relationships among saline water irrigation, soil, water, salt, and crops, but most research focuses on salt-tolerant crops (such as cotton) in areas with water salinity of 2–5 g · L ^{1}. However, after saline water irrigation, leaching and drainage measures must be employed to maintain surface soil desalination for sustainable agricultural development and food security [101].

Saline water (16 dS · m^{1}) irrigation significantly inhibits barley growth, while zeolite amendment greatly promotes barley growth by reducing Na , Mg^{2} , and Ca^{2} concentrations, particularly in surface soil [67]. Mulching measures can improve the vertical distribution of salts under high-salinity water irrigation, inhibit upward salt movement, prevent surface salt accumulation, and show more pronounced salt reduction effects than under brackish water irrigation conditions [38–39].

Winter saline water ice irrigation technology involves using local saline groundwater to irrigate saline-alkali land in winter. Under low temperatures, saline water forms an ice layer. Due to different freezing points of saline water with different salt contents, the high-salinity portion melts first and infiltrates, followed by lower-salinity and freshwater portions that leach soil salts [102–103]. This promotes surface soil desalination, leaches harmful ions such as Na and Cl , and maintains lower salt levels and base ion balance in the dense root distribution layer, alleviating or eliminating salt and base ion damage to crop growth [97]. Saline water ice irrigation technology must be combined with straw mulching for optimal effect; without mulching measures or with delayed mulching, ideal salt control effects cannot be achieved [104].

Subsurface pipe drainage technology is a mature technique for saline-alkali land reclamation. Its principle is based on the water-salt movement mechanism of "salt comes with water, salt leaves with water." During precipitation or irrigation, salts move downward with water to the subsurface pipes and are removed from the soil profile, achieving salt leaching effects while controlling groundwater depth below the critical level to effectively inhibit upward movement of high-salinity water and reduce soil secondary salinization [105]. Subsurface pipe drainage technology shows significant effects in preventing secondary salinization in saline-irrigated soils, particularly in coastal lowland plains where it has broad applicability. This technology expands cultivable land area in coastal saline regions and enhances regional ecological service functions [106–107].

Current practical experience shows that any single measure for preventing soil secondary salinization has limited and unstable effects. Using a single amelioration measure may have incomplete effects or different degrees of negative impacts. Countries tend to emphasize comprehensive amelioration measures, with particular attention recently given to combining different amendments, especially the combined application of biological amendments and agricultural/industrial wastes. Mixtures of multiple amelioration substances combined with fertility improvement can alleviate problems of poor structure and low fertility in saline-irrigated soils, truly achieving sustainable land use and protection [108]. For example, bio-organic fertilizer combines beneficial microbial communities with organic fertilizer to form a new, efficient, and safe microbial organic fertilizer [109].

We should focus on brackish or saline water supplementary irrigation, combined with rainwater resource utilization. By planting salt-tolerant varieties, returning straw to fields to reduce evaporation and suppress salt, applying microbial fertilizers and soil conditioners to improve soil buffering capacity, and implementing ridge-furrow and plastic film mulching to reduce soil evaporation and inhibit surface salt accumulation, we can enhance soil rainwater salt leaching and rapid nutrient improvement. Integrating safe and efficient brackish water irrigation technology models, establishing standardized technical application procedures, and organically combining various amelioration measures (such as chemical amelioration, tillage improvement, and straw mulching) can effectively control soil secondary salinization in saline water irrigation areas, achieving efficient, safe, and sustainable utilization of saline water resources and improving water resource security capacity.

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