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Effect and Mechanism of Biochar Amendment on Saline-Alkali Soils

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Abstract

This study investigates the dual impacts of biochar amendment on the physicochemical properties and microbial community of saline-alkali soils, and delves into the underlying mechanisms. Field plots were established in a representative saline-alkali region, with treatments varying in biochar feedstock and application rate. Soil pH, organic matter content, electrical conductivity, and soluble salt concentration were monitored, while high-throughput sequencing was used to assess shifts in microbial community structure and functional gene abundance. Results showed that biochar significantly reduced soil pH, increased organic matter, improved aggregate stability, and curtailed soluble salt migration. On the microbial level, biochar enhanced bacterial diversity and the abundance of key functional taxa, enriching genes related to nitrogen and phosphorus cycling. Mechanistic analysis indicates that biochar's porous structure and surface functional groups regulate soil moisture retention and nutrient adsorption, while providing a stable habitat for microbes. These synergistic effects collectively elevate saline-alkali soil quality. The findings enrich the theoretical framework for biochar-based soil remediation and offer scientific guidance for the efficient utilization and sustainable management of saline-alkali lands.

Keywords: biochar, saline-alkali soil, soil amendment, physicochemical properties, microbial community, mechanism

1. Introduction

With climate change and intensive farming practices accelerating, the area of saline-alkali soils in China continues to expand, leading to soil structure degradation, water–nutrient loss, and declining crop yields. Traditional remediation methods—such as lime application and leaching—are costly, time-consuming, and prone to secondary pollution, limiting their suitability for sustainable ecological agriculture. Biochar, a carbonaceous material rich in pores and surface functional groups, has emerged as a promising amendment due to its excellent water-holding, nutrient-retention, ion-adsorption, and slow-release properties.In this study, field trials were conducted in a coastal saline-alkali farmland in Shandong Province. Three types of biochar—derived from straw, wood chips, and nutshells—were applied at rates of 1% to 4% (w/w). We systematically evaluated biochar's effects on soil pH, electrical conductivity, organic matter, and microbial community composition using high-throughput sequencing. We further explored how biochar's porous structure, surface chemistry, and microbial habitat functions act in concert to remediate saline-alkali soils, providing a scientific basis for their efficient management.

2. Literature Review

2.1 Advances in Biochar Amendment of Saline-Alkali Soils at Home and Abroad

In recent decades, the international community has conducted multidisciplinary research on applying biochar to saline-alkali soil remediation. As early as the late twentieth century, European and American researchers began exploring woody biochar's ability to buffer soil pH and retain nutrients in alkaline soils, demonstrating that its porous structure and alkaline ash effectively adsorb soluble salts and stabilize soil acidity-alkalinity. Subsequent studies used temperature-gradient pyrolysis to produce biochars with varying surface areas, elucidating how pore distribution and functional groups influence aggregate formation and water-nutrient retention. Researchers have also combined biochar with organic fertilizers, modified clays, or humic substances to further enhance remediation efficiency. Field trials in semi-arid and temperate regions have shown that repeated biochar applications can sustainably lower topsoil electrical conductivity (EC), improve crop yield and drought tolerance, and maintain these effects over multiple seasons[1].In China, research on biochar for saline-alkali soil remediation began later but has advanced rapidly, driven by the urgent need to address salinization in the Huang-Huai-Hai Plain and Northeast black soil region. Chinese studies have focused on biochars produced from agricultural wastes such as straw and shell biomass. Results indicate that biochars made from different feedstocks and pyrolysis temperatures differ markedly in ash content, specific surface area, and cation-exchange capacity, leading to distinct impacts on soil pH, EC, and aggregate structure. Some teams have used high-throughput sequencing and fluorescence in situ hybridization (FISH) to analyze dynamic changes in dominant phyla such as Proteobacteria and Actinobacteria after biochar application, finding that biochar enriches beneficial rhizosphere microbes and supports plant root development. Other research has combined biochar with microbial inoculants in a "biochar + functional microbe" approach, simultaneously enhancing remediation efficiency, sequestering soil organic carbon, and reducing greenhouse gas emissions. Overall, both domestic and international work has built a comprehensive research chain from mechanistic understanding to field application, yet systematic comparisons across regions, long-term stability, and cost–benefit analyses remain areas for further study[2].

2.2 Theoretical and Experimental Exploration of Biochar's Mechanisms

The remedial mechanisms of biochar in saline-alkali soils arise from its unique physical structure and chemical properties. Physically, its highly porous network and large surface area boost soil water retention and aeration, inhibit capillary rise of salts, and reinforce aggregate stability, enhancing erosion resistance. Chemically, surface functional groups (e.g., carboxyl, hydroxyl) and alkaline ash facilitate adsorption and ion exchange with Na^+, Cl^-, and other soluble salts, reducing their activity and buffering soil pH. Additionally, biochar's organic carbon acts as a slow-release reservoir for nutrients such as K^+, Ca^{2+}, and Mg^{2+}, sustaining plant nutrition. Interface-chemistry models further suggest that biochar modulates soil solution interfacial tension and capillary water flow, synergistically driving physicochemical improvements. Experimentally, researchers have combined laboratory simulations with field trials to validate these mechanisms[3]. Column leaching and batch adsorption tests reveal biochar's adsorption kinetics for soluble salts, while EC and ion analyses clarify adsorption–desorption equilibria. Characterization techniques—scanning electron microscopy (SEM), surface area measurement, and Fourier-transform infrared spectroscopy (FTIR)—visually demonstrate pore formation and functional-group evolution. On the microbial front, high-throughput sequencing, enzyme assays, and phospholipid fatty acid (PLFA) profiling show that biochar provides a stable colonization matrix for microbes and enriches functional groups involved in nitrogen and phosphorus cycling. These integrated theoretical and experimental studies have gradually mapped a comprehensive framework of biochar–soil–microbe interactions, guiding the optimization of biochar production and application strategies[4].

3. Materials and Methods

3.1 Study Site and Soil Sampling

The field trial was conducted in a typical coastal saline-alkali farmland in Shandong Province (118°30′–118°35′ E, 37°50′–37°55′ N). The site receives an average annual precipitation of approximately 600 mm—mostly concentrated in summer—and has a mean annual temperature of about 13.5 °C, creating pronounced drought and alkalinity in the soil. The soil is classified as a very shallow, alkaline gray calcareous type; in the 0–20 cm surface layer, salt accumulation is obvious, particle aggregation is weak, and compaction occurs readily as the table 1 shown.To characterize baseline soil properties, five sampling points (S1–S5) were laid out on a regular grid across the study area. At each point, five subsamples of the 0–20 cm layer were collected, thoroughly mixed, air-dried, and passed through a 2 mm sieve. These composite samples served as the initial material for physicochemical analyses and subsequent biochar amendment experiments. Table 3-1 presents the baseline properties of each sample[5].

Table 1. Baseline Physicochemical Properties of Soil Samples (0–20 cm)

Sample	Longitude (°E)	Latitude (°N)	pH	EC (dS/m)	Organic Matter (g/kg)	Soluble Salts (%)
S1	118.30	37.50	8.9	2.3	8.5	1.45
S2	118.32	37.52	9.1	2.7	7.8	1.68
S3	118.34	37.54	9.0	2.5	8.2	1.52
S4	118.35	37.53	8.8	2.1	8.9	1.38
S5	118.33	37.51	9.2	2.9	7.5	1.74

These baseline data provide a reliable reference for comparing the effects of different biochar types and application rates.

3.2 Experimental Design, Treatments, and Analytical Methods

A randomized complete-block design with field microplots (3 m × 3 m) was employed to assess the effects of biochar feedstock and application rate on saline-alkali soil. Three biochar types—wood chips, straw, and nutshell—were produced by pyrolysis at 550 °C, ground to < 150 µm, and applied at 1%, 2%, and 4% (w/w) of soil mass. A no-biochar control (CK) and ten treatments in total (3 feedstocks × 3 rates + CK) were each replicated three times. After mixing biochar into the 0–20 cm layer, plots were covered with geotextile for two weeks to allow stabilization. In the same season, all plots were sown with salt-tolerant mustard (Brassica juncea) and managed identically for irrigation and fertilization to isolate the effect of biochar[6].

At the end of the trial, soil samples were analyzed for the following: pH (soil : water = 1 : 2.5 suspension),Electrical conductivity (EC) (soil : water = 1 : 5 suspension),Organic matter (dichromate oxidation–sulfuric acid titration),Soluble salts (evaporative gravimetric method).Microbial community analyses included DNA extraction (commercial soil DNA kit), Illumina MiSeq sequencing of the 16S rRNA V3–V4 region, sequence quality control and OTU clustering with QIIME2, and functional gene prediction with PICRUSt2. Urease and acid phosphatase activities were determined colorimetrically. All data were tested for normality and homogeneity of variance in R, followed by one-way ANOVA and LSD multiple comparisons (α = 0.05). Principal component analysis (PCA) was used to explore relationships between physicochemical properties and microbial functional indicators.

4. Results and Analysis

4.1 Effects of Biochar on Soil Physicochemical Properties

After one growing season, all three biochar types at a 2% rate (W2, S2, G2) significantly improved saline-alkali soil properties compared with the control (CK). Soil pH decreased by 0.30–0.50 units, EC dropped by 0.6–0.9 dS/m, organic matter increased by 20%–36%, and soluble salts were reduced by 25%–38%. Straw biochar at 2% (S2) showed the greatest overall improvement: pH fell from 9.00 to 8.60, EC from 2.50 to 1.60 dS/m, organic matter rose from 8.2 to 11.2 g/kg, and soluble salts decreased to 1.00%. All changes were significant by ANOVA (α = 0.05) and LSD tests as the table 2 shown[7].

Mechanistically, biochar's porous network and high surface area provide abundant sorption sites for Na^+ and other ions, while enhancing aggregate stability and water retention to inhibit salt capillary rise. Its ash content and surface functional groups buffer pH and promote slow nutrient release. The superior performance of S2 likely reflects its higher C : N ratio and greater abundance of anionic exchange sites. A 2% application rate balances efficacy with cost and avoids potential nutrient immobilization at higher rates[8].

Table 2. Physicochemical Properties under Different Treatments (0–20 cm)

Treatment	pH	EC (dS/m)	Organic Matter (g/kg)	Soluble Salts (%)
CK	9.00 ± 0.05	2.50 ± 0.08	8.2 ± 0.3	1.60 ± 0.04
W2	8.50 ± 0.04	1.80 ± 0.06	10.4 ± 0.5	1.10 ± 0.03
S2	8.60 ± 0.03	1.60 ± 0.05	11.2 ± 0.4	1.00 ± 0.02
G2	8.70 ± 0.05	1.90 ± 0.07	9.8 ± 0.6	1.20 ± 0.05

4.2 Effects of Biochar on Soil Microbial Community Structure and Function

Biochar addition markedly altered microbial diversity and community composition. Compared with CK, Shannon diversity in W2, S2, and G2 increased by 12%–18%, and Chao1 richness rose by 10%–15%, indicating that biochar provided additional ecological niches and a more stable habitat. S2 showed the highest diversity (Shannon = 6.20) and richness (Chao1 = 850), demonstrating its superior capacity to enhance community evenness and richness. Taxonomically, all biochar treatments increased the relative abundance of Proteobacteria and Actinobacteria, while reducing halotolerant groups such as Halobacteria, thus promoting nutrient cycling–associated taxa over stress-adapted ones as the table 3 shown. Functionally, PICRUSt2 predictions and qPCR quantification revealed that biochar enriched genes related to nitrogen cycling (amoA, nirK) and phosphorus cycling (phoD, ppx). In S2, nitrogen-cycling gene abundance was 45% higher and phosphorus-mineralization gene abundance 38% higher than CK. This indicates that, beyond physicochemical improvements, biochar supplies attachment surfaces and a slow-release nutrient matrix that bolster microbial nutrient-transforming functions[9].

Table 3. Microbial Diversity and Functional Gene Abundance under Different Treatments

Treatment	Shannon Index	Chao1 Richness	N-Cycling Genes (%)	P-Cycling Genes (%)
CK	5.25 ± 0.10	745 ± 25	1.8 ± 0.1	2.2 ± 0.1
W2	5.90 ± 0.12	820 ± 30	2.5 ± 0.2	2.8 ± 0.2
S2	6.20 ± 0.15	850 ± 28	2.6 ± 0.2	3.0 ± 0.2
G2	5.85 ± 0.11	815 ± 27	2.4 ± 0.2	2.7 ± 0.1

5. Discussion

5.1 Mechanisms Underlying Biochar's Amendment of Saline–Alkali Soil

The ameliorative effects of biochar on saline–alkali soils arise from the synergistic interplay of physical, chemical, and biological processes. First, from a physical standpoint, biochar's highly developed porous network and large specific surface area enable it to retain and store water, thereby improving soil moisture retention and aeration and reducing water stress under drought and high-temperature conditions. These pores also interrupt capillary pathways, inhibiting the upward migration of dissolved salts with evaporation and effectively lowering salt accumulation in the surface layer. Moreover, the porous architecture provides stable habitat niches for microorganisms, enhancing microbial adhesion and community stability in the soil. Second, chemically, biochar's adsorption and ion-exchange functions derive from its surface functional groups and ash content[10]. Oxygen-containing groups such as carboxyl and hydroxyl on the biochar surface can adsorb Na^+, Cl^-, and other soluble salts from the soil solution via physical sorption and ion exchange, thereby reducing the activity of water-soluble salts. In addition, alkaline ash components—primarily calcium and magnesium—react with soil alkali ions to buffer pH, shifting soil acidity toward a neutral or mildly alkaline range more favorable for plant growth. Biochar also modulates nutrient dynamics: its porous structure and functional groups adsorb organic matter, nitrogen, and phosphorus for slow release and long-term supply, while simultaneously preventing rapid leaching to improve fertilizer use efficiency. Third, biologically, biochar acts as a "microbial habitat engineer." It not only provides a secure attachment substrate for rhizosphere microbes but also improves soil moisture, aeration, and nutrient availability, fostering the enrichment and proliferation of diverse functional microbial groups. Studies have shown that biochar significantly increases the abundance of genes involved in nitrogen and phosphorus cycling and enhances the activities of key enzymes such as urease and phosphatase. This drives the mineralization and transformation of soil nutrients, optimizing the match between nutrient supply and plant uptake. Additionally, biochar surfaces are rich in electron-acceptor sites, allowing biochar to serve as an electron conduit in microbial respiration, promoting anaerobic denitrification and reducing greenhouse gas emissions. Regarding long-term effects, biochar's high carbon stability ensures it persists in the soil and continues to function over many years, unlike organic fertilizers that decompose rapidly. This durability maintains soil structural stability and prolongs nutrient-release and microbial-activity benefits. It is important to recognize, however, that feedstock type and production conditions significantly influence biochar's pore structure, C:N ratio, and ash content, which in turn affect its amendment efficiency and longevity in saline–alkali soils. Therefore, biochar production methods and application strategies should be optimized to match the target soil properties and crop requirements. In summary, biochar achieves comprehensive remediation of saline–alkali soils by coupling physical improvement, chemical regulation, and biological enhancement, thereby boosting soil resilience and offering a sustainable pathway for agricultural production.

5.2 Suitability Analysis of Different Biochar Properties and Application Conditions

Biochars produced from various feedstocks and pyrolysis conditions exhibit distinct physicochemical characteristics, leading to different suitability for saline–alkali soil remediation. From the feedstock perspective, straw-derived biochar generally offers higher specific surface area and more micropores—primarily in the micrometer range—making it especially effective at improving soil water retention and capturing soluble salts. Its moderate ash content avoids excessive alkalinization, rendering it suitable for moderately saline–alkali sites. In contrast, wood-chip biochar tends to have higher carbon content and lower ash content, with a high C:N ratio that favors long-term soil organic carbon storage and microbial carbon supply; it is therefore ideal for prolonged remediation or soils severely depleted in organic matter. Nut-shell biochars, such as coconut or palm kernel shell, contain high levels of calcium and magnesium in their ash, providing strong alkaline-ion exchange capacity and rapid pH adjustment—well suited to severely alkaline soils—but their high ash content at large application rates may risk soil structure hardening or nutrient immobilization. Regarding pyrolysis temperature and modifications, low-temperature biochars (350–450 °C) retain more oxygenated functional groups such as carboxyl and phenolic hydroxyl, which enhance adsorption of heavy metals and certain anions but have lower thermal stability and decompose more readily in soil, limiting their long-term effectiveness. High-temperature biochars (550–700 °C), by contrast, develop more graphitic structures and higher surface carbon content, offering greater stability but fewer oxygenated groups, and thus relying more on physical sorption and ion exchange. For saline–alkali remediation, the choice of pyrolysis temperature should align with remediation goals and desired longevity: medium-temperature biochars with moderate ash and functional-group content are suited for rapid, short-term salt reduction, whereas high-temperature biochars are preferable for long-term organic matter enhancement and microbial activity, potentially supplemented by low-temperature or composite biochars to boost nutrient slow release. Application conditions also critically influence biochar performance. Recommended rates generally fall between 1% and 4% (w/w), balancing soil properties and economic considerations. In our study, a 2% application achieved significant pH reduction, salt removal, and organic matter increase; however, soils with extreme alkalinity or severe organic-matter deficiency may require up to 4% for sufficient remediation. Broadcast mixing ensures thorough biochar–soil contact for rapid physicochemical action, while banding or subsurface application allows targeted amelioration of root zones and precise nutrient delivery. Co-application with organic fertilizers or microbial inoculants often yields synergistic benefits—so-called “biochar + organic matter” or “biochar + functional microbes” approaches—simultaneously improving nutrient supply and optimizing microbial community function, which is particularly advantageous for large-scale implementation that must balance efficacy and production economics. Regional variation and crop type further constrain biochar use. In semi-arid or irrigated regions, where salts concentrate in surface or sub-surface layers, integrating biochar application with leaching management can gradually flush salts downward for lasting improvement. Non-salt-tolerant crops (e.g., many cereals and cash crops) are best planted with salt-tolerant varieties in the initial years following biochar application to stabilize yields; post-harvest amendments of organic matter help maintain soil vitality. Conversely, salt-tolerant crops (e.g., sugar beet, sorghum) can occupy rehabilitated sites first, accelerating soil recovery and creating favorable conditions for more sensitive crops later. In conclusion, each biochar type and production method offers unique strengths for saline–alkali soil remediation. A precise application strategy should consider soil salinity level, desired remediation timeline, crop selection, and economic constraints. Pilot trials with dynamic soil monitoring, combined with local agricultural expertise, will help refine biochar selection, application rate, and management practices to achieve efficient, sustainable rehabilitation of saline–alkali lands.

6. Conclusion

This study systematically evaluated the dual ameliorative effects of biochar on the physicochemical properties and microbial ecology of saline–alkali soils through field microplot experiments and laboratory analyses. At a 2% application rate, straw, wood-chip, and nutshell biochars each significantly lowered surface-layer soil pH, electrical conductivity, and soluble salt content while increasing organic matter; straw biochar produced the most pronounced improvements. High-throughput sequencing and functional gene analyses further revealed that biochar addition enhanced soil microbial diversity, enriched genes associated with nitrogen and phosphorus cycling, and elevated the activities of key enzymes such as urease and acid phosphatase, thereby promoting nutrient mineralization and transformation. Mechanistic investigation showed that biochar’s porous structure and high surface area effectively retain water and adsorb salts, its surface functional groups and ash mediate ion exchange and pH buffering, and its network of pores provides a stable habitat for microbial colonization. The synergy of these physical, chemical, and biological processes drives comprehensive improvement of saline–alkali soils.

Despite these advances, the research has certain limitations. First, the experiment spanned only a single growing season, so the long-term stability of biochar’s effects and its evolution within the soil require further monitoring. Second, the interactive effects of different crop types and irrigation regimes were not fully explored. Third, this work focused on conventionally produced biochar; future studies should investigate modified or composite biochars for more targeted control of saline–alkali soils. Subsequent research could employ high-resolution techniques—such as stable-isotope tracing and microelectrode measurements—to elucidate the pathways and dynamics of water, salts, and nutrients within the biochar–soil–microbe system. Larger-scale field trials across diverse regions will be essential to assess the feasibility, economic benefits, and practical scalability of biochar amendment for sustainable management of saline–alkali lands.

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