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Progress of Applied Research on Saline Soil Management Using PGPR

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Abstract **Review Article**

With the continuous growth of population and urbanization, the shrinking of arable land resources has become a problem that cannot be ignored. Land salinization aggravates the deterioration of the ecological environment and poses a great threat to the sustainable development of agriculture. We describe the occurrence of land salinization and its hazards, briefly summarize the current widespread implementation of saline-alkaline land management techniques, summarize the mechanism of action of plants after prophylactic bacteria (PGPR) and the research process of saline-alkaline land management using PGPR, and provide a summary of previous work on saline-alkaline land management.
Keywords: PGPR, Saline-Alkaline Land, Biological Control, Soil Remediation, Soil Microorganisms.

1 Occurrence and Hazards of Land Salinization

Land salinization is a global problem faced today, and the Global Status of Salt-affected soils, published by the Food and Agriculture Organization of the United Nations (FAO), provide evidence for a new estimate of the global area of salt-affected soils. The report estimates that by 2024, the total area of saline soils in the world will be 1.381 billion hectares, or about 10.7% of the world's total land area. The country with the largest area of saline soils is Australia, with 357 million hectares of saline soils, and China ranks tenth with 36 million hectares of saline soils.

1.1 Causes of Land Salinization

Research highlights the salinized soils contain large amounts of soluble salts, and the alkali content reaches levels that inhibit normal plant growth, exacerbating ecological degradation and threatening agricultural production (Daan, 2014).The causes of land salinization include mainly natural, biological and anthropogenic factors.

1.1.1 Natural Factors

Academic research shows that the formation of land salinization is closely related to the characteristics of climatic zonation, in which precipitation and the intensity of surface evaporation are important causes (Hong-biao *et al.*, 2010). It is evident that land salinization mainly occurs in arid, semi-arid, semi-humid and coastal plains of the depression area (Jianhong, 2008), with the climatic characteristics of low precipitation and intense evaporation. On the one hand, the intensity of surface evaporation in arid and semi-arid areas is high, and soluble salts in groundwater accumulate at the surface with capillary rise in the soil. On the other hand, the uneven distribution of annual precipitation in the semi-humid and coastal areas causes dynamic changes in soil water salinity formation over time (Donghao, 2005).

The influence of geomorphology on soil salinization is mainly related to soil-forming parent material, groundwater distribution and soil water transport. Topography controls the direction and distribution of water and salt transport in the soil, and soil water transport is related to the depth of groundwater, which is related to the ability of groundwater to reach the surface by capillary phenomenon. Shallow groundwater is a direct source of salts for soil salinization (Changming & Yi, 1992).

1.1.2 Biological Factors

The study provides compelling evidence for uncultivated saline land or cultivated land abandoned due to soil salinization will gradually develop dominant species dominated by salt-tolerant plant communities (Dong-ling & ji, 2002). The main plants include white spurge (Nitraria tangutorum Bobrov), alkali fluff (Suaeda glauca Bunge), reed (Phragmites australis), etc (Dong-mei *et al.*, 2018). Salt-tolerant plants accumulate salts from deep underground into the plant through well-developed vascular bundles and root structures, and at the end of the growth cycle, the results support the claim that the plant dies and the accumulated salts in the plant return to the land (Dong-ling & ji, 2002; J-ing *et al*., 2023).

1.1.3 Human Factors

With the growth of the population and the development of the national economy, the influence of human factors on soil salinization can no longer be ignored. On the one hand, the inadequacy of irrigation water conservation projects leads to poor drainage of canals and fields, which raises the water table and aggravates the degree of soil salinization; on the other hand, irrational cultivation management and agricultural and pastoral development behaviors reduce the surface vegetation cover rate and increase the intensity of soil evaporation, resulting in the accumulation of salt on the soil surface (Baoqing *et al*., 2019; Wen-jie *et al*., 2017; Xiangle, 2014). There are also some areas affected by oil extraction, such as parts of Daqing City, Heilongjiang Province, where the construction of oil extraction facilities and the intensification of human activities have led to the reduction of vegetation and the salinization of grassland (Shuwen *et al.*, 2010).

1.2 Hazards of Land Salinization

Soil salinization has a major impact on the sustainable development of agriculture. The dual stress of salinity in agricultural production causes ionic toxicity and osmotic stress (Guohui *et al*., 2024). Excess salt ions in saline soils produce an osmotic effect that makes it more difficult for plants to take up water and nutrients from the soil, while certain ions in the soil solution can be toxic to plant growth (Baojin *et al*., 2023; Yuxia & Xingqiang, 2019). Soil salinization results in low vegetation cover, leading to a significant reduction in biodiversity and ecosystem degradation (Ying, 2025).

2 Saline-Alkaline Land Treatment Technologies and Current Situation

The remediation of saline-alkali lands presents significant challenges due to regional variations in climatic characteristics, salt sources, and soil structures, making a one-size-fits-all remediation model inadequate to address the heterogeneous demands. Current strategies emphasize four principal technical frameworks tailored to distinct etiologies of soil salinization: physical salt drainage and barrier techniques, chemical soil amendment and stabilization, agronomic water conservation and salt regulation strategies, and biological salt-tolerance remediation approaches.

Among these approaches, biological remediation has emerged as a predominant research focus owing to its soil rehabilitation capacity and environmentally sustainable nature. This methodology primarily involves the cultivation of halophytic vegetation and strategic manipulation of soil microbial community diversity to enhance soil quality. Li's team demonstrated that Zobellella sp. DQSA1 can significantly promote the growth of Coix lacryma seedlings under saline and alkaline stress and improve their salt tolerance, and its mechanism of action mainly includes regulating the level of endogenous plant hormones, enhancing the antioxidant capacity, and promoting the development of root system. Its mechanism of action mainly includes regulating the levels of endogenous plant hormones, enhancing antioxidant capacity, and promoting root development(Li *et al*., 2025). Through the study of Klebsiella pneumoniae NP36, Jin Jiayue *et al*., found that this bacterium has genes for synthesizing organic acids and transporting phosphates, which can improve the resistance of rice to saline and alkaline environments and promote rice growth (Jiayue *et al*., 2024).

3 Mechanism of Action of PGPR

Plant growth-promoting rhizobacteria (PGPR) are essential for plant development, utilizing both direct and indirect methods (Wahab *et al*., 2024). Directly, PGPR facilitate the uptake of soil mineral nutrients by synthesizing or modulating phytohormones, biologically fixing nitrogen, solubilizing phosphorus, and releasing potassium (Ying *et al*., 2021). These processes directly promote plant growth and mitigate plant stress. Indirectly, PGPR aid plants by producing antibiotics to combat pathogens. Concurrently, by producing antibiotics to reduce pathogenic toxins in the root system, PGPR induce plant systemic resistance, thereby indirectly promoting robust plant growth (Yasir *et al*., 2021).

3.1 Direct Effects

3.1.1 Nitrogen Fixation

Nitrogen constitutes an essential macronutrient, fundamentally impacting plant development and overall productivity. Biological nitrogen fixation (BNF) represents a critical biological process within the nitrogen cycle, wherein specific microbial agents employ nitrogenase enzymes to catalyze the conversion of atmospheric dinitrogen into a bioavailable form (Burgess & Lowe, 1996; Seefeldt *et al*., 2009). Certain Plant Growth-Promoting Rhizobacteria (PGPR) exhibit the capacity to facilitate nitrogen fixation, thereby converting atmospheric nitrogen into ammonium nitrogen, which is readily assimilated by plants. This process subsequently augments nitrogen acquisition by crops, thereby optimizing nutritional status and, ultimately, enhancing yields (Yufeng *et al*., 2015). The application of PGPR in agricultural practices underscores its significant potential.

3.1.2 Dissolved Phosphorus

Phosphorus is an essential macronutrient for plant growth, participating critically in energy transduction and fundamental biological processes, including photosynthesis. Despite the prevalence of phosphorus in the soil matrix, its bioavailability to plants is often constrained. The application of phosphorus-solubilizing bacteria (PSB), encompassing genera such as *Pseudomonas*, *Bacillus*, *Azotobacter*, and

Burkholderia, has been shown to augment phosphorus acquisition in the rhizosphere.

3.1.3 Dissolved Potassium

In instances of potassium deficiency during plant development, characteristic symptoms such as foliar chlorosis, restricted root elongation, and heightened vulnerability to lodging may be observed. Prior investigations have elucidated the significant contribution of Plant Growth-Promoting Rhizobacteria (PGPR) in the facilitation of potassium acquisition within the plant system. These edaphic bacteria synthesize potasholytic enzymes, thereby promoting the release of potassium ions via the degradation of potassium-bearing minerals or direct interfacial interactions (Qingdong *et al.*, 2017). Furthermore, PGPR-mediated secretion of organic acids, including oxalic and acetic acid, results in the chelation of potassium ions, consequently augmenting soil potassium availability and optimizing potassium assimilation by the plant (Iqbal *et al*., 2013).

3.1.4 Production of Plant Growth Promoting Substances

The extant literature substantiates the significant contribution of Plant Growth Promoting Rhizobacteria (PGPR) to plant development and yield enhancement, primarily through the biosynthesis and secretion of phytohormones, particularly Indole-3-Acetic Acid (IAA) (H. *et al.*, 2021). IAA exerts its influence predominantly on the cellular architecture of root tissues, thereby promoting the proliferation of the root system. This enhanced root architecture facilitates improved acquisition of water and essential nutrients from the soil matrix, consequently augmenting plant tolerance to water deficit conditions (Chen *et al*., 2017). Specifically, investigations have revealed that IAA synthesized by Pseudomonas fluorescens demonstrably enhances the growth of Brassica napus, thereby highlighting the critical role of PGPR in modulating plant growth and defense responses.

3.2 Indirect Effects

3.2.1 Synthetic Antimicrobial Components

The efficacy of Plant Growth Promoting Rhizobacteria (PGPR) in plant disease management is primarily attributed to the secretion of antimicrobial compounds. These bioactive substances, including antibiotics, target the cellular integrity and metabolic pathways of phytopathogens, thereby attenuating their pathogenicity and, consequently, inhibiting or eliminating the pathogens (Gustavo *et al*., 2021). Furthermore, PGPR elicit the production of signaling molecules within the host plant, which subsequently triggers the synthesis of pathogenesis-related proteins and enhances their expression. In addition, PGPR-mediated secretion of specific endopeptidases and proteins activates the plant's innate immune responses, thereby augmenting drought tolerance (Jong-Hui & Sang-Dal, 2013). At the molecular level, PGPR-induced modifications in the host plant can facilitate adaptive responses to drought stress.

3.2.2 Stimulating Systemic Resistance

Induced systemic resistance (ISR) denotes the heightened innate immune capacity of plants following exposure to external stimuli. ISR primarily relies on the interaction between plant growth-promoting rhizobacteria (PGPR) and the plant root system. This interaction modulates cell wall architecture or elicits the synthesis of specific pathogenesis-related proteins, thereby conferring systemic resistance against bacteria, fungi, and other pathogens. This mechanism is central to the biocontrol efficacy of PGPR (Yu & Jun, 2022). ISR is typically triggered by non-pathogenic microbes, often through the interaction of PGPR-derived metabolites with the plant, leading to the establishment of physical or chemical defense barriers (Kloepper *et al*., 1992).

Table1: Inter-root biotrophic bacteria of major salinity-tolerant plants and their salinity-tolerance capacity

Genus	Representative strain	Salt and alkali resistance	Primary growth-promoting mechanism
Pseudomonas spp. *Pseudomonas*	*Pseudomonas fluorescens*	High (1-10 % NaCl resistant)	ACC deaminase-producing, ferredoxin, IAA, phospholysis, pathogen inhibition(Tang *et al*., 2014)
Bacillus (genus of bacteria) *Bacillus*	*Bacillus subtilis*	High (5-15 % NaCl resistant)	Potassium-dissolving, antimicrobial-producing substances, antioxidant enzymes(Mamta *et al*., 2016)
Nitrogen-fixing bacteria *Azotobacter*	*Azotobacter chroococcum*	Medium-high (3-8 % NaCl resistant)	Biological nitrogen fixation, secretion of cytokinins, improvement of soil structure(Steel *et al*., 2012)
Streptomyces (genus of bacteria) *Streptomyces*	*Streptomyces griseus*	Medium-high (3-10 % NaCl resistant)	Phosphorus solubilization, antibiotic production, induction of systemic resistance(Kim & Kim, 2009)
Burkholderia (genus of bacteria) *Burkholderia*	*Burkholderia phytofirmans*	High (5-12 % NaCl resistant)	ACC deaminase, degradation of pollutants, promotion of root development(Salme *et al*., 2014)

4. PGPR-Mediated Remediation of Saline-Alkali Soils

The application of plant growth-promoting rhizobacteria (PGPR) in saline-alkali soils can significantly influence the physiological metabolism of cultivated plants (eVacheron *et al*., 2013), modulate soil microbial communities, and stimulate root metabolic activity, thereby promoting the production of organic acids. This, in turn, enhances the host plant's stress resistance (Dilfuza *et al*., 2019), leading to the regulation of soil pH and total salt content, and ultimately facilitating the sustainable remediation of saline-alkali land.

4.1 PGPR Inoculants for Saline-Alkali Soil Remediation

Rhizosphere soil samples were collected from various halophytes within saline-alkali environments. Through pure culture techniques and a comprehensive evaluation of PGPR strains based on salt stress tolerance and plant growth-promoting traits, superior strains were selected and formulated into PGPR inoculants using optimized fermentation carriers. These PGPR inoculants have demonstrated the capacity to enhance the germination and growth of various crops under salt stress conditions, thereby mitigating plant damage. Bhart (Nidhi *et al*., 2016) conducted a comparative study on rice cultivated in saline-alkali soil with and without PGPR inoculation, observing enhanced expression of salt tolerance-related genes in inoculated rice, which correlated with improved yield and quality. Jha (Jha & Subramanian, 2013) demonstrated significant alterations in antioxidant levels and growth physiology in PGPR-inoculated plants under salt stress compared to non-inoculated controls. Naz (Naz *et al*., 2009) *et al*., reported that PGPR application increased stem height, root length, and plant dry weight in soybeans and wheat under salt stress, indicating a significant growth-promoting effect. The research group of Li Qingpu (Qing-Pu *et al*., 2024) assessed the growth indicators and physiological characteristics of *Leymus chinensis* under varying PGPR treatments and salt concentrations. The PGPR inoculants improved plant growth under salt stress, reduced cell damage, and enhanced plant salt tolerance.

4.2 Composite PGPR Inoculants for Saline-Alkali Soil Amelioration

The application of composite PGPR inoculants, achieved through co-inoculation of multiple PGPR strains, offers a strategy for mitigating soil salinity and pH, concurrently improving soil nutrient availability and crop productivity. Zhang *et al*., (Xiaoli *et al*., 2022) conducted a controlled trial in the moderately saline-alkali soils of the Hetao Plain to assess the ameliorative effects of PGPR inoculants. The study compared three PGPR treatments, including composite and integrated applications, against single PGPR applications. Results indicated that composite PGPR inoculants significantly enhanced the levels of alkali-hydrolyzable nitrogen, available potassium, and available phosphorus within the rhizosphere. Chen *et al*., (Yanhong *et al.*, 2025) isolated fifteen bacterial strains from the rhizosphere of salt-tolerant rice, evaluating their salt tolerance, degradation capabilities, and plant growth-promoting traits. Halotolerant and alkaliphilic strains, primarily from the genera Bacillus and Enterobacter, were identified as suitable candidates for constructing composite PGPR inoculants. The salt tolerance threshold for mung bean seeds treated with composite PGPR inoculants increased from 10 g/L to 15 g/L, demonstrating a synergistic effect on mung bean seed germination under salt stress. This research provides a scientific basis for the rational utilization of microbial resources and the improvement of soil environments. Pang *et al*., (Huancheng *et al*., 2011) investigated the impact of three composite PGPR inoculants on soil salinity and alfalfa growth under varying salt stress conditions, revealing that microbial inoculants significantly increased alfalfa biomass under moderate salt stress. Yiling (Yiling *et al*., 2019) conducted a pot experiment, demonstrating that the application of composite microbial inoculants containing PGPR strains exhibited notable effects in soil amelioration and plant growth promotion.

4.3 PGPR Biofertilizers for Saline-Alkali Soil Remediation

PGPR inoculants can be formulated into PGPR biofertilizers through the incorporation of enzymes and functional compounds, or by combining them with organic fertilizers, to further enhance plant growth promotion under salt stress. Marwa (Marwa *et al*., 2019) reveal that the application of PGPR biofertilizers to cowpea in saline-alkali soils in Egypt improved both yield and quality under salt stress conditions. Alotaibi (Alotaibi *et al*., 2024) conducted field trials to assess the impact of PGPR biofertilizers on barley under saline-alkali conditions, demonstrating increased barley yield and enhanced plant tolerance to salt stress. Khaled (Shaban *et al*., 2023) *et al*., applied PGPR biofertilizers in conjunction with mineral nitrogen fertilizer in field trials, leading to a more diverse microbial community in the saline-alkali soil, a reduction in soil salinity and pH, and an improvement in faba bean quality.

5 CONCLUSION

The global area of saline land is about one tenth of the total land area, and soil salinization is a global environmental problem. Saline and alkaline soils are an important reserve of arable land, which is of great importance for the sustainable development of world agriculture and food security. Due to the different reasons for the formation of saline and alkaline soils in different regions, different treatment and restoration measures can be taken, including physical, chemical and biological measures, among which biological improvement measures have broad prospects, and many countries in the world have carried out comprehensive and in-depth research on PGPR, and the isolation of salt-tolerant genes has been routinely achieved, but it has not yet been possible to achieve large-scale production

(Kexin & Peng). The formation process of saline and alkaline soils is complex, and it is difficult to adapt to the needs of a single management mode, so it is necessary to adopt a variety of management modes and integrate them to form comprehensive improvement measures according to local conditions.

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