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Research Progress and Outlook on Desalination and Anti-Saline Re-precipitation Technologies for Coastal Saline-Alkali Soils

Wenxiao Chu, Yi Wang, Xiaoyu Zhang, Xiyue Zhang and Xuetao Yuan*

School of North China University of Science and Technology, Tangshan 063210, China
* Corresponding author

Abstract: The remediation of saline-alkali land is of crucial importance in alleviating pressure on arable land resources and promoting sustainable agricultural development. The present paper undertakes a systematic review of the primary technical systems currently employed for the remediation of coastal saline-alkali land, and the underlying mechanisms that govern them. With regard to leaching desalination, the study focuses on analysing the desalination efficiency and limiting conditions of techniques such as freshwater irrigation, saline irrigation, and frozen saline irrigation. In the field of soil improvement, the mechanisms that regulate soil physicochemical properties are examined through the implementation of measures such as soil replacement, the addition of soil conditioners, and biological remediation. With regard to salt rebound suppression, the review considers the effectiveness of surface mulching and open ditch-closed pipe systems in controlling salt migration. A plethora of research has been conducted on the subject, and the results indicate that while each improvement technique possesses distinct advantages, they also exhibit limitations. Future efforts should focus on synergistic optimisation of multiple technologies to establish site-specific integrated management models for saline-alkali land, providing theoretical foundations and technical support for sustainable land resource utilisation in coastal regions.

Keywords: Coastal saline-alkali land, soil salinization, desalination technology, salt suppression.

1. Introduction

China's position as a major agricultural powerhouse has been a cornerstone of its socioeconomic development. A salient feature of China's agricultural natural resources is its extensive land resources [1]. However, on a global scale, arable land suitable for agriculture is gradually decreasing, with soil salinization emerging as a pivotal factor contributing to the loss of farmland. Statistical data indicates that approximately 1×109 hectares of global soil are threatened by salinization, accounting for about 7% of the Earth's land surface. Of greater concern is the fact that this issue has had a direct impact on approximately 10% of the world's arable land, thereby posing a persistent threat to food security and ecosystems. At present, the area of salinized soil is expanding at a rate of 1×10^6 to 2×10^6 hectares per annum. China is among the nations most severely affected by soil salinization on a global scale, with saline-alkali lands exhibiting extensive distribution and diverse types.

Coastal saline-alkali lands represent a pivotal area in China's broader strategy to address the issue of soil salinization in a comprehensive manner. The region's extensive coastline, spanning 32,000 kilometres, and its vast coastal area, measuring 217,000 square kilometres, are characterised by the pervasive presence of saline-alkali soils. Inadequate drainage capacity and the ingress of seawater have been identified as key factors contributing to the exacerbation of soil salinization and the degradation of coastal soil environments. This has had a detrimental effect on crop yields and quality. However, given its status as a vital strategic reserve land resource, the potential ecological and economic value of coastal saline-alkali land demands urgent and in-depth development. This paper systematically reviews and analyses existing remediation technologies with a view to providing guidance for improving coastal saline-alkali land.

2. Distribution and Formation of Coastal Saline-Alkali Soils

2.1. Section HeadingsDistribution of Coastal Saline-Alkali Land

Coastal saline-alkali soils represent a distinct category of saline soil, distinguished by their poor structure, predominance of chloride salts, and reliance on saline groundwater. The distribution of the subject is primarily in the vicinity of coastal zones characterised by muddy terrain, with the typical topography of the region consisting of deltas and tidal flats. Examples of such regions include the Atlantic coastlines of France and the Netherlands, the Wash region in the UK, Canada's Bay of Fundy, the Amazon River estuary and the coast of Guyana in South America, as well as the coastal areas of Japan and China [2].

China's extensive maritime territory is distinguished by its vast coastline, which is characterised by the presence of significant areas of coastal saline-alkali land. These saline-alkali lands extend across multiple latitudes and exhibit a broad spectrum of climatic and geological conditions. A primary classification system can be proposed, dividing the lands into three major distribution zones: the Bohai Sea coast, the Yellow Sea coast, the East China Sea coast, and the South China Sea coast.

2.2. The Formation of Coastal Saline-Alkali Land

The formation mechanisms of coastal saline-alkali soils demonstrate a high degree of homogeneity across diverse geographical regions. Firstly, the parent material of these minerals primarily originates from marine and fluvial sediments. Prolonged exposure to tidal action has been demonstrated to result in the continuous endurance of seawater inundation and salt permeation, thereby leading to significant salt accumulation during the early stages of soil formation. This process constitutes the common foundation for the formation of coastal saline-alkali soils [3]. Secondly, the high salinity of shallow groundwater in coastal areas is attributable to the intrusion of seawater and the interaction between the land and the sea [4]. The accumulation of surface soil salinity is predominantly attributable to the phenomenon of capillary action, whereby salts present in shallow groundwater migrate towards the surface in conjunction with water, thereby reaching a concentration at the surface. Moreover, the texture of coastal saline-alkali soils is typically heavy and clayey, which impedes permeability, thereby significantly reducing water infiltration and salt leaching rates. Consequently, even precipitation struggles to sufficiently leach salts from the crop root zone, ultimately leading to continuous surface soil salinization. It is evident that factors such as climate and geographic location exert varying influences across different distribution zones of coastal saline-alkali soil.

3. Coastal Saline-Alkali Land Improvement Technology

The three primary natural causes of coastal saline-alkali land are significant accumulation of salts in parent material, shallow groundwater table, and poor soil physicochemical properties. The paper categorises existing remediation technologies into three major systems: leaching desalination technology, soil physicochemical property improvement technology, and salt return suppression technology [5].

Salt leaching technology is a process that involves the removal of salts from soil through the utilisation of water movement. The technology of soil physicochemical improvement has been developed for the purpose of enhancing soil properties via physical barriers, chemical reactions, and biological activity. The result of this process is to promote desalination and to mitigate salinity damage. The implementation of salt migration suppression technology has been demonstrated to have a dual impact: firstly, it has been shown to reduce water evaporation, and secondly, to control salt migration through agricultural water infrastructure and field management practices.

3.1. Leaching Desalination Technology

3.1.1. Sub-section Headings

The fundamental principle of leaching desalination technology is the regulation of soil water-salt migration through irrigation and drainage measures, thereby facilitating the removal of excess salts from the soil. This renders it one of the key engineering techniques for improving coastal saline-alkali soils [5]. In the realm of existing saline-alkali land remediation technologies, freshwater leaching irrigation has emerged as a prominent method, distinguished by its widespread utilisation and proven effectiveness. This approach is notable for its substantial desalination capabilities and its operational simplicity. Freshwater effectively leaches salts from soil by dissolving soluble salts in irrigation water and flushing them to deeper layers or out through drainage systems. However, it is important to note that freshwater resources are often scarce in coastal areas. This makes the development of efficient, water-saving leaching techniques critically important for improving coastal saline-alkali soils. In addition to continuous high-volume flushing, intermittent flushing techniques offer greater water-saving potential for coastal saline-alkali areas.

3.1.2. Saltwater irrigation

In certain coastal saline-alkali areas, despite severe freshwater shortages, reserves of brackish or slightly saline groundwater remain relatively abundant. Consequently, in the context of irrigation and leaching methodologies, these waters, which exhibit a slight saline character, can be contemplated for direct substitution with freshwater, or alternatively, for incorporation into mixed irrigation or rotational irrigation systems with freshwater, thereby mitigating pressure on freshwater resources [6]. Furthermore, saline irrigation has been demonstrated to promote desalination and reduce freshwater consumption to a certain extent, rendering it a strategic choice in water-stressed environments that is both necessary and highly promising. However, the implementation of this technology is fraught with numerous challenges. Saline water introduces additional salts into the soil, and leached salts have the potential to contaminate freshwater aquifers. In areas where drainage is inadequate, this can result in soil salinization [7]. In instances where the groundwater table is at a shallow level, salts contained within the soil may migrate towards the upper levels through a process known as capillary action, thereby accumulating within the topsoil [8]. Consequently, the implementation of saline irrigation frequently necessitates complementary measures, including drainage for salt leaching, cultivation of salt-tolerant crops, and the employment of precision irrigation techniques. These methodologies advocate the extraction of salts through the process of leaching water, thereby effectively regulating the elevation of the groundwater table.

In northern regions of China, such as North China and Northeast China, where water resources are limited, brine freezing irrigation has emerged as a pivotal technology for enhancing saline-alkali land [9]. This technique is characterised by its comprehensive utilisation of the substantial subterranean brine reserves and the winter cold resources that are prevalent in northern regions. During the winter season, the process of freezing leads to the separation of saline water, thereby reducing the salinity of the surface ice. Upon thawing, the brine infiltrates the soil, followed by brackish water or freshwater that leaches surface salts, promoting their migration to deeper layers and achieving soil desalination [10-11]. However, research on the effects of this modification method on plants remains limited. The potential for further research and development is indicated by the fact that it is applicable across different plant types and soil types, and this area requires systematic and in-depth exploration.

3.2. Leaching Desalination Technology

3.2.1. Soil replacement

The introduction of imported soil, characterised by its superior physicochemical properties, to replace native saline-alkali soil has been shown to result in a rapid improvement in the soil's quality. This process has been found to lead to a significant reduction in soil salinity and an increase in organic matter content. However, imported soil is subject to constraints in terms of availability, and its extraction frequently results in the disruption of local ecosystems. Subsequent maintenance costs are characterised by their elevated nature. Furthermore, the unique climate and hydrogeological conditions present in coastal regions render imported soil susceptible to secondary salinization, thereby compromising its capacity to engender sustained improvement. Consequently, the utilisation of imported soil remediation as the predominant approach for enhancing soil physicochemical properties has not gained widespread acceptance.

3.2.2. Soil Conditioner

The addition of soil conditioners is a prevalent technique employed to enhance the physicochemical characteristics of saline-alkali soils in coastal regions. Soil conditioners can be categorised into three distinct groups: inorganic, organic, and biological. Desulfurized gypsum, a prevalent component in the domain of saline-alkali soil remediation, functions as an inorganic conditioner. Following the application of desulfurization gypsum, the dissolution process results in the release of Ca^{2+} ions, which displace Na^{+} ions from soil colloids. It has been demonstrated that soil colloids containing Ca^{2+} exhibit poor mobility, thereby significantly reducing the risk of soil compaction. This results in an expansion of the root development space for plants and an enhancement of their capacity to absorb water and fertilisers, thereby achieving the objective of improving saline-alkali soil [13]. However, the implementation of this amendment technique results in the introduction of substantial quantities of Ca^{2+} and SO_4^{2-} ions, which consequently leads to a substantial increase in their proportion within the soil's ionic composition. The imbalance in the ratios of ions can be considered a possible secondary risk of pollution.

Common organic soil conditioners possess colloidal properties and adsorption capabilities, enabling them to bind soil particles and promote aggregate formation, thereby enhancing soil permeability. Concurrently, organic matter has been demonstrated to enhance soil fertility and augment its capacity to buffer against acidity and alkalinity. However, it has been demonstrated that certain organic conditioners have the potential to leach into groundwater during application, thereby constituting a risk of water pollution. Consequently, scientific management is imperative during application to prevent secondary environmental contamination.

Microbial inoculants represent a conventional form of biological soil conditioner. The primary mechanism of action of these organisms involves enhancing the metabolic activity of bacteria and actinomycetes, thereby improving the physical and chemical properties of soil. During microbial life processes, large quantities of organic acids are produced, effectively neutralising the alkalinity of saline-alkali soils. Furthermore, these inoculants have been demonstrated to increase the diversity of soil microbial communities, thereby enhancing soil remediation capacity and preventing crop diseases [14]. However, the implementation of microbial remediation technologies necessitates extended periods of time, rendering them particularly well-suited for land management in areas characterised by low economic returns or idle land.

3.2.3. Plant salt uptake

The process of afforestation on saline-alkali land is a pivotal strategy for enhancing the physical characteristics of the soil. The interweaving and compaction effects of tree roots, in conjunction with the biochemical effects of root exudates, result in a more compact and organised arrangement of soil particles. This multifaceted approach has been shown to enhance soil porosity and significantly promote the formation of soil aggregate structure, thereby comprehensively improving soil quality on saline-alkali land [15]. This process has been shown to inhibit soil moisture evaporation, enhance soil permeability, and optimise water-salt migration patterns. Consequently, it has been demonstrated to enhance the efficiency of precipitation leaching and improve soil desalination outcomes [16].

The planting of artificial forests on saline-alkali land has been demonstrated to absorb groundwater through transpiration, thereby lowering the water table and reducing surface salt accumulation [17]. Furthermore, as soil structure improves, the leaching effect of rainfall on salts is enhanced, thereby reducing soil salinity in coastal artificial forests [18].

The selection of salt-tolerant tree species for afforestation on saline-alkali land is limited. These species characteristically demonstrate sluggish growth and diminished forest establishment efficiency, culminating in suboptimal ecological and economic outcomes. Concurrently, the necessity for continuous irrigation engenders escalating costs, poses substantial technical challenges, and heightens the risk of secondary salinization or vegetation degradation, rendering long-term maintenance and management particularly arduous. Consequently, the process of afforesting saline-alkali land necessitates meticulous scientific planning, encompassing the integration of salt-tolerant plant breeding with a comprehensive array of improvement measures. This multifaceted approach is imperative to achieve sustainable ecological restoration objectives.

3.3. Anti-Salt Backflow Technology

In the early stages of research into the management of saline-alkali land, the primary focus was on the implementation of flooding with freshwater, with the objective of eliminating salts from the soil. However, the absence of systematic drainage facilities meant that prolonged irrigation could elevate groundwater levels, potentially worsening salinization. Consequently, research into techniques to suppress salt efflorescence gained momentum.

3.3.1. Surface film

The utilisation of straw or plastic mulch has been demonstrated to enhance soil characteristics and stimulate plant growth through the conservation of water, the reduction of inter-plant evaporation, and the regulation of soil salinity. Additionally, straw mulching has been shown to be an effective measure for reducing surface runoff, promoting rainfall infiltration, and prolonging water retention time in the topsoil. This phenomenon not only facilitates the dissolution of soluble salts in the soil but also significantly enhances the leaching efficiency of rainfall. Straw mulching is a process that transforms agricultural waste into a resource that conserves materials and energy while reducing environmental pollution [19]. Conversely, plastic mulch coverage provides a comparatively diminished degree of ecological benefit. Excessive mulch residue from this technology has been shown to degrade soil environments, thereby impairing the absorption of soil moisture and nutrients by crops. Recent years have seen the emergence of "dual-purpose mulching" practices, whereby mulch left over from previous crop harvests is reused for direct seeding. This method has been demonstrated to be an effective means of reducing mulch residue and enhancing resource utilisation efficiency [20]. Surface mulching has been demonstrated to have the most marked effect on the control of soil salinity in the topsoil layer. As soil depth increases, the effect of salinity control becomes more uniform across layers. The impact on deeper soil layers is weaker, and the underlying mechanisms remain unclear, necessitating further research [19, 21].

3.3.2. Open-Ditch and Concealed-Pipe Technology

Open-channel drainage technology is an engineering remediation measure that utilises a network of excavated open ditches to remove salts from soil through water drainage by gravity, transporting them to regional drainage systems. This approach is distinguished by its cost-effectiveness in comparison with alternative remediation methods. It is notable for its simplicity and rapid construction, and it has been shown to achieve high levels of both drainage and salt removal efficiency. It has been demonstrated to be efficacious in the treatment of severely saline-alkali coastal soils. However, it requires extensive land area and incurs high maintenance costs, rendering it more appropriate for short-term salt drainage projects. Subsurface pipe drainage technology involves the installation of a network of perforated pipes buried at a specific depth underground. The system functions by extracting salts from saline-alkali soils through the process of draining water from the fields. The installation of subterranean conduits addresses the deficiencies associated with excessively spaced open ditches, thereby markedly enhancing soil desalination efficiency while achieving water conservation. This innovative solution offers a promising approach for the rehabilitation of severely saline-alkali coastal regions. However, the implementation of subsurface drainage systems necessitates a higher initial financial investment, is susceptible to pipe blockages, and involves complex maintenance and repair procedures. Consequently, this approach is more suitable for long-term, meticulous management.

3.3.3. Other Technologies

The utilisation of low-cost construction waste gravel for the construction of a barrier layer in deep soil has been demonstrated to be a viable means of salt-affected soil remediation through the effective recycling of resources. The capillary radius is the pivotal factor determining the height of the capillary water rise, with the two exhibiting a negative correlation. It has been demonstrated that the finer the soil particles and the denser the structure, the narrower the internal pore channels become, thereby intensifying capillary action. The gravel barrier layer exhibits higher porosity in comparison to the soil, thereby reducing capillary forces and preventing the occurrence of capillary rise. This layer has been shown to suppress capillary water ascent, thereby forming a physical barrier that prevents underlying salts from migrating upward with moisture into the topsoil cultivation layer. This process achieves highly efficient soil improvement [22].

4. Conclusion

Coastal saline-alkali land reclamation is a pivotal approach to enhancing land resource utilisation efficiency and ensuring sustainable agricultural development. The present paper reviews the extant research in relation to three major categories of coastal saline-alkali land reclamation technologies. In the realm of leaching desalination techniques, freshwater irrigation has been shown to yield rapid results; however, this approach is predicated on the availability of water resources. In regions experiencing water scarcity, brackish water irrigation and frozen brackish water irrigation present viable solutions. However, it is imperative to enhance salt leaching efficiency to ensure optimal outcomes. In relation to the subject of soil amendment techniques, soil replacement is a rapid process but requires substantial engineering efforts. By contrast, soil conditioners and biological amendments have the potential for more widespread adoption. In the realm of desalination suppression methodologies, surface mulching has been demonstrated to engender substantial short-term outcomes. Conversely, subsurface drainage has been shown to manifest notable long-term efficacy. It is recommended that future efforts concentrate on the integration of multiple technologies in order to address the dynamic salt migration issues

It is recommended that future research should focus on the following areas: (1) the development of low-cost, environmentally friendly novel amendment materials to enhance the sustainability of saline-alkali land remediation; (2) the deepening of the mechanisms for integrated application of multiple technologies, such as the system integration of "amendments-salt-tolerant crops-subsurface drainage," to synergistically address desalination and inhibit salt rebound; and (3) the strengthening of long-term ecological impact assessments that balance reclamation outcomes with soil health and biodiversity conservation. Furthermore, the provision of policy support and the promotion of technologies that are adapted to the regional environment will be pivotal in facilitating large-scale saline-alkali land reclamation. Through interdisciplinary collaboration and technological innovation, coastal saline-alkali land reclamation holds promise to play an increasingly significant role in both food security and ecological conservation.

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References

[1] Xu W S, Li K S, Kong W H, et al. Effect of application amount of desulphurization gypsum on water transport of coastal saline-alkali soil[J]. Yellow River, 2021, 43(9): 110-114.

[2] Wei Y X, Wang Z, Zhang C K. Review of researches on exploitation of coastal tidal flats[J]. Advances in Science and Technology of Water Resources, 2010, 30(5): 85-89.

[3] Zhao F X, Yang J S, Yao R J. Characteristics of soil salinization in mudflat of north Jiangsu province based on canonical correspondence analysis[J]. Acta Pedologica Sinica, 2010, 47(3): 422-428.

[4] ARULMATHI C,PORKODI G.Characteristics of coastal saline soil and their management:A review[J].International Journal of Current Microbiology and Applied Sciences, 2020, 9(10): 1726−1734.

[5] Hang L Y U, Yue Z, Xulong G, et al. Review of techniques and case studies for saline-alkali land amelioration in the coastal regions of China[J]. Hydrogeology & Engineering Geology, 2025, 52(2): 25-43.

[6] LIU Bingxia,WANG Shiqin,LIU Xiaojing,et al.Evaluating soil water and salt transport in response to varied rainfall events and hydrological years under brackish water irrigation in the North China Plain[J].Geoderma,2022,422:115954.

[7] GAO H, ZHAO L, LIU B, et al. Study on shallow mild saline groundwater use safety in winter wheat irrigation based on the subsurface drainage system in the coastal area of Hebei Province in China[J]. Chinese Journal of Eco-Agriculture, 2023, 31(7): 1102-1109.

[8] SHOKRI-KUEHNI S M S,RAAIJMAKERS B,KURZ T,et al.Water table depth and soil salinization:From pore-scale processes to field-scale responses [J]. Water Resources Research, 2020, 56(2):e2019WR026707.

[9] WANG J, LI A R. Overview of Saline-alkali Land Improvement Technologies in China[J]. Modern Agricultural Science and Technology, 2019, (No.21): p.182-183+185.

[10] Li J J, Qu Z Y, Yang W, et al. Analysis of dynamic migration characteristics of Soil water, heat, and salt in saline-alkali soils under saline water freezing irrigation[J]. Journal of Soil and Water Conservation, 2023, 37(2): 377-384.

[11] Che S G, Lin Z A, Zhao B Q. Effects of agricultural irrigation by melting saline water ice on soil salt and ion movement under fluvo-aquic soils[J]. Journal of Soil and Water Conservation, 2011, 25(4): 88-93.

[12] Lu Z, Fan Y, Zhichun W. Research advances of saline soil reclamation by freezing saline water irrigation and meltwater leaching[J]. Soils and Crops, 2021, 10(2): 202-212.

[13] Mao Y, Li X. Amelioration of flue gas desulfurization gypsum on saline-sodic soil of tidal flats and its effects on plant growth[J]. China Environ. Sci, 2016, 36(1): 225-231.

[14] ZHANG L, WU W Q, WANG W R, et al. Effects of Soil Conditioner Combined with Microbial Fertilizer on the Improvement of Secondary Salinization Soil in Greenhouse Vegetable Field[J]. Soil and Fertilizer Sciences in China, 2021, (No.3): p.264-271.

[15] NIU X,LIU X,LI T,et al.Long-Term Planting of Taxodium Hybrid'Zhongshanshan'Can Effectively Enhance the Soil Aggregate Stability in Saline–Alkali Coastal Areas[J].Forests 2024,15(8):1376.

[16] Yang J S, Yao R J, Wang X P, et al. Research on salt-affected soils in China: History, status quo and prospect[J]. Acta Pedofil. Sin, 2022, 59(1): 10-27.

[17] MINHAS P S,DAGAR J C.Use of tree plantations in water-table drawdown and combating soil salinity[J].Agroforestry for the management of waterlogged saline soils and poor-quality waters,2016,33-48.

[18] TANG S Q,SHE D L,Wang Hongde.Effect of salinity on soil structure and soil hydraulic characteristics[J].Canadian Journal of Soil Science,2020,101(1):62-73.

[19] LI X N, SU P L. Effects of Different Straw Mulching Rates on Soil Salt Content in Moderately Saline-Alkali Land[J]. Journal of Irrigation and Drainage, 2017, 36(S1): p.66-70.

[20] Lu C, Zhang H, Liu N, et al. Increasing soil organic carbon in aggregates and microflora diversity in moderate salt-affected soils through no till combined with plastic film mulching[J]. Trans. Chin. Soc. Agric. Eng, 2019, 35: 116-124.

[21] MENG D C, ZONG X C. Effects of plastic film mulching on soil water and salt status and transplanting effect of Ley- mus chinensis in heavy saline-alkali land[J]. Journal of Jilin Agricultur- al University, 2018, 40(6): 722-726.

[22] Su X, Wang Y, Wang G, et al. Assessment and prediction of coastal saline soil improvement effects combining substrate amendments and salt barrier materials in typical region of the Yangtze River Delta[J]. Soil and Tillage Research, 2022, 223: 105483.