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Review

Research Advances in the Impacts of Biochar on the Physicochemical Properties and Microbial Communities of Saline Soils

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Abstract: The scientific management of salinized agricultural lands and the use of undeveloped saline lands to ensure food security have become one of the most urgent tasks nowadays. Biochar contains rich carbon (C) and functional groups, and processes high alkalinity, porosity, and specific surface areas. Thus, it has been widely used as an effective organic conditioner in acidic or neutral soils to improve their fertility. However, so far, the impacts of biochar application on properities of saline soils and the underlying mechanisms remain unveiled. Therefore, in this study, we focus on the investigation of the impacts of biochar on the physical, chemical, and biological properties of saline soils. We found that biochar could: (1) decrease soil bulk density (BD), increase soil porosity, promote the formation of soil aggregation and enhance the leaching of soil salts; (2) increase the cation exchange capacity (CEC) of soil, decrease the salinity of soil through ion exchange and adsorption, directly act as the nutrient supplements to compensate the nutrients deficiency in soil, and indirectly adsorb water and nutrients or improved nutrient availability; (3) directly act as the nutrient supplements, indirectly adsorb water and nutrients or improved nutrient availability (e.g., soil organic carbon (SOC) turnover and sequestration, nutrient cycling); and (4) improve the structure and functioning of the soil microbial community and therefore indirectly impact the carbon, nitrogen (N) and phosphorus (P) cycling in soil systems. However, these impacts heavily depend on the properties, the concentration of the biochar added to the soil, and the type and location of the soil. In fact, some studies have shown that the addition of biochar in soil could even increase the salinity of saline soils. Another issue is the lack of long-term and large-scale field experiments regarding the impact of biochar addition on properties of saline soils. Therefore, future studies should focus on long-term field experiments with the combination of traditional soil analytical, methods and mordern molecular techniques (high-throughput sequencing, macro-genomics, and metabolomics) to comprehensively reveal the response mechanism of physicochemical properties and microbial characteristics of saline soils to exogenous biochar. Our study can provide a scientific foundation for the practical agricultural production and ecological management of biochar.

Keywords: biochar; saline soil improvement; physicochemical properties; nutrient cycling; biochar-microorganisms interaction

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1. Introduction

According to incomplete statistics from the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the Food and Agriculture Organization (FAO), the global area of saline soils is approximately 1 billion hm^2 and the saline soil is distributed in more than 100 countries [1,2]. Salinization is one of the most serious problems responsible for soil degradation worldwide. For example, an excessive amount of Na^+ during salinization can deteriorate soil structure, inhibit soil microbial activity and population and decrease the effectiveness of soil nutrients. Moreover, Na^+ can also produce osmotic stress and ionic toxicity to plants, disrupting their normal physiological metabolism and even causing their death [1–3]. According to Qadir et al. [4], the annual agricultural economic losses due to soil salinization amount to as much as $27 billion US dollars. By 2025, two-thirds of mankind will face water scarcity and, consequently, 15 million m^3/day of untreated wastewater would be used for crop irrigation, which, in turn, will cause soil salinity to increase and salty soils to become more saline [5]. Due to improper water and fertilizer management practices in agricultural production, the extensive use of pesticides, and the negative impact of global warming, about 33% of the world's arable land experiences various degrees of soil salinization, which is increasing year by year. It has been predicted that 50% of the arable land will be affected by salinization by the year 2050 [3,6]. At present, China's available saline and alkaline land resources are about 36.7 million hm^2 [7], of which 12.3 million hm^2 [1] is with agricultural utilization prospects. With the rapid progress of industrialization and urbanization, China's high-quality arable land resources decrease by about 400,000 hm^2 every year. In the face of the severe situation of shortage of available land resources, the scientific management of arable land affected by salinization as well as utilization of undeveloped saline and alkaline land is of great significance in guaranteeing the security of food production and restoration of ecosystem function of wetlands [7–9]

Over the past several decades, many engineering, agronomic, chemical and biological approaches have been implimented for the improvement and utilization of saline soils, and each of these approaches has its own advantages and disadvantages [7]. For example, based on the principle that "salt comes with water, salt goes with water", the engineering approach focuses on establishing wells, ditches, canals, etc., to reduce salt from irrigation and drainage. This method has immediate effects, but has high project volume and cost limited maintenance time, as well as high sensitity to water resources. Agronomic practices, such as land levelling, harrowing, and mulching, can increase soil aeration and water permeability, promote salt washing, and effectively reduce salt aggregation in the soil surface layer; thus, an increased application of organic fertilizers can quickly enhance soil fertility and promote plant growth. However, the effects of these agronomic practices are unstable, short-lived, and often accompanied by re-salinization. Chemical practices mainly use desulfurization gypsum, calcium superphosphate and aluminum sulfate to reduce soil pH and replace base cations, which are selectively adsorbed onto the soil colloids. These measures are convenient and have immediate effects. However, they are expensive, and can easily cause secondary pollution if used inappropriately. Biological measures majorly rely on the cultivation of salt-tolerant plants or the application of microorganisms. Although such practices offer both ecological and economic benefits, they are time-consuming to show obivious effects. For example, Jesus et al. [10] reported that it would take at least 13 years to lower soil electrical conductivity (EC) from 20 dS $m-m$ to 4 dS $m-m$ by phytoremediation. While it is urgent to improve and utilize the land suffered from affected by salinization, these aforementioned approaches show various limitations such as high costs, operational difficulties, limited duration of de-salinization, and unsatisfactory effects; therefore, it is urgently necessary to develop a simple, environmentally friendly, cost-effective, and easily scalable material or technique to improvement of saline soils. This review summarized biochar performance and mechanisms in improving the physical, chemical, and biological properties of salt-affected soils, and offered valuable insights for developing sustainable biochar-based tools for remediating salt-affected soil.

2. Biochar—A Potential Material for the Improvement of Saline Soils

Biochar is normall idenfitied as the C-rich particles produced from biomass (plants residues, manure, sludge) under high temperatures (<700 °C) and limited-oxygen conditions. Most biochar has alkaline pH (8.0–10.4), low BD, high specific surface area (SSA) and porosity, rich functional groups (e.g., carboxyl, carbonyl, and phenol groups), and strong ion adsorption and exchange capacity. Due to the highly aromatic structures, the half-life of biochar in the soil can be stored for several hundred or even thousands of years [11,12]. Thus, biochar is increasingly being recognized by scientists and policy makers for its potential role in mitigating anthropogenic climate change (e.g., C sequestration, reducing greenhouse gas emissions, renewable energy, waste mitigation,), improving soil fertility, and ultimately enhancing crop production [13]. Numerous studies also have shown that biochar can act as a good soil conditioner to decrease soil BD, increase soil porosity, promote soil aggregation by acting as a cementing substance to improve soil water, gas, and heat conditions, regulate soil pH, and enhance the effectiveness of nutrients in soil minerals, and provide a favorable habitat for soil microorganisms and plant roots. Through π–π interactions, pore filling, hydrogen bonding, and electrostatic attraction, biochar can adsorb heavy metals (e.g., Cu^{2+}, Cd^{2+}, and Pb^{2+}) and organic pollutants (e.g., pesticides, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, petroleum hydrocarbons, and antibiotics) to reduce their bioavailability and environmental risks [14–17]. Meanwhile, as a regenerated product of agricultural, forestry, and livestock wastes, biochar can not only be used as a resource but can also reduce the release of greenhouse gases emissions, such as CO_2, CH_4, and NO_2, acting as a feasible C sequestration practice [11,18]. However, it should be noted that all these positive effects of biochar in soil are from studies focused on acidic or neutral soils in tropical, subtropical and temperate areas, and excessive application of biochar, which typically tends to be alkaline, may exacerbate soil salinization. Therefore, the application of biochar application in the improvement of salinized soil has been rarely studied, the conclusion is controversial, and the underlying mechanisms remain unclear [9,19].

Differences in pyrolysis temperature, time, and raw materials result in relatively large differences in biochar's structure and surface properties, which in turn result in significant differences in the environmental effects of its application [12,16,20]. Generally, the higher the biochar's pyrolysis temperature, the higher its ash content, carbon/nitrogen (C/N) ratio, pore size, and specific surface area. The higher pyrolysis temperature of biochar also leads to the faster dehydration and decomposition of acidic components such as organic acids, reducing its surface charge and ionic functional groups while increasing alkalinity. The increased pyrolysis time also increases the ratio of the aromatic ring structure of biochar and its stability [21]. Compared with livestock manure, biochar made from cellulose-, hemicellulose- or lignin-rich wood have a large C/N ratio and high stability, but low nutrient content. Zhang et al. [22] produced biochar from bamboo, rice husk and fruit tree branches, and found that the biochar prepared from fruit tree branches contained more humic substances, acidic functional groups, such as carboxyl, carbonyl and phenol groups on the surface, and had relatively low pH. As biochar aged, its fatty C content started to decrease, whereas the number of acidic functional groups, surface negative charges, oxygen/carbon ratio and cation exchange capacity (CEC) of biochar increased [18]. Recently, studies have shown that biochar can effectively improve saline soil and promote plant growth [2,23–27]. For example, under the premise of considering ecological benefits, Li et al. [28] pointed out that the production cost of biochar is negative under the trading price of organic waste feedstock and C emission reduction; with the continuous progress of preparation technologies, its production cost will be further reduced. In addition, biochar can be prepared from a wide kinds of raw materials, making it favorable for a wide-scale application in saline–alkali soil reclamation [12].

Therefore, this review summarizes the research on biochar's improvement of saline soils, and discusses the effects of biochar on the physicochemical properties, nutrient utilization, and microbial regulation of saline soils. This paper also analyzes the deficiencies and urgent issues that need to be addressed and propose the next-step research direction and focus to provide a theoretical basis and technical support for the large-scale application of biochar in the reclamation of salinized soil.

3. Statistics of Studies Related to Biochar and Saline Soil

We first performed statistical analysis on the relevant papers published on the topic of biochar and saline soil based on the ISI Web of Science database (https://www.webofscience.com accessed on 20 September 2023) and China Knowledge Resource Synthesis Database (http://www.cnki.net/ accessed on 20 September 2023). When searching with the keywords of “soil”, “biochar” and “biomass charcoal”, we found 6435 Chinese articles and 13,380 English articles. Among them, 176 Chinese articles and 297 English articles (in total 473 articles) contain keywords such as “saline soil”, “saline–alkaline land”, “saline lands” or “alkaline land”. When we further searched these articles with the keywords of “physical structure”, “bulk density”, “porosity”, “aggregate”, “hydraulic”, “conductivity”, “chemical properties”, “electrical conductivity”, “SAR”, “ESP”, “nutrient”, “soil organic matter (SOM)”, “potassium (K)”, “nitrogen (N)”, “phosphorus (P)”, “microbial properties”, “microorganism”, “bacteria”, “fungi”, “enzyme”, “actinomycetes”, we found that the total number of literature retrieved in both English and Chinese on the physical, chemical and microbiological properties with biochar amendment in salinized soils were 77, 417 and 170, respectively.

Using the JavaScript programming language and ECharts, the above-mentioned data were visualized. As shown in Figure 1, relevant papers on the topic of biochar soil have appeared since 2007. However, research on biochar in the field of saline soil reclamation emerged only in 2009, and after 2018, the numbers of relevant research showed an explosive growth trend. This shows that the application of biochar application in saline soil reclamation has now gained increasing attention and is one of the future directions of sustainable green agriculture. As shown in Figure 2, biochar improvement of saline soils mainly concentrates on soil chemical properties. In addition, the studies on biochar in terms of microbial properties of saline soils have gradually increased since 2015, and the attention on it has increased rapidly since 2019.

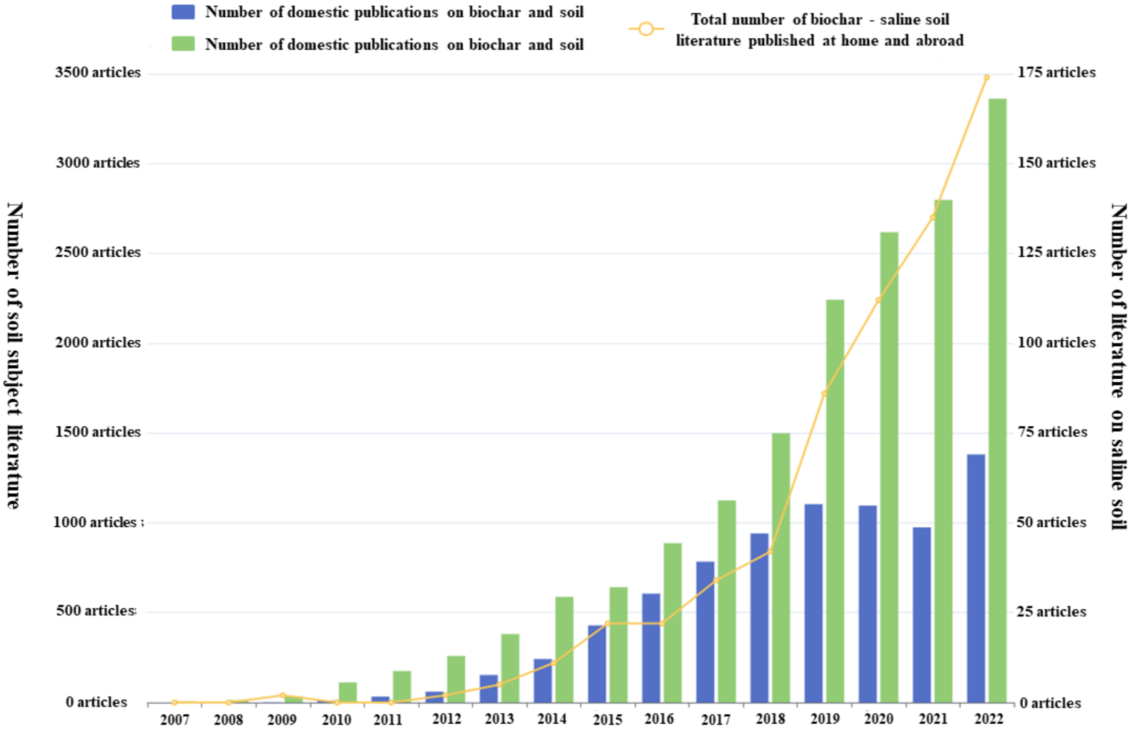

Figure 1. Number of research papers in the field of biochar in saline soil and its development trend.

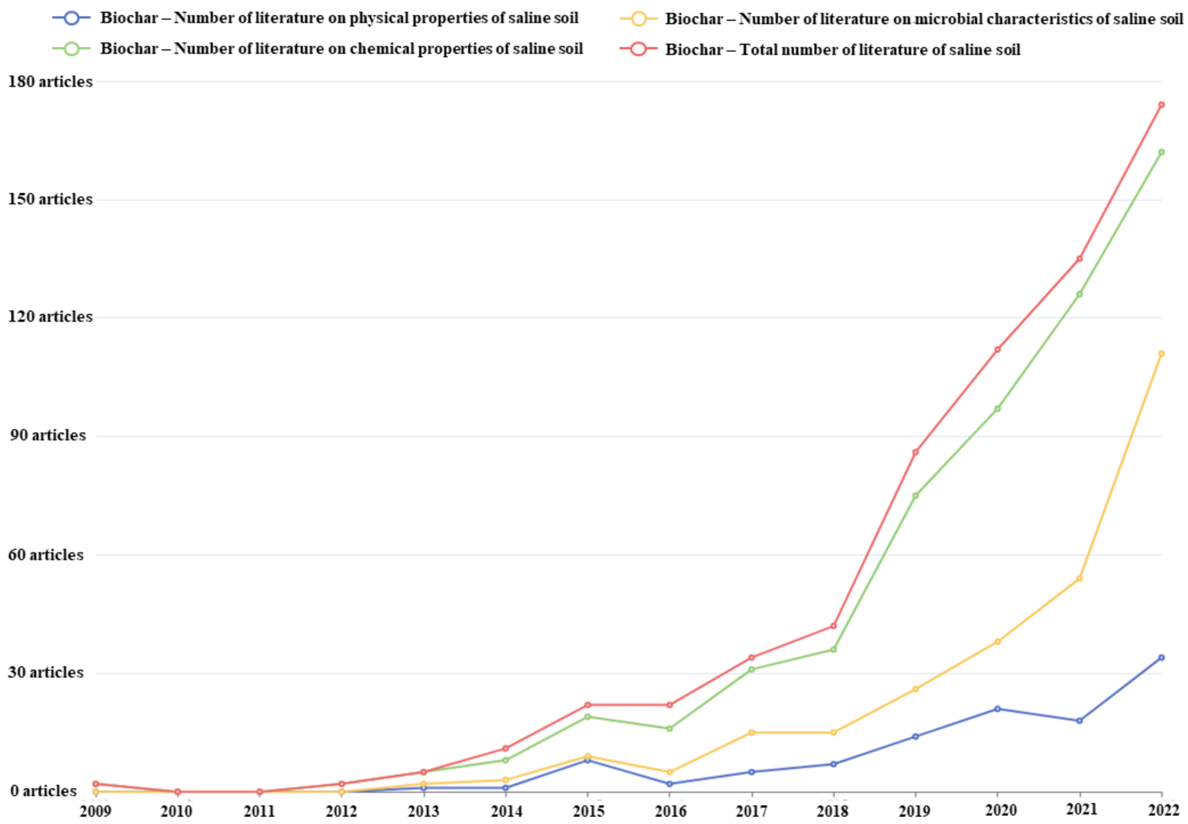

Figure 2. Relevant research on physical, chemical and biological properties of saline soils improved by biochar and its development trend.

4. Impact of Biochar Application on the Physiccal Properties of Saline Soils

The main physiochemical properties of soil are reflected through BD, porosity, aggregate composition, and moisture characteristics. More specifically, the aggregates are the basic unit of soil structure, determining soil porosity, BD, and water and salt movement, as well as mediating soil functions (e.g., SOC turnover and sequestration, nutrient cycling and availability, and organism diversity and activity [29]. Generally, saline soil possesses poor physical structure due to the following reasons: (1) the excess amount of Na^+ can replace Ca^{2+} or Mg^{2+} on the surface of soil colloids, resulting in the swelling and dispersion of clay particles, and eventually causing soil crusting and hardening; (2) excessive salinity ions can inhibit seed germination and plant growth, leading to reduced OM inputs and increased soil structure degradation [1,3]. Colloid is the fundamental unit in soil structure and its formation can significantly enhance salt leaching and soil fertility, therefore promoting the transformation of saline soil to agricultural soil [30]. Biochar can be used directly as a cementing substance to promote the aggregation of soil mineral particles, especially the formation of macro aggregates. Biochar contains a substaincial Ca^{2+} and $Mg^{2+,}$ which can effectively replace Na^+ on the surface of soil clay minerals and prevent colloidal dispersion. Soil column leaching experiments by Chaganti et al. [31] also showed that the higher the Ca^{2+} content of biochar, the better the effect on the formation of saline soil aggregates as well as on the improvement of saturated hydraulic conductivity. On the other hand, biochar is rich in easily degradable OM and nutrients (e.g., 0.1–3.9% N, 0.01–0.2% P, 0.03–6.1% K [32], which can stimulate and support the growth of microorganisms and plants and thus further enhancing the formation of soil colloids and aggregates [33,34]. Moreover, biochar charcteristized by low BD and high porosity can significantly improve the soil pore structure and moisture. Notably, the larger the particle size of biochar, the better its effect on lowering soil BD. It has been reported that particles that are <0.5 m can easily clog the pores in the soil [35], leading to a decrease in the improvement effects of biochar over time [18]. Cao et al. [36] conducted a disk infiltration experiment and, with the addition of 2% biochar, found a 46.4% increase in saturated hydraulic conductivity of coastal saline soil compared with the control experiment. The total effective porosity and effective porosity with a radius > 100 µm increased by 8.3% and by 10.2%, respectively. An indoor culture experiment with biochar application rate at 10 g kg^{-1} conducted by Zhou et al. [37] indicated that the saturated hydraulic conductivity of saline soil increased from 1.16×10^{-4} cm s^{-1} to 4.08×10^{-4} cm s^{-1}. The soil column leaching experiment of Xiao et al. [38] pointed out that the BD of saline soil decreased from 1.42 g cm^{-3} to 1.30 g cm^{-3}, and the saturated hydraulic conductivity increased from 0.15×10^{-5} cm s^{-1} to 0.91×10^{-5} cm s^{-1}. The pot culture experiment by Kong et al. [39] also showed that after the application of 50 t hm^{-2} biochar, the average infiltration rate, cumulative infiltration amount and saturation infiltration coefficient were 28.5, 24.4 and 24.8 times higher than those of the control, respectively. Generally, the positive effects of biochar on saline soil aggregate structure and stability, porosity, BD, and conductivity were mainly determined by the biochar characteristics (such as oxygen-containing functional groups, polyvalent cations, BD, and SSA) and applicaiton rate.

Notably, laboratory simulation can be very different from the actual field conditions; therefore, laboratory studies cannot accurately predict the effects of biochar in the field. For example, Jeffery et al. [40] and Kumari et al. [41] found that in field studies, the addition of biochar resulted in negative impacts on the physical structure of the soil. They explained such observations from the following aspects: (1) the biochar used in their study has very strong hydrophobicity on the surface; (2) it also has very high alkalinity, which increases the repulsive force between soil particles and accelerates the dispersion of clay particles; (3) it has high adsorption capacity towards cations, especially divalent ion. Therefore, the addition of such biochar will decrease the concentration of cations in the soil and lead to the dispersion of soil colloids; (4) fine-grained biochar might block the soil micropores and then reduced soil penetration rate; (5) excessive application of biochar caused an increase in the soil moisture coefficient of viscosity, therefore affecting the water transportation in the soil. Under uncropped conditions, Sun et al. [42] also indicated that wheat straw biochar deteriorated the physical structure of heavily saline coastal soils, such as increasing the density, decreasing the saturated water content, water holding capacity, and total porosity of the soil. Conversely, biochar with organic fertilizers [43], yellow humic acid [44,45], wood vinegar liquid [46,47], etc., in combination with crop planting [48–50], almost always showed a positive effect on the improvement of saline soil. For example, one year after the application of biochar livestock manure compost (12 t hm^{-2}) and wood vinegar liquid (0.15 t hm^{-2}), the BD of saline soil decreased by 0.1 g cm^{-3} [45]. After the application of biochar (12 t hm^{-2}), the BD of saline soil in the Yellow River delta planted with wheat and maize decreased by 9.1% and by 14.5%, respectively, and the saturated hydraulic conductivity increased by 82.7% and by 91.2% [49], respectively. Liang et al. [48] reported that biochar (10–30 t hm^{-2}) in combination with cotton planting could effectively reduce the BD and enhance the porosity, saturated hydraulic conductivity, and field water holding capacity of saline soils in Xinjiang province. Therefore, a single application of biochar to saline soils under field conditions is not recommended, but a combination of different materials or crop planting should be more effective in the improvement of saline soil. Moreover, the properties of biochar, such as particle size, surface charge nature, and hydrophobicity, should also be considered when evaluating its effects on saline soil improvement.

5. The Impact of Biochar Application on the Chemical Properties of Saline Soils

Salinity is the primary obstacle limiting the ecological development of saline soils, and biochar can alleviate soil salinity by (1) adsorbing salt ions; (2) increasing the porosity and hydraulic conductivity, therefore enhancing salt leaching [38,51–54]. Yue et al. [52] reported that, with a 5% biochar application, the time required for the electrical conductivity (EC) in the elute from a soil column group to be lowered to 5 dS m^{-1} was 56–62 days faster compared with the group without the addition of biochar. Xiao et al. [38] indicated that the efficiency of Na^+ leaching was increased by 25.55–60.30% with the application of 4 g kg^{-1} biochar. Compared with conventional gravel, biochar as a salt barrier increased the drainage rate of the culvert pipe by 16.1% and shortened the drenching time by 13.3% [53]. However, Luo et al. [50] suggested that charcoal-based fertilizers (1.5–15%) prepared from biochar with shellac, humic acid, and inorganic fertilizers exacerbated the salinization of coastal soils in the Yellow River Delta, with surface and subsurface soil EC increasing from 2.11 dS m^{-1} and 0.98 dS m^{-1} in the control to 3.15–3.48 dS m^{-1} and 1.15–1.48 dS m^{-1}. Zhang et al. [55] collected coastal mudflats for a 3-year rice potting experiment and found that the EC of saline soils increased by 8.8–44.8% after the application of 5–20% biochar. The short-term (56 d) incubation experiment by Singh et al. [56] also showed that EC significantly increased with increasing biochar application (1–4%) in different saline soils (EC = 2, 8, and 16 dS m^{-1}), with increases ranging from 0.8 to 3.0 dS m^{-1}, 1.7 to 3.8 dS m^{-1}, and 0.7 to 2.4 dS m^{-1}, respectively. Zhou et al. [37] also found that the EC of coastal saline soil was significantly higher in the treatment with 40 g kg^{-1} biochar than the ones with 10 and 20 g kg^{-1} biochar ($p < 0.05$). The differences among these studies might result from the different sources of feedstock, resulting in large differences in the EC of the prepared biochar; or the excessive application or the high number of salt-based ions in the biochar that was used in the experiments. In addition, the aging process of biochar should also be considered, since such a process can lead to the release of salt-based ions that are previously adsorbed or immobilized on the surface of biochar [18].

Biochar normally processes an alkaline pH and its function in saline soil reclamation remains debated. Soil pH is determined primarily by the hydrolysis of exchangeable sodium and sodium carbonate; therefore, if the biochar contains a high amount of Ca^{2+} and Mg^{2+}, they can replace the Na+ adsorbed on the surface of soil colloids and lower the soil pH [31,47,50]. Chaganti et al. [31] and Lashari et al. [47] reported that the ability of biochar to decrease the ESP of saline is closely related to the Ca^{2+} content and the porosity of biochar, whereas Luo et al. [50] suggested that the most important property of biochar that determines their effect on improving saline soil is the surface property such as CEC and functional groups. Moreover, biochar can also affect soil pH through microorganisms and plants. For example, biochar can enhance the adsorption of K^+, Ca^{2+}, and Mg^{2+} base cations by plant roots, therefore enhancing the release of H^+ [50] and decreasing soil pH. Biochar can also have a great impact on microbial activity (dehydrogenase) and dissolution of carbonates [57]. With aging, biochar also forms more acidic surface functional groups or produces acidic substances through decomposition to lower soil pH [19]. Overall, the impact of biochar on soil pH requires long-term observation. Compared to unmodified biochar, acidic biochar [58] or biochar combined with hydrochloride acid (HCl) [59] showed better effects on decreasing the pH of saline soils. Biochar made from different materials usually has very different pH. For example, biochar prepared from wood, bamboo, and rice husk has a pH from 8.63 to 9.45 [22], respectively, whereas biochar prepared from furfural residues directly shows an acidic pH [60]. When the pyrolysis temperature increases from 300 °C to 500 °C, the pH of biochar prepared from maize and corn increases from 7.59 to 10.51 and from 9.35 to 10.12 [61], respectively. The amount of biochar applied is also a crucial factor in determining its effect on improvment of saline soils. Li et al. [62] used rape as a test plant in a greenhouse pot experiment and found that there was no significant change in the pH of mildly saline soils (pH 8.51, salinity 0.17%) in Marina when biochar (pH 8.01) was applied at <20 g kg^{-1} and the soil pH was slightly elevated when it was applied at >20 g kg^{-1}. Overall, it can be concluded that the raw material used for preparation of biochar, and the pyrolysis temperature, quantity of application, and modification of biochar can individually or synthetically influence the effects of biochar on saline soil improvement, which should be emphasized in the future research.

Excessive salinity in the soil reduces the availability of nutrients and water, accelerates nutrient leaching, exerts ionic toxic effects and osmotic stress on plants, inhibits photosynthesis, and resulting in a reduction in plant residue and root secretion input. So the nutrient content in saline soils is generally low [3,19]. Biochar is produced by high-temperature degradation of OM and contains a large amount of nutrients, which can significantly increase the input of OM and nutrient content of saline soil, such as N, P, and K. At the same time, biochar can also mitigate nutrient mineralization and decomposition by (1) interacting with SOM, which can enhance its oxidative stability and accelerate the formation of humification; (2) promoting the formation of soil aggregates, insulating microorganisms or extracellular enzymes, as well as altering the structure of microbial communities (e.g., shifting to low-carbon types); (3) alleviating saline and alkaline stress to a certain extent, promoting plant growth, stimulating the release of root secretion and increasing soil carbon input, and indirectly promoting saline soil carbon accumulation [63–68].

High soil salinity can also enhance the evaporation of NH_3, leading to a low N content in the soil. Biochar can adsorb dissolved NH_3, NH_4^+, and NO_3^-, therefore reducing their leaching and improving soil physicochemical properties (e.g., water retention, pH, and CEC) and the community structure of N cycle-related microorganisms as well as enzyme activities, which can then influence the process of soil N cycling [69–76]. Shi et al. [76] reported that except for adsorbing NO_3^-, biochar can also inhibit denitrifying enzyme activity and reduces denitrification through certain components (e.g., phenols), therefore reducing N_2O emissions from saline and alkaline agricultural land in North China. Shi et al. [71] concluded that biochar reduces N_2O emissions mainly by decreasing nirS and nirK copy numbers and increasing nosZ copy numbers. Luo et al. [50] reported that charcoal-based fertilizer stimulated N fixation by inter-root microorganisms of Sesbania and significantly increased the NH_4^+ content of coastal saline soils in the Yellow River Delta. Soil column leaching test by Wang et al. [73] showed that N retention increased by 37.09% after biochar application compared to the control. Sun et al. [72] found that application of 0.5% and 1% of biochar reduced leaching losses of NH_4^+, NO_3^-, and total N, but NH_3 emissions increased significantly with higher application amounts of biochar (2–4%). Cao et al. [69] found that rice husk biochar promoted N reductase activity and its denitrification in coastal wetland soils, therefore exacerbating N loss. Soil NH3 volatilization and N_2O emission are the main pathways of N loss in the soil. To effectively enhance N utilization efficiency in saline soils by addition of biochar, more comprehensive studies should be carried out at both the micro-molecular mechanistic and macro-technological levels.

P is considered another important element limiting plant growth in saline soils, and biochar can increase soil P content and its effectiveness through the following four aspects: (1) acting as a direct source of P supply; (2) increasing the abundance of P-solubilizing bacteria such as Thiobacillus, Pseudomonas, and Xanthobacillus; (3) releasing soluble OC, which binds to adsorbent sites on the surface of soil colloids and reduces P immobilization; and (4) releasing acids, such as humic acid, to inhibit calcium phosphate crystal formation. The addition of biochar (10, 20, and 25 g kg^{-1}) increased the total and avaiable P contents of saline soils in Inner Mongolia by an average of 53.62% and 88.61%, respectively, compared with the control [77–79]. However, the high adsorption capacity of biochar may cause negative effects and reduce the effectiveness of P [80,81]. Xu et al. [81] found that biochar produced at low pyrolysis temperatures (<400 °C) had a limited effect on P effectiveness in saline soils, whereas there was a significant antagonistic effect between biochar prepared by pyrolysis at 500–600 °C and P fertilizers, which reduced the content of quick-acting P and led to a significant reduction of P content in tissue organs. K is considered to be one of the most important elements for alleviating salt stress in plants. Its main function is to reduce Na^+ uptake by plants and promote effective water use by controlling stomatal opening and closing [64,80]. Biochar is generally rich in K and can significantly enhance potassium content in saline soils. For example, Lin et al. [64] found that the quick K content of coastal saline soils increased by as much as 44% after adding 16 t hm^{-2} biochar, while the contents of exchangeable Na^+, Ca^{2+}, and Mg^{2+} did not change significantly. After adding 30% (v/v) of biochar, due to its strong adsorption effect, the quick-acting N and P contents of saline soil decreased significantly, but the quick-acting K content increased significantly [81]. Nguyen et al. [82] concluded that the improvement effect of biochar on saline soils was mainly reflected in the increase of quick-acting P, K, and CEC.

The interactions between the soil C cycle and nutrient cycling are complicated and there is only limited understanding of the coupling mechanisms. If nutrients are not sufficiently supplied, soil microorganisms will consume more energy for the production of ecological enzymes for the missing elements, which in turn affects the decomposition rate of SOM [83]. Therefore, combining soil C sequestration with nutrient cycling research, especially the study of the interactions between C stabilization and key nutrient cycling (e.g., N, P, and K) in saline soils after the application of biochar, will be an important research direction in the field of saline soil reclamation in the future [63].

6. The Impact of Biochar Application on the Microbiota Characterization of Saline Soils

Microorganisms are essential and active components of soil ecosystems, participating in almost all biological and biochemical reactions in the soil. They play an important role in the processes of SOM decomposition, nutrient cycling and transformation, and soil structure development [84]. Excessive base cations and too high pH in saline soils can produce a toxic environment and osmotic stress to microorganisms, and poor nutrient conditions, as well as degraded soil structure, can also negatively affect microorganisms [85]. As a result, the total number of microorganisms in saline soils was lower than that in normal soils in the same ecological region, and the number of microorganisms in composite saline soils was lower than that in single saline soils [85,86]. Using phospholipid fatty acid profiling, Li et al. [87] reported that the total number of microorganisms was significantly negatively correlated with soil salinity and alkalinity, and the stronger the salinity, the more homogeneous the marker diversity; moreover, the community structure shifted from fungal- to bacterial- dominated, with the reduced competition. The positive effects of biochar on microorganisms include (1) providing C sources and mineral nutrients for microorganisms, coupled with the huge specific surface area and porous structure that make it a good habitat for microorganisms; (2) strong adsorption of water and fertilizers to reduce the loss of nutrients by leaching, and to a certain extent keeping the soil pore space moist and maintaining the microbial demand for water even under drought conditions; (3) influencing the soil physicochemical properties, such as pH, salinity, nutrient content, and effectiveness, therefore indirectly influencing the structure and activity of the microbial community; and (4) promoting the growth of plants, and stimulating the release of root exudates containing substantial soluble C and N [14,63,66,88,89]. Singh et al. [56] reported that biochar has a strong adsorption capacity for salt-based ions, it can mitigate microbial salt stress, and significantly enhance soil microbial respiration rate and the C content in biomass. Nguyen et al. [90] reported that biochar reduces methane emissions from saline soils by decreasing the abundance of methanogenic genes and enhancing the abundance of methane-oxidizing genes. The addition of biochar to saline coastal soils resulted in a significant increase in the relative abundance of soil N-fixing bacterial taxa such as Ideonella and Skermanella [91], whereas Song et al. [92] found an increase in the abundance of ammonia-oxidizing bacteria and ammonia-oxidizing archaea and an enhancement of soil nitrification. You et al. [93] reported that biochar enhances the abundance of Erythrobacter, Sphingomonas, and Bacillus lysimachiae in saline coastal soils, which in turn promotes the growth of iceberg lettuce. Biochar [63] or biochar in combination with beneficial microorganisms [94] (mainly composed of lactic acid bacteria, photosynthetic bacteria, yeast and actinomycetes) can both increase soil phosphatase and urease activities and promote N and P nutrient cycling in saline soils. After the application of biochar and fermentation broth, Manasa et al. [65] found that the broad archaea in saline soils became the dominant flora, which played an important role in organic matter decomposition, N fixation, and iron and sulphur metabolism. He et al. [95] reported that biochar affects N and P nutrient cycling by influencing the structure and diversity of bacterial communities in coastal saline soils, which further affects N and P nutrient cycling.

After applying biochar, Shi et al. [71] found that soil moisture content, pH, NH^{4+} and NO_3^- were the main environmental factors affecting ammonia-oxidizing and denitrifying bacterial communities in saline soils. Tang et al. [96] used biochar prepared at different temperatures to remediate saline soils and found that soil BD, SOM, and the nature of the functional groups on the surface of the biochar were responsible for the succession of bacterial communities. Zheng et al. [66] found that a peanut shell biochar shifted bacterial communities toward C sequestration and P solubilization in a coastal saline soil. Increasing studies evidenced that biochar amendments can improve the biological health of saline soils by regulating microbial community structure and function through providing direct shelter or improving soil conditions indirectly or providing nutrients such as carbon, N, and P directly to the microbes [66,71,97,98] Notably, a few studies also observed adverse effects of biochar on microbial communities in salt-affected soils, mainly due to the hazardous substances in biochar such as polycyclic aromatic hydrocarbons and heavy metals [99,100]. To date, there is no unified understanding of the response of soil microorganisms to biochar in saline soils. Therefore, we spectulated that the response of core functional populations of soil microorganisms in saline-alkaline soils, especially the microorganisms that play an important role in saline-alkaline soil improvement, such as N-fixing bacteria, nitrifying bacteria, P-dissolving bacteria, *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Actinobacteria*, and tufted arbuscular mycorrhizal fungi (AMF) to biochar is an urgent issue that needs to be investigated in the future [65,66,71,79,93–96]. In addition, the direct or indirect intraspecificand interspecific interactions (e.g., predation, competition, symbiosis, and quorum sensing) between different microorganisms responding to exogenous biochar in the saline soils are still lacking. The scale of the study should be carried out in a wider area and an attempt should be made to sort out the intrinsic mechanism of regional differences, which is necessary for clarifying the relationship among biochar characteristic, soils physicochemical properties, and microbial community composition and ecological functions.

7. Outlook

The research on biochar as a useful conditioner of saline soil has been rising, and progression has been made over the decades. Biochar plays a positive role in improving the structure of saline soil, accelerating salt leaching, increasing soil water-holding and fertilizer-retaining capacity, enhancing soil microbial activity and quantity, and promoting crop growth (Figure 3). Globally, saline soils are widely distributed with various climate conditions, saline soils are widely distributed with various degrees of salization. Moreover, the type of biochar, the amount of application and the type of vegetation all play an important role in determining the effect of biochar on improving properities of saline soils. Actually, the improvement effect of biochar often fails to meet expectations, and sometimes even intensifies the issue. Therefore, the author think that the research on the effect and mechanism of biochar in improving saline soil is still insufficient, and the following aspects are recommended for further study in the future:

(1) The positive effects of biochar on remediation of saline soils are primarily determined by its properties (e.g., surface functional groups, porosity, and SSA) [31,50]. For example, biochar could provide exchangeable Ca^{2+} to replace Na^+ on the soil colloids, and facilitate Na^+ leaching from soil profile through improving soil porosity [31]. Specific modification of biochar could lead to unique properties (such as larger SSA, more functional groups, more elaborate pore structure, and lower pH), and played a vital role in adsorption of salt, nutrients, organic pollutants, or heavy from soil environment [101,102]. Therefore, calcium-rich, low-sodium, low-pH, and high SSA biochar is preferred. The specification and unification of raw material selection, preparation process (e.g., pyrolysis temperature and time), and modification optimization of biochar are the key directions for future research.

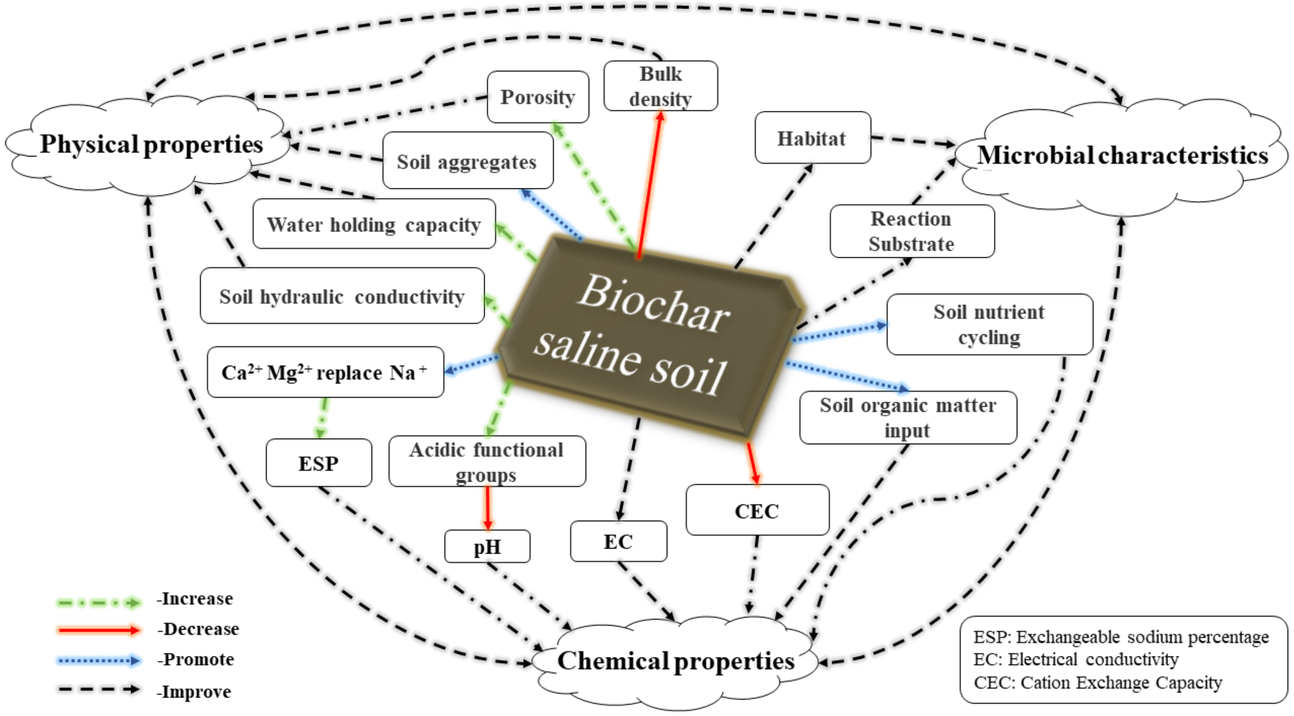

Figure 3. Schematic illustration of possible mechanisms for the improvement of physical, chemical and biological properties of saline soils with the addition of biochar.

(2) Almost all of the applications of biochar in combination with organic fertilizers, yellow humic acid and wood vinegar liquid or planting crops showed positive effects on saline soil improvement. Therefore, the construction of a composite process of biochar with other amendments (such as inoculation of functional microorganisms and planting of halophytes) and development of reasonable application technologies (e.g., integration of water and fertilizer, intelligent irrigation, and artificial intelligence technologies) to achieve the maximum ecological and economic benefits are two key problems needed to be solved for the agricultural application of biochar.

(3) Future studies should combine short-term laboratory studies and long-term field studies due to the following reasons: (i) although biochar is relatively stable, it will undergo aging after entering the soil. Aging of biochar can lead to great changes in its properties, further altering its interactions with soil minerals, OM, and microorganisms. (ii) Most of the current studies are mainly conducted in the laboratory. However, for example, when conducting a column experiment, the size of soil columns, the test period, and the volume and rate of leaching in the indoor experiment all strongly affect the test results, which are far from the actual situations in the field and can not be fully linked with agricultural production activities at all. Therefore, the results obtained from the laboratory can not fully reflect biochar’s comprehensive effects on saline soils under real environmental conditions.

(4) More attention should be paid to rhizosphere in the future research. By combining traditional soil analytical methods with cutting-edge genomics technologies (transcriptome, high-throughput sequencing, metabolomics, etc.), future studies should try to develop an in-depth understanding of biochar-soil nutrient-microbial interactions in saline soil environments and their response mechanisms to exogenous biochar from both macroscopic and microscopic perspectives. Particularly, the following issues should be addressed: (i) how root-microbial synergistic interactions can resist saline and alkaline environments, and (ii) what are the key microorganisms and environmental factors mediating nutrient cycling processes in saline soils. Full understanding of these control factors is helpful to amplify them in practical applications to achieve the best soil improvement effects.

(5) Computer and information technologies are widely used to establish mathematical models to quantitatively study the relationship between biochar properties and soil salinity, porosity, aggregation structure, nutrient content, and microbial community characteristics; therefore providing a reference for the design and manufacture of more personalized and specialized biochar to meet the needs of different types of saline soils for improvement.

(6) Advanced analytical testing methods (e.g., fluorescence microscopy and NanoSIMS isotope imaging, DNA-SIP, single cell Raman, gene chip and nanopore sensing, portable X-ray fluorescence, X-ray tomography and remote sensing techniques) should be used to in situ visualize the interaction between biochars and components in saline soils.

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