Proceedings of ICEGEE 2026 Symposium: AI-Based Medicine and Biological Data Analysis
DOI: 10.54254/2753-8818/2026.AU34660

Analysis of the Mechanism and Effect of Corn Straw Biochar and Nitrogen-Fixing Agent to Improve Saline-Alkali Land

Yuzhu Liu

College of Agriculture, Northeast Agricultural University, Harbin, China
Liuyuzhu323@outlook.com

Abstract. Straw biochar can effectively improve the physical and chemical properties of saline-alkali soil and regulate the microbial community by virtue of its high pore structure, strong adsorption and buffering capacity, while salt-tolerant nitrogen-fixing bacteria can achieve atmospheric nitrogen fixation, alleviate nitrogen deficiency in saline-alkali soils and improve plant stress resistance. This paper systematically expounds the distribution status of saline-alkali land and the challenges of ecological agriculture, sorts out the physicochemical regulation, nutrient cycling, microbial regulation, stress resistance and growth promotion mechanism of straw biochar and nitrogen-fixing agents to improve saline-alkali land, reviews the research progress and typical achievements of single biochar and modified biochar in saline-alkali land management at home and abroad, and focuses on the core problems existing in current research, such as unclear synergy mechanism, lack of long-term effect, insufficient technical adaptability, and cost constraints. The results show that the combined straw biochar-nitrogen fixing agent system can realize the improvement, nitrogen supply, and plant growth of saline-alkali land through the "physical-chemical-biological" synergy, However, it still faces challenges such as long-term stability, environmental adaptability of fungicides, technical standardization and economic cost. In the future, it is necessary to focus on the precise design of functional biochar, the optimization of microbial flora, long-term positioning observation in the field and the formulation of technical regulations, Promote green, efficient and sustainable management of saline-alkali land, and provide theoretical basis and technical reference for the resource utilization and ecological agriculture development of saline and alkali soil in arid places.

Keywords: Straw biochar, nitrogen-fixing bacteria, saline-alkali land improvement, soil microorganisms, sustainable agriculture

1. Introduction

In this study, straw biochar combined with salt-tolerant nitrogen-fixing bacteria to improve saline-alkali land was taken as the research object, and the synergistic mechanism and application technology of the two were systematically studied. To clarify the interaction relationship, survival and colonization law and nitrogen conversion characteristics of biochar and nitrogen-fixing bacteria in saline-alkali environment. The internal mechanism of improving soil physical and chemical properties, regulating microbial community structure, improving soil carbon and nitrogen storage

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2753-8818/2026.AU34660

capacity, and enhancing crop stress resistance was analyzed. To reveal the synergistic mechanism between biochar carrier and nitrogen-fixing bacteria under saline-alkali stress, This paper clarifies the carbon and nitrogen coupling cycle and microbial function response in saline-alkali soils, fills the research gaps such as insufficient analysis of joint improvement mechanism and unclear long-term effects, and enriches the theory of ecological rehabilitation and green improvement of saline and alkali soil. Realize the high-value utilization of agricultural waste such as corn straw, effectively alleviate the environmental pressure caused by straw waste and incineration, reduce the cost of chemical improvement and nitrogen fertilizer input in saline-alkali land. By constructing long-term, stable and environmentally friendly saline-alkali land improvement technology, the productivity and quality of saline-alkali land can be improved. Nowadays, the global saline soil area is estimated to be more than 833 million hectares, most of which is distributed in natural arid or semi-arid zones in Africa, Asia, and Latin America [1-3]. The total area of saline-alkali land in China is about 115 million mu, of which about 80% is saline-alkali land in arid areas, mainly distributed in the "three north" regions such as northeast China, northwest China, and the Qinghai-Tibet Plateau [4]. Among them, soda saline-alkali soil has a heavy, strong alkaline (pH >9), poor soil structure, low nutrient availability, and extremely difficult treatment. Salt accumulation leads to an increase in soil osmotic pressure, which induces physiological drought in plants, inhibits seed germination and seedling growth, and when the salt content of the soil layer exceeds 0.6%, crops are almost cut off. Saline-alkali stress can severely limit plant growth and yield improvement, including ionic toxicity, pH imbalance, osmotic stress and other adverse factors, resulting in inhibition of plant growth, hindering the uptake of nutrients, and ultimately leading to abnormal metabolism and even death of plants [2]. Although traditional improvement methods such as salt washing, guest soil, and chemical improvement have certain results, they have problems such as high cost, easy rebound, and secondary pollution. Therefore, this study focuses on the combined application system of straw biochar and salt-tolerant nitrogen-fixing agents, focusing on the internal interaction mechanism, carbon and nitrogen synergistic action law and microbial function response of the two to synergistically improve saline-alkali land, clarify the optimal application parameters and long-term improvement effects under different saline-alkali land types, and construct a green and efficient improvement technology model suitable for multi-regional saline-alkali land. Fill the gap in the systematic research on the stability of carbon pools, nitrogen turnover pathways, and expression of microbial functional genes in saline-alkali land with straw biochar and nitrogen-fixing agents, improve the multi-interface interaction system of "biochar-microorganism-soil-crop", and enrich the theoretical basis for green color improvement and soil ecological restoration in saline and alkali land. Realize the high-value resource utilization of agricultural wastes such as corn straw, solve the dual problems of straw burning pollution and high cost and poor effect of saline and alkali soil improvement, and construct low-cost, long-term, and secondary pollution-free ecological improvement technology, so as to provide replicable and generalizable practical solutions for the efficient agricultural utilization, expansion and quality improvement of cultivated land in the "Three North" regions and various types of saline-alkali soil in China.

Corn straw has numerous sources, and the environmental pollution caused by incineration is very serious. Additionally, it is difficult for agricultural waste to decompose after returning to the field, resulting in a decrease in the seedling rate of crops in the following year. Based on this, it shows that the utilization of straw resources has become more and more important, and the quantity of corn straw is large and widely sourced, and it is prepared into high-stability biochar adsorption materials through high-temperature pyrolysis, gasification pyrolysis and other methods, which not only effectively utilizes a large amount of agricultural waste to a certain extent, but also reduces the

DOI: 10.54254/2753-8818/2026.AU34660

production cost of adsorbents and realizes the high-value utilization of agricultural waste, which has both economic and environmental benefits [5, 6]. As a new functional soil conditioner, biochar can effectively improve soil physical and chemical properties, enzyme activity, and microbial growth environment due to its high specific surface area, strong electron exchange, and strong adsorption [7]. At the same time, biochar significantly enhances the ability to buffer soil acidity, regulates pH value, improves water retention capacity, total organic carbon content, total nitrogen, and cation exchange capacity through mechanisms such as the secretion of organic acids by soil microorganisms, and provides a habitat for soil microorganisms to enhance soil biological activity [8, 9].

On the other hand, nitrogen-fixing bacteria can convert inert nitrogen in the atmosphere into ammonia nitrogen that can be used by plants, increasing nitrogen levels in the environment and alleviating nitrogen deficiency in saline-alkali soils [10]. In addition, the nitrogen fixed by biochar can be released slowly in the later stage, thereby increasing fertilizer efficiency and reducing fertilizer consumption, which is more conducive to the nutrient demand of crops in the later stage of growth [11, 12].

In recent years, scholars at home and abroad have carried out a lot of research on biochar in improving saline-alkali land. Studies have shown that biochar can effectively alleviate the toxic effects of salt stress on crops and provide a good growth environment for crop roots by improving soil pore structure, enhancing water and fertilizer retention capacity, regulating soil temperature, and effectively adsorbing and retaining nutrient separators in soil, such as NH_4^+, K^+, Ca^{2+}, Mg^{2+}, etc. [12, 13].In terms of microbial research, Alamus Qige [14] isolated, purified, and identified nitrogen-fixing bacteria, and analyzed their growth-promoting properties and activation of soil nutrients, showing that Lysobacterantibioticus (Antibiotic lysobacter); Bacillusaerius (Bacillusaerius aerobis), these two strains significantly increased the content of soil total nitrogen and alkali-hydrolyzed nitrogen. Nitrogen-fixing bacteria can supplement soil nitrogen through biological nitrogen fixation, secrete plant growth-promoting substances, and inhibit soil-borne pathogens as biocontrol preparations. However, there are still shortcomings in the existing studies: first, most studies have applied biochar and nitrogen-fixing bacteria as independent amendments, ignoring the synergistic potential of the two in carbon and nitrogen coupling and establishing the combination of microorganisms and soil environment [15]; Second, the research on the interaction mechanism of biochar-nitrogen-fixing bacteria in saline-alkali land is mostly limited to the description of apparent phenomena, and there is a lack of systematic analysis of carbon pool stability, nitrogen turnover pathway, and microbial functional gene expression. Third, most of the existing studies are based on short-term (35 years) experiments. There is a lack of long-term (more than 10 years) positioning observations in the field. The technical parameters, such as the optimal ratio, application depth, and timeliness. They are not yet mature, which restricts the practical promotion of the technology.

2. Mechanism of action of straw biochar and nitrogen-fixing agent to improve saline-alkali land

2.1. Regulation of soil physicochemical properties

Straw biochar is alkaline or weakly alkaline, but its pH regulation of soda saline soil is not simply neutralized, but can be complexed and adsorbed with cations in the soil through surface functional moieties (such as hydroxyl moieties, aldehyde moieties, etc.) and adsorption sites, thereby increasing the cation exchange capacity (CEC) of saline-alkali land [12]. The porous structure of biochar can improve soil aeration and water-holding capacity, especially in soda saline-alkali soils

DOI: 10.54254/2753-8818/2026.AU34660

with a cohesive texture, which helps to break compaction and promote root development. Its surface negative charge can adsorb cations (CECs) and enhance soil buffering capacity.

2.2. Affect soil nutrient cycling and phosphorus conformation transformation

Phosphorus in saline-alkali soil is easily fixed by calcium and magnesium to form insoluble phosphate. Biochar can activate insoluble phosphorus by releasing organic acids and changing the pH of the microenvironment. It was found that after the application of straw biochar, the content of active phosphorus in soda saline soil increased, while the closed storage phosphorus (NaOH-Po) decreased, indicating that it promoted the release and conversion of phosphorus. In addition, biochar itself contains a certain amount of total phosphorus and potassium, which can be used as a slow-release nutrient source.

2.3. Regulate soil microbial community and enzyme activity

Biochar provides suitable habitat and nutrients for microorganisms, significantly improving soil microbial diversity. Studies have shown that the absolute abundance of nitrogen-fixing bacteria functional gene nifH increased after applying different amounts of biochar, and the abundance of ammonia-oxidizing archaea and denitrifying bacteria functional genes nirK and gene amoA in saline-alkali soil increased, and some pathogens were inhibited. At the same time, the activities of protease, urease, and soil nitrate reductase were enhanced, indicating that soil biochemical processes were activated and nutrient cycling rate was accelerated [16].

2.4. Screening and functional characteristics of salt-tolerant nitrogen-fixing bacteria

In recent years, researchers have isolated a variety of strains from saline-alkali soils, such as salt-tolerant nitrogen-fixing strain NG-051, phosphorus-solubilizing strain JL-022, and potassium-dissolving strain JL-017. Salt-tolerant nitrogen-fixing strain NG-051 can maintain high nitrogenase activity at NaCl concentrations of 2 g and L [17]. Its salt tolerance mechanisms include accumulation of compatible solutes, regulation of membrane permeability, and antioxidant system.

2.5. Enhance plant stress resistance

Nitrogen-fixing bacteria can also produce plant auxin (IAA), siderophores, ACC deaminase and other substances, regulate plant hormone balance, reduce ethylene stress, and enhance crop tolerance to saline-alkali stress.

3. Related technological developments

Soil salinization is a global soil degradation problem, and it is one of the core problems restricting the sustainable development of agriculture and the security of cultivated land resources. Saline-alkali land in China is widely distributed and has a large area, including coastal saline-alkali land and inland saline-alkali land, which causes soil compaction, increased pH, and low nutrient availability, resulting in land resource waste. In recent years, domestic saline-alkali land improvement research has gradually transformed from physical and chemical means to green ecological improvement, and straw is an important product of agricultural waste resource utilization, and its value in improving soil has been confirmed. The research on saline-alkali land improvement in foreign countries started early, focusing on the application of chemical amendments, water

DOI: 10.54254/2753-8818/2026.AU34660

conservancy project salt discharge, bioremediation technology, etc. The biochar improvement of soil has become a research hotspot, some relevant studies have proved that the pore structure of biochar can optimize the microbial environment, microbial metabolism can improve the availability of soil nutrients, However, the mechanism and research on the application mechanism of straw biochar and nitrogen-fixing agents are relatively fragmented, and the study on the suitability of saline and alkali soil in different regions are insufficient.

3.1. Improvement technology of single biomass charcoal

In order to solve the problem that the application of primitive biochar in saline-alkali land may aggravate salinization, nitric acid and phosphoric acid were innovatively used to modify cotton stalk biochar. Three materials, original biochar (BC), nitric acid modified biochar (NBC) and phosphoric acid modified biochar (PBC), were applied to saline-alkali soil at an addition rate of 1%-3%, and the improvement effect was evaluated by 120-day culture experiment. In this study, the effects of acid modification on the improved performance of biochar saline-alkali land were systematically compared, and the key role of surface chemical property regulation on the adsorption selectivity of salt separators was revealed. It was found that nitric acid and phosphoric acid modification could significantly reduce the content of basic metal elements on the surface of biochar, increase the specific surface area, enhance the specific adsorption of Na^+, Cl^-, SO_4^{2-}, CO_3^{2-}, and HCO_3^{2-}, and enhance the nitrogen fixation capacity [18]. The core advantage of this technology is that biochar can be converted from a "potential salt source" to a "salt absorbing material" through chemical modification, breaking through the limitations of traditional biochar application in heavily saline-alkali lands. However, the acid modification process increases the preparation cost and process complexity, and phosphoric acid modification may bring secondary environmental risks of phosphorus leaching. In addition, this study is only based on indoor culture experiments, lacking long-term field observations, and the stability and safety of acid-modified biochar in real agricultural ecosystems need to be verified.

3.2. Research on sustainable agriculture with modified biochar

Ail Fakhar systematically integrated the characterization technology, preparation method, and farmland application performance of modified biochar, constructed a framework for the correlation between structural characterization, soil performance, and agricultural efficiency, proposed the core innovation of targeted customized modification and multi-technology joint characterization, and clarified the synergistic mechanism of biochar adsorption, slow release, and microbial interaction in soil [19]. Studies have confirmed that modified biochar can significantly improve soil porosity, water and fertilizer retention capacity, and cation exchange, efficiently fix heavy metals and degrade organic pollutants, and achieve carbon sequestration and greenhouse gas emission reduction, which has multifunctional advantages in sustainable agriculture. However, this technology has limitations such as high preparation cost, poor product stability, unknown long-term ecological risks, and potential hidden dangers of secondary pollution, and lacks unified industry standards and field application specifications, and large-scale application is still limited by technology, cost and safety.

DOI: 10.54254/2753-8818/2026.AU34660

4. Challenges and development

4.1. Uncertainty of long-term stability and ecological securityr

Most of the existing studies are based on short-term (<1 year) indoor or potted experiments, but the aging process of biochar in soil (oxidation, fragmentation, pore clogging, etc.) and its impact on long-term colonization of nitrogen-fixing bacteria are still unclear. Long-term application may lead to saturation of functional groups and pore collapse on the surface of biochar, reducing the viability of microorganisms.

4.2. Stability and environmental adaptability of the agent

In complex soil environments, exogenous agents are easily affected by indigenous microbial competition, salt stress and other factors, and the colonization efficiency is unstable. In addition, the adaptability of the geographical environment is insufficient, and there are various types of Chinese saline and alkali land, including coastal chloride, inland sulfate, soda alkalization, etc., and their salt composition, pH and texture are significantly different. Most of the existing studies are specific regions (e.g., Yellow River Delta, Northeast Soda saline-alkali soil), and the generalization of technical parameters (biochar particle size, application rate, and agent concentration) has not been verified. In the future, the research and development of basic engineering bacteria or compound bacterial flora should be strengthened to improve their ecological adaptability.

4.3. Economic costs and constraints of large-scale application

Although the cost of straw raw materials is low, the comprehensive cost of biochar preparation, including equipment investment, energy loss, fungicide production (fermentation, embedding), and field application (machinery, labor), etc., is still high, and the lack of corresponding subsidy policies and market incentives restricts the large-scale promotion of technology.

4.4. Precise design of functional biochar materials

Future research will tend to design functionalized biochar for specific saline-alkali land types. By regulating the pyrolysis temperature, retaining more dissolved organic carbon at a low temperature of 300-400°C, enhancing the pore structure at a high temperature of 600-700°C, and chemically modifying, including pickling, oxidation, loaded metal oxides, etc., and bioactivation (compost fermentation), functionalized biochar with multiple functions of "targeted adsorption, slow-release carbon supply, and microbial carrier" can be prepared. For example, iron oxide-loaded biochar can simultaneously achieve nitrogen-fixing bacteria protection, which is suitable for compound polluted saline-alkali land.

5. Conclusion

The combined application of straw biochar and nitrogen-fixing agents is an valid green strategy for improving saline and alkali soil. The former improves the soil environment through physical adsorption, chemical regulation, and biological support, while the latter enhances plant nutrition and stress resistance through biological nitrogen fixation and growth-promoting effects. The synergy between the two can realize the integration of "soil modification, nitrogen supply, and growth promotion", and significantly improve the productivity and ecological function of saline-alkali land.

DOI: 10.54254/2753-8818/2026.AU34660

In the future, it is important to strengthen mechanism deepening, technical standardization, and large-scale promotion to promote the development of saline-alkali soil management in the direction of ecology and sustainability.

References

[1] FAO. (2021). Distribution map of saline soils in the world. Comprehensive Agricultural Development in China, (10). Retrieved March 12, 2026.
[2] Hasegawa, P. M., Bressan, R. A., Zhu, J. K., et al. (n.d.). Plant cellular and molecular responses to high salinity.
[3] Fang, S., Hou, X., & Liang, X. (2021). Response mechanisms of plants under saline-alkali stress. Frontiers in Plant Science, 12, Article 667458.
[4] Gu, X. (2026). Comprehensive management and prospects of saline-alkali land in arid areas in China. China's Agricultural Comprehensive Development, (1). Retrieved March 12, 2026.
[5] Zhang, H., Liang, M., Tang, C., et al. (2026). Study on phosphate removal performance in biochar-fortified water for preparation of functional biochar from microbial pretreatment of corn straw. Renewable Energy Source, 44(2). Retrieved March 13, 2026.
[6] Chang, F., Zhang, P., Yao, Z., et al. (2024). Effects of different modified maize straw biochar on soil hydraulic characteristics in loess hilly area. Environmental Science, 45(11). Retrieved March 13, 2026.
[7] Wang, J., Jing, M., Zhang, S., et al. (2020). Response of soil microbial community structure to exogenous application of jade rice straw biochar under oil pollution stress. Soil and Water Conservation Circular, 40(3). Retrieved March 13, 2026.
[8] Yi, C., Zhou, C., Mo, Y., et al. (2026). Study on the mechanism of modified biochar in reducing fluoride content in tea leaves and improving soil environment. Journal of Agriculture and Food Research, 27, Article 102769.
[9] Liu, D., Feng, Z., Zhu, H., et al. (2020). Effects of corn straw biochar application on soybean growth and alkaline soil properties. BioResources, 15(1), 1463–1481.
[10] Ming, T., Ruan, H., Zhang, H., et al. (2026). Research progress on the remediation of degraded soil by nitrogen-fixing bacteria. Shandong Agricultural Sciences, 58(1). Retrieved March 11, 2026.
[11] Mukherjee, A. (n.d.). Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures.
[12] Zhang, X., Geng, X., Wang, L., et al. (2025). Research progress on the effect and mechanism of biochar on improving saline-alkali soil. Journal of Yangzhou University (Agricultural and Life Sciences Edition), 46(3). Retrieved March 13, 2026.
[13] Zhang, Y., Yang, J., Yao, R., et al. (2020). Short-term effects of biochar and gypsum on soil hydraulic properties and sodicity in a saline-alkali soil. Pedosphere, 30(5), 694–702.
[14] Alamusiqiqige. (2025). Isolation and screening of rhizosphere nitrogen-fixing bacteria of three plants in desert grassland of Inner Mongolia and their proliferation effects should be studied, Inner Mongolia Normal University. Retrieved March 12, 2026.
[15] Xue, W. (2025). Effects of biochar and nitrogen fertilizer reduction on the stability of saline-alkali soil aggregates and organic carbon in the Tarim River Basin, Nanjing University of Information Science & Technology. Retrieved March 12, 2026.
[16] Song, J., Zhang, X., Liu, M., et al. (2026). Effects of biochar on soil physicochemical properties, enzyme activity and nitrogen cycle microbiomass abundance under continuous cropping-rotation conditions. Journal of Heilongjiang Bayi Agricultural Reclamation University, 38(1). Retrieved March 13, 2026.
[17] Si, X., Zhang, A., Zhang, X., et al. (2025). Preparation of salt and nitrogen fixing agent NY-I and its biogenerating efficacy in saline-alkali soils. Salt Science and Chemical Engineering, 54(12). Retrieved March 13, 2026.
[18] Zhu, S. (2025). Effects of cotton straw charcoal and its acid modification on saline-alkali land improvement and cotton growth, Xinjiang Agricultural University. Retrieved March 13, 2026.
[19] Fakhar, A., Galgo, S. J. C., Canatoy, R. C., et al. (2025). Advancing modified biochar for sustainable agriculture: A comprehensive review on characterization, analysis, and soil performance. Biochar, 7(1), Article 8.