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Original Article

Microbial Interventions for Reclamation of Saline-Alkali Soils: A Review of Community Dynamics, Soil Properties, and Restoration Mechanisms

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Abstract:
Saline-alkali soil degradation is a major global challenge to agricultural productivity and ecosystem sustainability. Excessive soluble salt content and high pH values of these soils cause severe soil and ionic stress on plants and soil biota, resulting in poor soil structure, inadequate nutrient cycling and diminished biological activity. Traditional remediation methods, including leaching and chemical amendments, are often costly, energy-intensive and unsustainable with adverse environmental impacts. Consequently, there is growing interest in using soil microorganisms to improve saline-alkali soils, which is an economical, effective and sustainable method. This review synthesizes current knowledge on the complex relationships between saline-alkali stress, soil physicochemical properties, and soil microbial community structure and function. It examines how salinity and alkalinity alter microbial diversity, biomass and community composition, selecting for stress-tolerant specialists such as halophilic and alkaliphilic bacteria. Mechanisms through which beneficial microorganisms, including plant growth promoting rhizosphere bacteria (PGPR), arbuscular mycorrhizal fungi (AMF), contribute to reclamation are detailed. These mechanisms include the production of exopolysaccharides (EPS) for soil aggregation, the synthesis of compatible solutes for soil regulation, the production of organic and biological acids for reducing pH, and the enhancement of nutrient availability. Furthermore, the review also explores the synergistic effects of microbial inoculants with organic amendments (e.g., biochar, compost) and plants within an integrated phytoremediation framework. Finally, challenges in translating laboratory findings into field-scale applications, such as inoculant survival, establishment, and ecological predictability, are discussed. Future research directions are highlighted, including the application of advanced omics techniques to uncover novel microbial functions and the design of targeted microbial communities tailored to specific saline-alkali soil conditions. We emphasize that strategic management of the soil microbiota is a fundamental component of efficient and ecologically sound restoration of saline-alkali lands.

Keywords: Saline-alkali soil, soil remediation, microbial community, soil properties, sustainable agriculture

Introduction

Soil salinization and alkalization is one of the most prevalent forms of land degradation, as a serious environmental threat that constrains agricultural development and ecosystem diversity globally [1, 2]. Saline soils are formed mainly by the accumulation of soluble salts, such as sodium, calcium and magnesium chlorides and sulphates, resulting in an electrical conductivity (EC) of the saturation extract greater than 4 dS m^{-1}. Alkali (or sodic) soils are characterized by a high exchangeable sodium percentage (ESP > 15) and elevated pH (pH ≥ 8.5), which lead to dispersion of clay particles, degradation of soil structure, and presenting a complex set of abiotic stresses [3]. The primary threat to plant growth in these soils are osmotic stress, which impedes water uptake,

and specific ion toxicity, particularly from Na^+ and Cl^-. Additionally, high pH leads to plant nutrient imbalances and deficiencies in essential elements such as phosphorus (P), iron (Fe), and zinc (Zn) due to precipitation and reduced solubility, while also triggering oxidative stress. These factors created a hostile environment for root development and microbial activity [4].

Conventional remediation strategies for saline-alkali soils predominantly rely on physical and chemical approaches [5-7]. These approaches include leaching with excess water to remove soluble salts from the root zone and application of chemical additives such as gypsum ($CaSO_4$-$2H_2O$) or sulfuric acid, which displace exchangeable sodium with calcium, ultimately reducing soil pH and improving structure. Although these methods are sometimes effective, they are often prohibitively expensive, require large volumes of high-quality water, and can generate negative environmental impacts [8]. Analysis of National-scale data (since 1960s) show chemical amendments dominate (78 % of projects) but biological + organic combinations deliver higher long-term yield gain and lower cost [9]. Therefore, developing economically and environmentally sustainable alternative measures is imperative.

Bioremediation of saline–alkaline soils—particularly through soil-microbe-based approaches—has emerged as an effective and promising strategy [10, 11]. Soil microbiome is a vital component of terrestrial ecosystems, driving key biogeochemical processes such as organic-matter decomposition, nutrient cycling, and soil-structure formation [4, 12]. Specific beneficial microorganisms can help plants grow under saline conditions, offering a natural and sustainable remediation pathway. But, salinity and alkalinity, however, are primary environmental filters that profoundly shape microbial community structure and function [13]. A thorough understanding of these processes is essential for designing effective microbe-based strategies for the restoration of saline–alkaline soils. Therefore, this review aims to: (1) elucidate the effects of saline–alkali stress on soil physicochemical properties; (2) analyze how soil microbial communities (bacteria, fungi, archaea) respond to salinity and alkalinity, including changes in diversity, composition, and function; (3) detail the mechanisms by which microorganisms, both native and introduced, can ameliorate saline-alkali stress and improve soil health; (4) evaluate integrated approaches that combine microbial inoculants with plants and organic amendments for synergistic reclamation effects; (5) discuss current challenges and future prospects for applying microbial technologies in the remediation of saline–alkaline soils.

1. Effects of Saline–Alkali Stress on Soil Physicochemical Properties

The deterioration of soil physicochemical properties is the fundamental cause of ecosystem dysfunction in saline–alkaline lands. The vicious cycle created by the interplay between chemical and physical degradation is extremely difficult to break (Fig. 1).

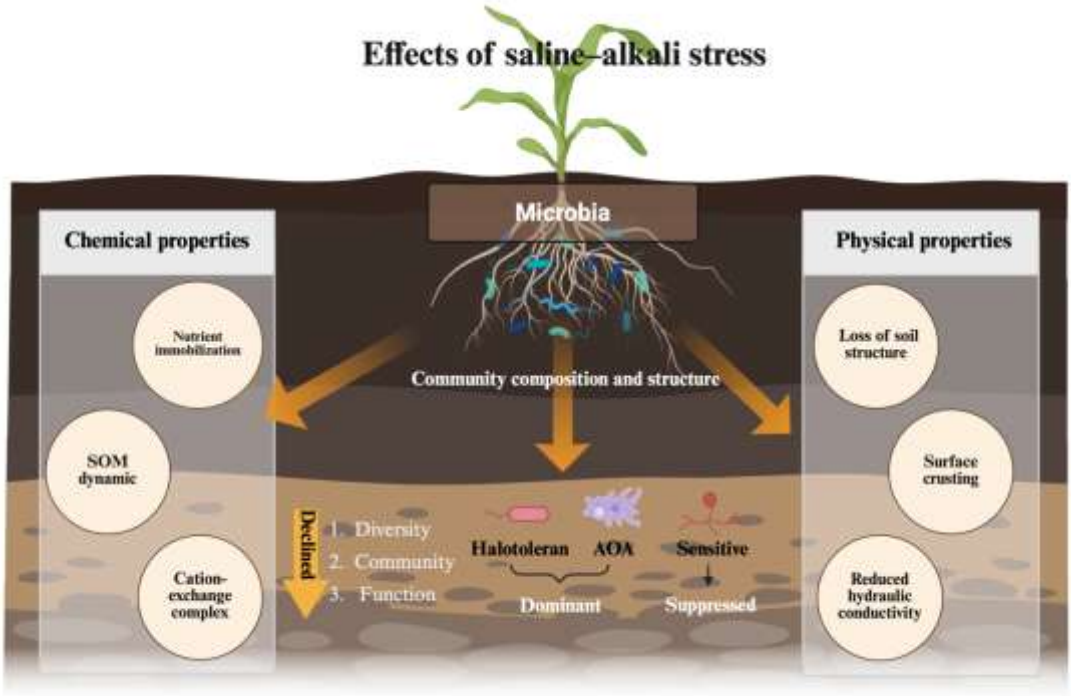

Fig. 1 Effects of saline–alkali stress on soil physicochemical and microbial community structure

2.1 Chemical Properties

The primary chemical characteristics of saline–alkaline soils are high concentrations of soluble salts and the presence of sodium ions on the soil exchange complex [9, 14]. The elevated EC raises the osmotic potential of the soil solution, making it more difficult for plants and microbes to absorb water—a condition analogous to physiological drought [15]. Ionic toxicity, particularly from Na^+, disrupts enzyme activity, damages cell membranes, and interferes with the uptake of essential nutrients such as K^+ [16]. High pH is a hallmark of alkaline soils and triggers multiple cascading effects. Elevated pH slows organic-P mineralization and siderophore production, reducing nutrient mobilization. Soluble phosphate ($H_2PO_4^-$) reacts rapidly with Ca^{2+} to form insoluble hydroxyapatite ($Ca_5(PO_4)_3OH$) and inducing acute P deficiency in crops [17]. Fe^{3+}, Mn^{2+}, Cu^{2+} and Zn^{2+} hydrolyse to form highly stable hydroxide or carbonate minerals, resulting in chlorosis, stunted growth and impaired enzyme function [18]. Sulfur-oxidizing bacteria are phylogenetically diverse and employ multiple metabolic pathways for sulfur oxidation, playing vital roles in biogeochemical cycling and potential applications in soil reclamation [19]. Although microbial stress can slow SOM decomposition under saline conditions, the chemical stability of SOM is altered in alkaline soils [20, 21], often leading to accumulation of more recalcitrant forms but also to increased solubility of humic substances that may be lost through leaching. Bxesides, a high exchangeable sodium percentage (ESP) indicates that Na^+ dominates exchange sites instead of Ca^{2+} and Mg^{2+}. This not only supplies toxic ions to the biota but also creates conditions for physical soil degradation [22]. High exchangeable Na^+ disperses clay colloids, exposing previously sorbed micronutrients to further precipitation and leaching.

2.2 Physical Properties

The physical degradation of sodic soils is primarily a consequence of the dispersion of clay particles. This dispersion has several detrimental consequences, like stable aggregates, which are crucial for aeration, water infiltration, and root

growth, are destroyed [14]. The soil becomes compacted. When dispersed clay particles are transported by water and then dry, they form a hard, impermeable crust on the soil surface that impedes seedling emergence and increases surface runoff [23]. The dispersed clay particles clog soil pores, severely reducing the infiltration rate of water. This makes leaching of salts inefficient and can lead to waterlogging, even in arid regions [4]. This degraded physicochemical environment creates a vicious cycle: poor soil structure and low permeability impede salt leaching, thereby perpetuating saline–alkali conditions.

2. Response of Soil Microbial Communities To Saline-Alkali Stress

Soil microorganisms are highly sensitive to changes in their surrounding environment [11], and salinity–alkalinity acts as a powerful environmental filter that effectively selects for specialized, stress-adapted microbial communities [24], and beneficial microbes can help plants thrive in salty soil (Fig. 1).

3.1 Shifts in Microbial Biomass, Diversity, and Activity

A meta-analysis by Yuan et al. [25] confirmed that soil salinity is generally associated with marked declines in microbial biomass and respiration. Salty soils have smaller and less active microbial populations, which slows down nutrient cycling. Similarly, elevated pH can denature proteins and disrupt cellular homeostasis. Consequently, microbial activity—measured as basal respiration or as enzyme activities involved in C, N and P cycling—is often suppressed in saline–alkali soils [13]. Microbial diversity, including both richness (number of species) and evenness (abundance distribution), typically declines with increasing salinity/alkalinity [26, 27], as the harsh conditions exclude a large proportion of the microbial taxa found in healthy soils. Soil salinity shapes microbial community structure and function, with high salinity generally suppressing microbial biomass and activity.

3.2 Changes in Community Composition

Saline-alkali stress acts as a selective force, leading to a shift in community composition [28, 29]. Certain phylogenetic groups demonstrate remarkable tolerance and even preference for saline-alkali conditions. Take bacteria for instance, the relative abundance of Proteobacteria—especially Gamma- and Alphaproteobacteria—and Bacteroidetes often increases in saline soils. Proteobacteria was the most abundant phylum in both reseeded and natural grassland soils, likely due to its role in nitrogen fixation and decomposition of organic matter. Bacteroidetes, on the other hand, played a secondary role in this ecosystem [30]. These phyla harbor many well-known halotolerant and halophilic genera such as *Halomonas*, Salinivibrio, and *Chromohalobacter* [31, 32]. *Halomonas beimenensis* employs a multi-faceted strategy for salt adaptation, including the synthesis of compatible solutes like ectoine, ion transport, and cell envelope modification, as revealed by integrative omics [32]. By contrast, Acidobacteria and Verrucomicrobia, which are typically abundant in non-saline soils of neutral pH, are highly salt-sensitive and show sharp declines in abundance [25, 33] to salt. Alkaline conditions favor alkaliphilic bacteria, commonly found within phyla such as Firmicutes (e.g., *Bacillus*. sp) and Actinobacteria [34]. But for archaea, the acidity or alkalinity of soil determines which microbes are responsible for the first step of nitrification, a key part of the nitrogen cycle. The key adaptation is the dominance of ammonia-oxidizing archaea (AOA) over ammonia-oxidizing bacteria in saline environments. AOA generally have a higher affinity for ammonia and are more salt-tolerant, making them crucial players in the nitrogen cycle under stress [35]. The fungal community is also

restructured by saline-alkali stress. In general, fungi are considered more sensitive to salinity than bacteria, leading to an increased bacteria-to-fungi ratio in severely saline soils [36, 37]. However, certain halotolerant fungi, including some Ascomycetes and Basidiomycetes, persist. Arbuscular mycorrhizae (AM) are a type of mutualistic symbiosis between fungi vascular plant species. In this symbiosis, fungi enhance nutrient and water uptake for the plants, while plants provide organic molecules essential for fungal growth [38, 39]. AM are particularly sensitive to high salinity, which can reduce spore germination and hyphal growth, limiting their symbiotic potential [40]. Symbiotic fungi can help plants cope with salt stress by improving their nutrient and water uptake, but pairing the right fungus with the right plant is key.

3.3 Functional Adaptations of the Microbiome

The surviving microbial community under saline-alkali stress is not just taxonomically distinct but also functionally adapted. Bacteria have a rapid-response system that uses a metabolic signal to directly tweak their gene-control proteins, allowing them to adapt quickly to new conditions. Metagenomic and transcriptomic studies reveal an enrichment of genes involved in osmoprotection, ion homeostasis, stress response, and alternative metabolisms.

Synthesis and uptake of compatible solutes (e.g., glycine betaine, proline, trehalose) that balance internal osmotic pressure without perturbing cellular metabolism [41, 42]. *Bacillus subtilis* can acquire the osmoprotectant proline not only by uptake but also by importing and degrading proline-containing peptides, providing a flexible mechanism for osmotic stress adaptation [41]. Increased activity of Na^+/H^+ antiporters and K^+ uptake systems to maintain a low cytosolic Na^+/K^+ ratio [43-46]. The Na^+/H^+ antiporter NhaA directly interacts with Na^+ ions via a specific binding site, providing crucial mechanistic insight into how cells maintain ion homeostasis under salt stress. Upregulation of genes for chaperones, DNA-repair systems, and antioxidant enzymes (e.g., catalase, superoxide dismutase) to manage oxidative damage in response to stress. *Bacillus subtilis* integrates the DNA damage response (SOS response) with its regulatory network for biofilm formation, directly linking genotoxic stress to the decision between motility and multicellular development [47]. Heteroresistance to levofloxacin in *Pseudomonas aeruginosa* is linked to the upregulation of DNA replication and repair genes, suggesting a novel mechanism where increased replication fidelity can transiently enhance antibiotic tolerance [48]. Adaptations to utilize less common substrates that might be available under saline-alkali stressed conditions, i.e., alternative metabolism. Scientists have isolated and studied new types of marine bacteria that are essential for converting nitrogen in the ocean, a key step in global nutrient cycling. [49]. Konishi Nobu et al. [50] demonstrated that "Ca. Lithacetigenota" switches from CO_2 to formate/glycine catabolism at pH 11, doubling energy yield per mole H_2 and maintaining growth at 10 % NaCl, providing a template for engineering alternative metabolisms into halo-alkaliphilic bio-inoculants. Alternative metabolisms (formate lithotrophy, glycine reduction, polysaccharide scavenging, acetyl-CoA flexibility) enable extremophiles to thrive on geogenic or recalcitrant substrates when conventional CO_2 is scarce, offering new gene cassettes for microbial reclamation of saline-alkali soils. Although diversity is reduced, this salt/alkali-adapted microbiome retains the functional capacity to deliver essential ecosystem services, albeit sometimes at slower rates. Harnessing these native, stress-adapted microbes is a key principle of phytoremediation.

3. Mechanisms of Microbial Remediation of Saline-Alkali Soils

Beneficial microorganisms can mitigate the adverse effects of salinity and alkalinity on plants

and soils, either directly or indirectly, through a variety of mechanisms [51]. The recent investigation into the mechanisms of microbial remediation of saline-alkali soils is presented in Fig. 2 and Table 1.

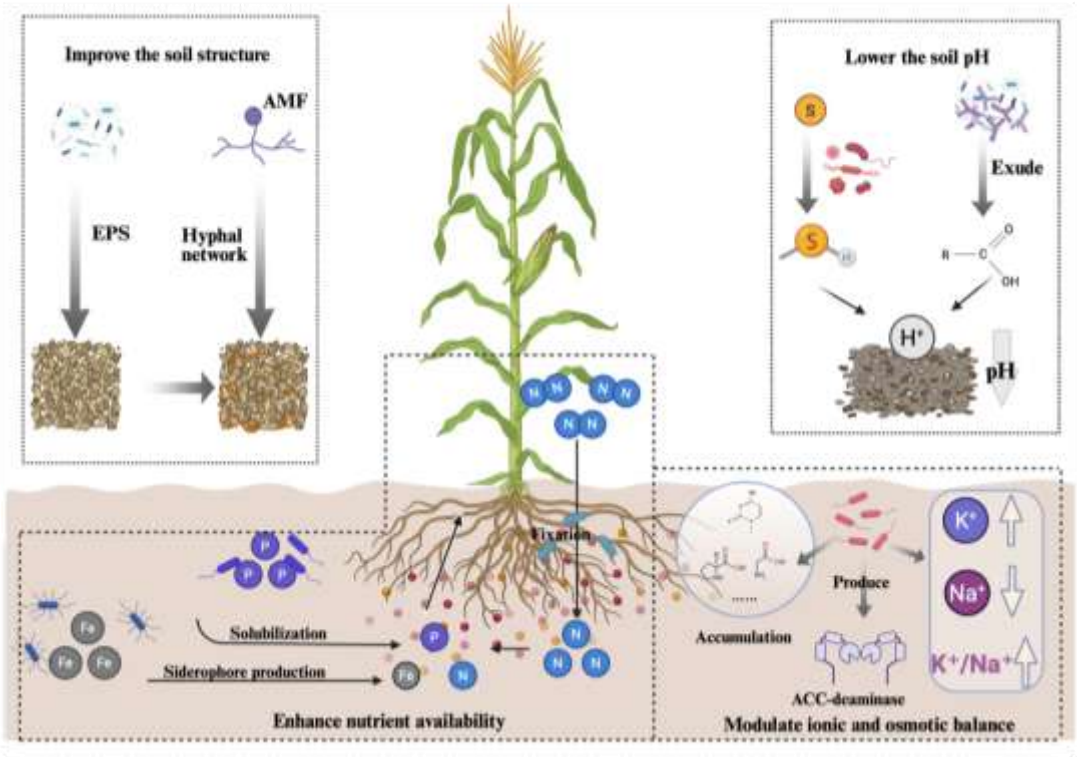

Fig. 2 Mechanisms of microbial remediation of saline-alkali soils

4.1 Improvement of Soil Structure

Production of extracellular polysaccharides (EPS) primarily composed of polysaccharides, proteins, and DNA. They play crucial roles in microbial life and environmental interactions [52, 53], by binding soil particles, enhancing water retention, and providing a protective matrix for microbial communities. Many bacteria and fungi secrete EPS, which are high-molecular-weight polymers that act as glues, binding soil particles into microaggregates that subsequently form stable macroaggregates [54]. This process enhances porosity, water infiltration, and aeration, while simultaneously reducing erosion and surface crusting [55]. A complex, cross-kingdom nutrient exchange network exists between plants, arbuscular mycorrhizal fungi, and associated bacteria, which is fundamental to nutrient cycling and plant health in the rhizosphere. The extensive hyphal networks of fungi—especially arbuscular mycorrhizal fungi (AMF) and saprotrophs—act like “sticky mesh bags” that enmesh soil particles [56, 57], creating stable aggregates and establishing channels for water and nutrient transport [38, 39, 56, 58]. AMF have the capacity to selectively coexist with a diverse array of microbial taxonomic groups throughout various stages of their life cycle and across a wide spectrum of soil environments [39, 57].

Table 1 Mechanisms of microbial remediation of saline-alkali soils

Approach	Pathway	Mechanisms	References
Directly remediation: Remediation of saline-	Produce EPS	Improve the soil structure	52, 53, 54
	Form hyphal network		56, 57

slkali soils	Reduced Na^+ uptake and enhanced K^+ acquisition	Modulate ionic and osmotic balance	54, 59
	Compatible-solute production		62
	Producing organic acids, sulfuric acid and carbonic acid	Lower the soil pH	64, 65
	Organic-acid production		66
	Biological acidification		17, 68
	Nitrogen fixation	Enhance nutrient availability	69-71
	Phosphate solubilization		72, 73
	Fe–siderophore production		74-76
Indirectly remediation: Synergistic phytoremediation	Biochar–microbe synergy	Improve microbial survival and activity	80-83
	Targeted microbe＋Compost	Introduce a diverse community of beneficial microorganisms	82, 85
	PGPR＋plants	Enhance plant establishment, Rhizosphere engineering	88, 89, 93, 95
	AMF＋plants		91

4.2 Modulation of Ionic and Osmotic Balance

Beneficial root bacteria improve soil and stimulate plant growth through a variety of natural tactics, reducing the need for chemical inputs. Plant-growth-promoting rhizobacteria (PGPR) raise the plant K^+/Na^+ ratio both by increasing K^+ availability through mineral weathering and by expressing high-affinity K^+ transporters [44, 54, 59]. Some microbes can produce ACC-deaminase, an enzyme that lowers stress-induced ethylene levels in plants, thereby improving root growth and ion selectivity [60, 61]. For instance, inoculation with the bacterium *Achromobacter piechaudii* conferred resistance to water stress in tomato and pepper plants by reducing stress-induced ethylene production via ACC deaminase activity [60]. Also, under osmotic stress, rhizosphere bacteria and fungi rapidly accumulate compatible solutes such as proline, glycine-betaine, trehalose, and ectoine to balance internal osmotic pressure for self-protection. Crucially, these metabolites are not retained intracellularly; instead, they are actively secreted or leaked into the rhizosphere, where they perform dual protective functions. Ocean microbes have a versatile toolkit of molecules they use to maintain water balance, allowing them to thrive in different salt concentrations [62]. Rhizosphere microbes export compatible solutes that act as shared osmoprotectants, membrane stabilizers and ROS quenchers, offering an immediate, low-cost strategy to enhance plant membrane integrity during salinity or drought events [63].

4.3 Adjustment of Soil pH

Lowering the high pH of alkaline soils is a central goal of salt-alkali land remediation and microbes contribute to this by producing acids [64, 65]. Using sulfur together with bacteria that convert it to sulfuric acid is an effective way to improve alkaline soil and boost chickpea harvests. Microbes generate organic acids, sulfuric acid and carbonic acid that dissolve calcite, displace Na^+ and re-acidify the rhizosphere, offering an economically attractive alternative to chemical amendments. Many rhizosphere bacteria and fungi exude low-molecular-weight organic acids (e.g., citric, gluconic, oxalic) as part of their metabolism; these acids directly dissociate H^+, neutralizing soil alkalinity [66]. Different types of

bacteria work together to convert sulfur in the soil into sulfuric acid, which helps to lower pH and release nutrients. Specific microbes can be harnessed to catalyze acid-generating reactions. For example, sulfur-oxidizing bacteria (e.g., *Thiobacillus spp.*) biologically convert elemental sulfur to sulfuric acid, mimicking the effect of chemical amendments [19, 67]. Similarly, the application of organic matter stimulates microbial respiration, leading to the production of carbonic and other acidic metabolites [68].

4.4 Enhancement of Nutrient Availability

In saline–alkali soils, where nutrient availability is very low, microbes—acting as the engines of soil nutrient cycling—play a vital role. Diazotrophic bacteria—whether free-living (e.g., *Azotobacter*, *Azospirillum*) or symbiotic (e.g., *Rhizobium*)—convert atmospheric N_2 into plant-available ammonium, overcoming nitrogen deficiency [69-71]. Phosphate-solubilizing microorganisms (PSM) secrete organic acids and phosphatases that dissolve insoluble calcium phosphates in alkaline soils, making phosphorus available for plant uptake [72, 73]. And under high pH, iron becomes extremely insoluble. Microbes secrete siderophores—high-affinity iron-chelating compounds—that scavenge Fe^{3+} [74-76]. Plants can then take up these Fe–siderophore complexes, alleviating iron chlorosis.

4. Synergistic Phytoremediation

5.1. Microbial Inoculants with Organic Amendments

The application of organic matter (e.g., farmyard manure, compost, biochar, straw), are potential alternative nutrient sources for sustainable agriculture, is a cornerstone of sustainable soil management. When combined with microbes, the benefits are amplified [77-79]. Biochar, a porous, carbon-rich material, offers microbes protective habitats that shield them from desiccation and predation, enhances soil water retention, and serves as a slow-release nutrient source [80, 81]. Pre-inoculating biochar with specific bacteria or fungi to create "bio-inoculated biochar" has shown promising results for improving microbial survival and activity in saline–alkali soils [82, 83]. Compost itself acts as a reservoir of beneficial microbes. Besides adding nutrients to saline–alkali soils and improving soil structure, compost introduces a diverse community of beneficial microorganisms [84, 85]. Supplementing compost with targeted microbial inoculants can further steer the community toward desired functions [82, 85], like faster maturation, higher humus content, and specific agro-functional traits.

5.2. Phytoremediation with Microbial Inoculation

Phytoremediation, particularly when enhanced with microbial inoculants and soil amendments, is a sustainable and effective technology for the cleanup of contaminated soils. The use of salt-tolerant plants (halophytes) or moderately salt-resistant crops to reclaim land is termed phytoremediation. Plants help by reducing the water table (via transpiration), absorbing salts, and increasing organic carbon through root exudates and litter [86, 87]. Inoculating these plants with tailored PGPR or AMF significantly accelerates the process [24]. Besides, the synergistic interaction between AMF and a microbiome enriched with PGPR significantly enhanced root development and shaped a beneficial microbial community.

The microbial inoculants alleviate plant stress, leading to better root and shoot growth, which in turn increases the plant's capacity to improve soil. Applying selected microbes is a proven way to boost soil health and crop productivity in an environmentally friendly manner. Microbial inoculants are effective tools for enhancing soil quality and plant health by improving nutrient supply, suppressing diseases, and promoting plant growth, contributing to sustainable agricultural systems [88, 89]. At field scale, microbial

inoculants successfully modulated the rhizosphere microbiome, downregulated stress-related genes in maize, and enhanced plant growth, demonstrating their practical potential [90]. Besides, combining local mycorrhizal fungi with a specific bacterium gave clover a much greater ability to withstand drought. The co-inoculation of native arbuscular mycorrhizal fungi (AMF) and Bacillus thuringiensis synergistically enhanced the drought tolerance and growth of clover native to semi-arid regions [91]. Plant roots exude metabolites that selectively stimulate beneficial microbial communities—the "rhizosphere effect." Inoculants can prime this process, creating a positive feedback loop in which healthier plants nurture a healthier microbiota, which in turn further benefits the plants [92]. Halophytes such as *Suaeda salsa*, *Salicornia europaea*, and *Tamarix* spp. have been successfully combined with PGPR for phytoremediation [93-95].

5. Alleviate salt stress and increase crop yield

Plant growth-promoting microorganisms (PGPMs), notably PGPR and AMF, can impart salt tolerance to plants and enhance productivity by employing diverse direct and indirect mechanisms.

6.1 Osmotic Adjustment and Ion Homeostasis

Microbes help plants maintain water balance under osmotic stress. Certain PGPR strains, such as those from the genera *Bacillus* and *Pseudomonas*, produce compatible solutes like proline, glycine betaine, and trehalose. These compounds act as osmolytAes, stabilizing cellular proteins and membranes [96]. Furthermore, PGPMs can regulate ion homeostasis by limiting sodium (Na^+) accumulation and promoting potassium (K^+) uptake. Microbial inoculation can modulate the expression of high-affinity K^+ transporters (e.g., HKT1) in plants, thereby increasing the K^+/Na^+ ratio—a critical factor for enzymatic activity under saline conditions [97].

6.2. Phytohormone Production

PGPMs are prolific producers of phytohormones such as auxins (e.g., IAA), cytokinins, and gibberellins. IAA, in particular, stimulates root system development, enabling plants to explore a larger soil volume for water and nutrients, which is vital in stressful environments [98]. Additionally, some microbes also reduce the level of the stress hormone ethylene in plants by producing the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase. This enzyme cleaves ACC, the immediate precursor of ethylene in plants, thereby alleviating ethylene-mediated growth inhibition under salt stress [99].

6.3. Enhancement of Nutrient Availability

Saline-alkali soils typically exhibit poor nutrient availability due to high pH and ion competition. Phosphate-solubilizing microbes (e.g., *Pseudomonas* and *Penicillium*) convert insoluble phosphates into plant-available forms. Similarly, nitrogen-fixing bacteria like *Azotobacter* and *Rhizobium* supplement soil nitrogen. AMF form extensive hyphal networks that act as extensions of the plant root system, significantly increasing the absorption surface area for phosphorus, zinc, and other immobile nutrients [100].

6.4 Promising Applications and Field Trials

Research has progressed from in-vitro and pot experiments to field trials, demonstrating the tangible benefits of microbial inoculants. For instance, inoculation with consortia of halotolerant (salt-tolerant) PGPR has shown remarkable success. A field study with rice in saline soils demonstrated that a consortium of *Bacillus* spp. significantly improved plant biomass, chlorophyll content, and grain yield compared to uninoculated controls [101, 102]. Similarly, the application of AMF like *Glomus* species has been effective in enhancing the salt tolerance of crops like maize,

tomato, and wheat. Mycorrhizal plants typically exhibit better growth, higher photosynthetic rates, and improved nutrient status under saline conditions [103]. Besides, the combination of microbial inoculants with organic amendments (e.g., compost, biochar) creates a synergistic effect. The organic matter provides a carbon source for the microbes, improving their survival and colonization, while the microbes accelerate the decomposition and mineralization of the organic matter, releasing nutrients for plants [104].

6. Challenges and Future Perspectives

7.1 Challenges in application of microbial interventions

Although controlled experiments and greenhouse experiments provide compelling evidence, for the potential of microbial technologies, large-scale application for saline-alkali land reclamation still faces several significant obstacles.

7.1.1 Inoculant Survival and Efficacy

A major challenge is ensuring that introduced microbial strains can survive, establish, compete with the indigenous microbiota, and maintain their metabolic activity and plant-beneficial functions in the harsh and highly competitive field environment. Abiotic stresses (e.g., extreme pH, salinity, temperature fluctuations, moisture stress) and biotic competition often lead to rapid declines in both the population density and the functional efficacy of the inoculants over time.

7.1.2 Context-dependency

The success of microbial inoculants is highly dependent on the specific context, including soil type, texture, native microbiome, climate conditions, plant genotype, and agricultural management practices. A universal "one-size-fits-all" inoculum is unlikely to work consistently across diverse environments. Therefore, developing region-specific or soil condition-specific microbial consortia is essential for reliable results.

7.1.3 Ecological Risk

Although introduced for beneficial purposes, non-native microbes carry a potential, though often overstated, risk of disrupting local soil microbial ecosystems and ecological functions. Careful risk assessment regarding the persistence, spread, and potential non-target effects of introduced strains is necessary before widespread application.

7.2 Future study directions

7.2.1 Advanced Omics and Culturomics

Integrating metagenomics, metatranscriptomics, metabolomics, and proteomics will provide a systems-level understanding of stress-adapted microbiomes. This will help identify keystone taxa, critical functional genes, and metabolic pathways that govern stress amelioration. Coupling these high-throughput omics approaches with advanced cultivation techniques (culturomics) will facilitate the isolation of novel, high-performance strains possessing desirable traits for soil reclamation.

7.2.2 Designing Synthetic Microbial Consortia

Moving beyond single-strain inoculants toward rationally designed synthetic microbial consortia that combine multiple, complementary species (e.g., nitrogen fixers, phosphate solubilizers, EPS producers, biocontrol agents, ACC deaminase producers) is likely to yield more robust, resilient, and multifunctional outcomes, as the consortia can perform complex tasks more efficiently.

7.2.3 Microbe–Plant Co-Adaptation

Breeding crop cultivars or selecting halophyte genotypes that are especially effective at recruiting and sustaining a beneficial microbiome—i.e., developing elite "holobionts" (the plant and its associated microbiome as a unit of selection)—could prove to be a powerful long-term strategy for enhancing stress tolerance and soil health.

7.2.4 Long-term Field Studies and Economic Analysis

Larger-scale, long-term field trials across different agro-climatic zones are essential to validate the efficacy, stability, and economic viability of microbial reclamation strategies under real-world conditions. Cost-benefit analyses comparing microbial approaches with conventional methods are needed to encourage adoption by farmers and land managers.

7. Conclusion

The reclamation of saline–alkali soils is a complex and urgent global challenge essential for ensuring food security and ecosystem sustainability. Although these degraded soils pose a daunting suite of physical and chemical challenges, the inherent adaptive and functional capacities of soil microorganisms offer a powerful, nature-based solution. Salinity and alkalinity act as potent environmental filters shaping a specialized but functionally critical microbial community. By elucidating the mechanisms through which these microbes improve soil structure, modulate ionic balance and pH, enhance nutrient availability, and alleviate plant stress, we can strategically harness their potential. The most promising way forward lies not in relying on microbial inoculants alone, but in integrating them—within a holistic ecological-restoration framework—with appropriate organic amendments and salt-tolerant plants. While challenges related to deployment, establishment, and scalability persist, rapid advances in microbial ecology, molecular biology and biotechnology hold the key to unlocking the full potential of the soil microbiome. Through continued interdisciplinary study and careful field application, we can transform degraded saline-alkali landscapes into productive, resilient, and sustainable ecosystems.

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Author Contributions

Conceptualization, Z.W.; Resources, Z.F. and L.S.; Writing-original draft preparation, Z.W.; Writing-review and editing, L.S.; Supervision, Z.W. and L.S. All authors have read and agreed to the published version of the manuscript.

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