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Assessment of the Effects of Biochar on the Physicochemical Properties of Saline–Alkali Soil Based on Meta-Analysis

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Abstract: Enhancing global agricultural sustainability critically requires improving the physicochemical properties of saline–alkali soil. Biochar has gained increasing attention as a strategy due to its unique properties. However, its effect on the physicochemical properties of saline–alkali soil varies significantly. This study uses psychometric meta-analysis across 137 studies to synthesize the findings from 1447 relatively independent data sets. This study investigates the effects of biochar with different characteristics on the top 20 cm of various saline–alkali soils. In addition, aggregated boosted tree (ABT) analysis was used to identify the key factors of biochar influencing the physicochemical properties of saline soils. The results showed that biochar application has a positive effect on improving soil properties by reducing the sodium adsorption ratio (SAR) and the exchangeable sodium percentage (ESP) by 30.31% and 28.88%, respectively, with a notable 48.97% enhancement in cation exchange capacity (CEC). A significant inverse relationship was found between soil salinity (SC) and ESP, while other factors were synergistic. Biochar application to mildly saline soil (<0.2%) and moderately saline soil (0.2–0.4%) demonstrated greater improvement in soil bulk density (SBD), total porosity (TP), and soil moisture content (SMC) compared to highly saline soil (>0.4%). However, the reduction in SC in highly saline soil was 4.9 times greater than in moderately saline soils. The enhancement of soil physical properties positively correlated with higher biochar application rates, largely driven by soil movements associated with the migration of soil moisture. Biochar produced at 401–500 °C was generally the most effective in improving the physicochemical properties of various saline–alkali soils. In water surplus regions, for mildly saline soil with pH < 8.5, mixed biochar (pH 6–8) at 41–80 t ha^{-1} was the most effective in soil improvement. Moreover, in water deficit areas with soil at pH $\geq$ 8.5, biochar with pH $\leq$ 6 applied at rates of >80 t ha^{-1} showed the greatest benefits. Agricultural residue biochar showed superior efficiency in ameliorating highly alkaline (pH $\geq$ 8.5) soil. In contrast, the use of mixed types of biochar was the most effective in the amelioration of other soil types.

Keywords: biochar production temperature; pyrolysis feedstocks; saline–alkali soil; physicochemical properties; meta-analysis

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1. Introduction

Soil salinization is a global environmental problem that not only threatens the ecological balance in many regions but also poses a serious challenge to agricultural production and environmental sustainability [1]. It is estimated that the area of saline–alkali soil in the world is about 1.0 × 10^9 hm^2, accounting for about 25% of the earth's land area and

76% of the world's cultivated land area [2]. Both natural and human factors contribute to soil salinity–alkalinity, and the area affected by saline–alkali conditions is expanding at a rate of 1.5–2.0 × 10^7 hm^2 per year [3]. By 2050, around 50% of the cultivated land without adequate mitigation measures will be affected by salinity [4]. Salinization has severely negative impacts on soil physicochemical properties. For example, excessive sodium ion (Na^+) leads to the disintegration of soil aggregate structure and clay dispersion and reduces soil porosity and permeability. These changes may further result in soil swells and sludges when wet and shrinks and slumps when dry [5,6]. Additionally, they can increase salt content and alkalinity [1,7], hinder seed germination, induce plant physiological drought stress [8], and reduce crop metabolism and yield [9]. Therefore, it is crucial to ensure global food security by improving saline–alkali lands and developing sustainable agriculture practices in these regions.

Biochar is a carbon-rich solid organic material derived from biomass pyrolyzed at high temperatures (200–1200 °C) under oxygen-limited conditions [10]. It has the characteristics of high nutrient content, large specific surface area, developed pore structure, and abundant organic functional groups [11]. It has been widely applied in waste resource utilization, soil carbon fixation, soil improvement, and pollution remediation.

To date, numerous studies have increasingly reported the beneficial effects of biochar application on the physicochemical properties of saline–alkali soil. The direct effect of biochar is to increase soil porosity, reduce bulk density, enhance water-holding capacity, and accelerate leaching of salts to decrease soil salinity [12]. In terms of indirect effects, biochar increases soil organic carbon and inorganic content and promotes the binding of polyvalent cations with clay particles and the exchange of cations such as Ca^{2+}, K^+, and Mg^{2+} with Na^+. This process inhibits soil colloid dispersion, promotes the formation and stability of soil aggregates, and ameliorates the structure and physicochemical properties of saline–alkali soil [13]. Li et al. [14] applied 5% rice straw biochar to saline–alkali soil, significantly reduced the bulk density of soil, and increased the porosity and water-holding capacity of soil. Zheng et al. [15] reported that the acidic oxygen-containing functional groups and high cation exchange capacity of biochar itself can reduce soil pH. Egamberdieva et al. [16] and Yue et al. [17] reported that biochar can reduce the excessive exchangeable sodium in saline–alkali soils by increasing organic carbon and cations in the soil. It also enhances soil porosity and water-holding capacity to decrease sodium salts in saline–alkali soils, thereby reducing the salinity and alkalinity levels in the surface layer of saline–alkali soils. Although most studies reported a positive effect of biochar on the physicochemical properties of saline soils, Xu et al. [18] and Wei et al. [19] concluded that the addition of biochar reduced the water retention capacity of saline soils. Most studies have reported the positive effects of biochar on the physical and chemical properties of saline–alkali soils. However, Wang et al. [20] found that biochar application had no significant effect on the improvement of saline soil pH. Meanwhile, Xu et al. [18] and Wei et al. [19] reported that the addition of biochar reduced the water retention capacity of saline–alkali soil. Ahmad et al. [21] and Kim et al. [22] found that biochar is obviously alkaline and contains a large number of mineral salts, and heavy biochar application can lead to an increase in soil pH and salinity. Overall, these contradictory findings are usually attributed to the fact that most studies focus on evaluating how individual biochar properties or specific soil conditions independently affect the physicochemical properties of saline–alkali soil. Moreover, this also indicated that less attention was paid to the combined effects and interactions between the properties of biochar and soil conditions.

2. Materials and Methods

2.1. Data Collection and Processing

To study the effects of biochar addition on the physical and chemical properties of saline–alkali soil, a literature search was conducted in databases including CNKI (China National Knowledge Infrastructure), Google Scholar, and Web of Science, using keywords like "Biochar" and "Saline-alkali/Saline-alkali Soil" for articles published between Jan.

2013 and June 2023. A total of 382 articles were retrieved. To avoid bias, the retrieved literature was screened according to the following criteria [23].

The soils measured must be in the topsoil layer (0–20 cm); if soil depth is not mentioned in the literature, it is assumed to be the arable soil layer.

The experimental treatment must include at least one pair of treatments with or without biochar applied while other experimental conditions remain consistent. Each pair of collected data (the control and treatment groups) must include at least one of the nine indicators involved in this study: the soil bulk density (SBD), soil moisture content (SMC), total porosity (TP), pH, exchange sodium percent (ESP), cation exchange capacity (CEC), electrical conductivity (EC), sodium adsorption ratio (SAR), and salt content (SC); and the number of replicates in the experiment should not be smaller than three. In the data analysis, it is essential to consider the mean value, sample size, and standard deviation/error. When a study involved different soil sampling times, data from the final sampling time was used.

Based on the above five criteria, a total of 137 articles were ultimately selected that met the requisites. The data extracted from the selected literature included the geographical location of the experiments, the physical and chemical properties of the soil in the 0–20 cm layer (e.g., salinity, pH), and biochar characteristics (e.g., feedstock, pyrolysis temperature, pH, application rate, etc.). The soil physicochemical properties included SBD, SMC, TP, pH, ESP, CEC, EC, SAR, and SC. This study collected a total of 1447 research data points. The collected data were statistically grouped according to the standards shown in Table 1.

Table 1. Categorical grouping of variables that were used in meta-analyses.

	Variables	N	Categorial Groups
Soil properties	pH	1258	<8.5, 8.5~9.5, >9.5
	Salinity	1148	Slightly (0~0.2%), moderately (0.2~0.4%), heavily (>0.4%)
	Water budget	1277	Deficit, surplus
Biochar characteristics	Feedstock	1272	Agricultural residue, wood category, mixed category (at least 2 raw materials pyrolyzed to prepare biochar, biochar mixed with other amendments), other category
	Pyrolysis temperature	1179	≤400 °C, 401–500 °C, 501–600 °C, >600 °C
	pH	1182	<6, 6–8, >8
	Application rate	1277	Low (<20 t ha^{-1}), middle (20–40 t ha^{-1}), high (41–80 t ha^{-1}), very high (>80 t ha^{-1})

Note: N represents volume of research data.

During the data collection process, data presented in textual and tabular forms in existing studies were directly extracted. The data in the graphs were digitized using GetData Graph Digitizer version 2.26 software, which has been widely validated as an accurate and reliable tool for digitizing scientific graphs [24]. Additionally, the degree of salinization refers to the classification of total soil SC standards in the "Specification of Land Quality Geochemical Assessment" (DZ/T 0295—2016) [23], and precipitation and potential evapotranspiration data were obtained by extracting from the CRU climate dataset based on the location of the study area. Due to variations in data units or missing data across different literature sources, pH($CaCl_2$) and pH(KCl) values were converted to pH(H_2O) using appropriate formulas [25]. When only the SE is presented in the literature, the SD can be calculated using the following formula [26]:

$$SD = SE \times \sqrt{n} \quad (1)$$

where n represents the number of replicates in the experiment.

For studies that did not provide SD or SE, the SD was calculated as one-tenth of the mean value [26].

For literature that only provided the soluble contents of Na^+, Ca^{2+}, and Mg^{2+} in the soil, the SAR was calculated using the formula [27]:

$$SAR = \frac{Na^+}{\sqrt{\left(Ca^{2+} + Mg^{2+}\right)/2}} \quad (2)$$

2.2. Meta-Analysis

We used Response Ratios (RRs) to assess the degree of impact that the application of biochar has on relevant indicators in saline–alkali soil within experimental treatments. For a given indicator, the effect size is the natural logarithm of the RR [25].

$$\ln RR = \ln\left(\frac{\overline{X}_T}{\overline{X}_C}\right) = \ln\left(\overline{X}_T\right) - \ln\left(\overline{X}_C\right) \quad (3)$$

where $\overline{X}_T$ represents the mean value of the treatment group with biochar, and $\overline{X}_C$ represents the mean value of the control group without biochar.

Meta-analysis involves the weighted calculation of effect sizes from each independent study to obtain the overall mean effect size $\ln R_{++}$. It is necessary to determine the variance V_i and weight W_i for each independent study, with the specific formulas as follows:

The calculation method for the within-study variance (V_i) corresponding to lnRR is as follows [24]:

$$V_i = \frac{SD_t^2}{N_t\overline{X}_T} + \frac{SD_c^2}{N_c\overline{X}_C} \quad (4)$$

where $\overline{X}_T$ and $\overline{X}_C$ represent the mean values of the treatment group and the control group, respectively. SD_t is the standard deviation of the target variable in the treatment group, and SD_c is the standard deviation of the target variable in the control group. N_t is the sample size of the target variable in the treatment group, and N_c is the sample size of the target variable in the control group.

In the random-effects model, the restricted maximum likelihood (REML) method is used to calculate the effect size. The formula for calculating the weights of each study is as follows [28]:

$$W_i = \frac{1}{V_i + \tau^2} \quad (5)$$

where W_i is the weight of an individual study, V_i is the within-study variance, and τ^2 is the between-study variance.

The formula for the weighted response ratio ($\ln R_{++}$) is as follows [4]:

$$\ln R_{++} = \frac{\sum_{i=1}^{k}(RR_i \times W_i)}{\sum_{i=1}^{k} W_i} \quad (6)$$

where $\ln R_{++}$ represents the natural logarithm of the response ratio for an individual study, and k is the number of lnRR values.

The formula for the overall standard error $SE\ln R_{++}$ of $\ln R_{++}$ is as follows:

$$SE_{\ln R_{++}} = \sqrt{\frac{1}{\sum_{i=1}^{k} W_i}} \quad (7)$$

The formula for the 95% confidence interval (CI) of $\ln R_{++}$ is as follows:

$$95\%CI = \ln R_{++} \pm 1.96 SE_{\ln R_{++}} \quad (8)$$

To facilitate the interpretation of the results, the growth rate is calculated according to the following formula, and the effect value is converted to a percentage of change. $\ln R_{++}$ percentage change formula is as follows [28]:

$$Es(\%) = \left(e^{\ln R_{++}} - 1\right) \times 100\% \quad (9)$$

where Es represents the percentage change of a certain indicator in the treatment group compared to the control group.

In the calculated results, when Es (%) results are greater than 0, the application of biochar treatment has a significant positive effect. Otherwise, if both are less than 0, it indicates that the application of biochar treatment has a significant negative effect. In particular, when the interval contains 0, the application of biochar treatment has no significant impact on the test results [23].

2.3. Statistical Analysis

Microsoft Office 2016 (Microsoft, Redmond, WA, USA) was used to collect, compile, and manage the database [29]. MetaWin 2.1 software was used to calculate the effect size and 95% CI for each categorical group, and the random effects model was selected based on the results of the heterogeneity test [29]. The standardized mean difference metric "Hedge's g" was used for computing the effect size (Equations (3)–(5)). "Hedge's g" was selected rather than "Cohen's d" because it was less biased by small sample sizes [30], which was the case for most studies included in the meta-analysis. For indicators with poor normality, the bootstrap resampling method ("bootstrapping") was used to calculate their effect sizes and 95% confidence intervals (CIs) [23]. For the data of each property variable, the response ratio and heterogeneity were calculated separately, and both the Q-test and the I^2-test were used to analyze the differences in the improvement effects of saline–alkali soil under biochar application for various indicators. For the Q-test, the Q-value represents the standardized sum of squares of effect sizes, with a larger Q-value indicating greater heterogeneity. The I^2 statistic represents the percentage of the total variability in effect estimates that is due to heterogeneity rather than sampling error. A higher I^2 value indicates a greater degree of heterogeneity among the study results.

Rosenthal's fail-safe number (Nfs) is a commonly used method in meta-analysis to test for the presence of publication bias. This study employed the file drawer analysis (Rosenthal Fail-safe Calculation) to detect publication bias and the robustness of meta-analysis results [24,26]. If the statistical data are significant (either or both the *p*-values of Kendall's Tau or Spearman Rank-order are less than 0.05), it is considered that bias has occurred, and further comparison of the (Nfs) for each indicator in the meta-analysis is required. When Nfs > 5n + 10 (n is the sample size), publication bias is considered but does not affect the data trend, and the results are reliable. Additionally, each category should have at least 10 observations for analysis; if there are fewer than 10 observations, the results will only be discussed if they originate from at least three independent articles [31]. The "dismo" package in R (Version 1.3-14) was utilized for aggregated boosted tree (ABT) analysis to evaluate the relative impact of treatment effects quantitatively and visually on soil chemical properties [32].

3. Results

3.1. Heterogeneity and Publication Bias Test of Effect of Biochar on Saline–Alkali Soil

The difference test of physicochemical properties of saline–alkali soil applied by biochar in Table 2 showed that, except for soil EC and SBD, all the physicochemical properties showed significant differences ($P_Q < 0.05$). The published bias test shows that, except for EC, the fail-safe numbers of each physicochemical property are much larger than the critical value (5n + 10), indicating that the average effect size of this study, except for EC, is reliable. Therefore, soil EC did not account for the further interpretation.

Table 2. Heterogeneity test and publication bias test for the effect of biochar application on saline–alkali soils.

Soil Property	Heterogeneity Test				Publication Bias Test		n
	Q	Degrees of Freedom	P_Q	I^2	Critical Value	Nfs	
SBD	92.3441	123	0.9822	0	630	3103.732	124
TP	643.4743	58	0 **	90.9864	305	3291.333	59
SMC	218.7404	147	0.0001 **	32.797	750	3112.522	148
pH	715.7791	387	0 **	45.933	1950	6960.182	388
EC	197.484	169	0.0661	14.4234	860	197.3936	170
CEC	581.4124	142	0 **	75.5767	725	17,960.99	143
SC	295.3952	187	0 **	50.6961	950	2154.478	188
ESP	180.0132	100	0 **	44.4485	515	7564.919	101
SAR	253.5297	126	0 **	50.6961	640	7947.145	126

Note: ** indicate significance at the PQ < 0.01 levels, n represents the number of respo nse variables, and Nfs greater than the critical value indicates the absence of bias.

3.2. Effect of Biochar on the Physicochemical Properties of Saline–Alkali Soils

The application of biochar effectively ameliorates the physicochemical properties of saline–alkali soil (Figure 1). Among them, SAR decreased most significantly, by 30.31% compared with the control (without biochar application), and pH showed a slight reduction. In addition, the greatest increase was observed in soil CEC, which increased by 48.97% compared to the control.

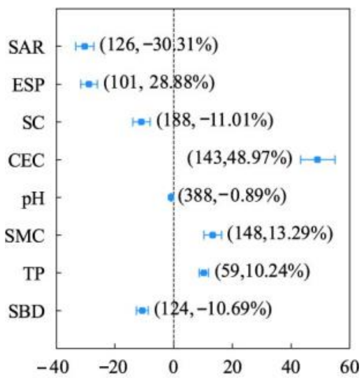

Figure 1. Total effect of biochar on soil bulk density (SBD), total porosity (TP), soil moisture content (SMC), soil pH, cation exchange capacity (CEC), soil salt content (SC), exchange sodium percent (ESP), and sodium adsorption (SAR). The dots and error bars indicate the mean percentage change and 95% confidence interval (CI), and the effect size was considered statistically significant if the CI did not include zero, with red dots representing no statistical significance. The numbers in parentheses indicate the number of response variables and the percentage change.

The impact of biochar on soil physicochemical properties and its Spearman correlation shows that the reduction in SBD is significantly negatively correlated with TP ($p < 0.05$), SMC, and pH ($p < 0.01$; Figure 2). The increase in TP showed a weak but significantly positive correlation with SMC ($p < 0.05$) and a weakly significant negative correlation with ESP ($p < 0.01$), SC, and SAR ($p < 0.05$). The increase in SMC is weakly significantly negatively correlated with SC ($p < 0.05$). Decreases in pH and ESP and increases in CEC were only associated with SAR. The decrease in SC is weakly significantly negatively correlated with ESP ($p < 0.05$) and significantly positively correlated with SAR ($p < 0.01$).

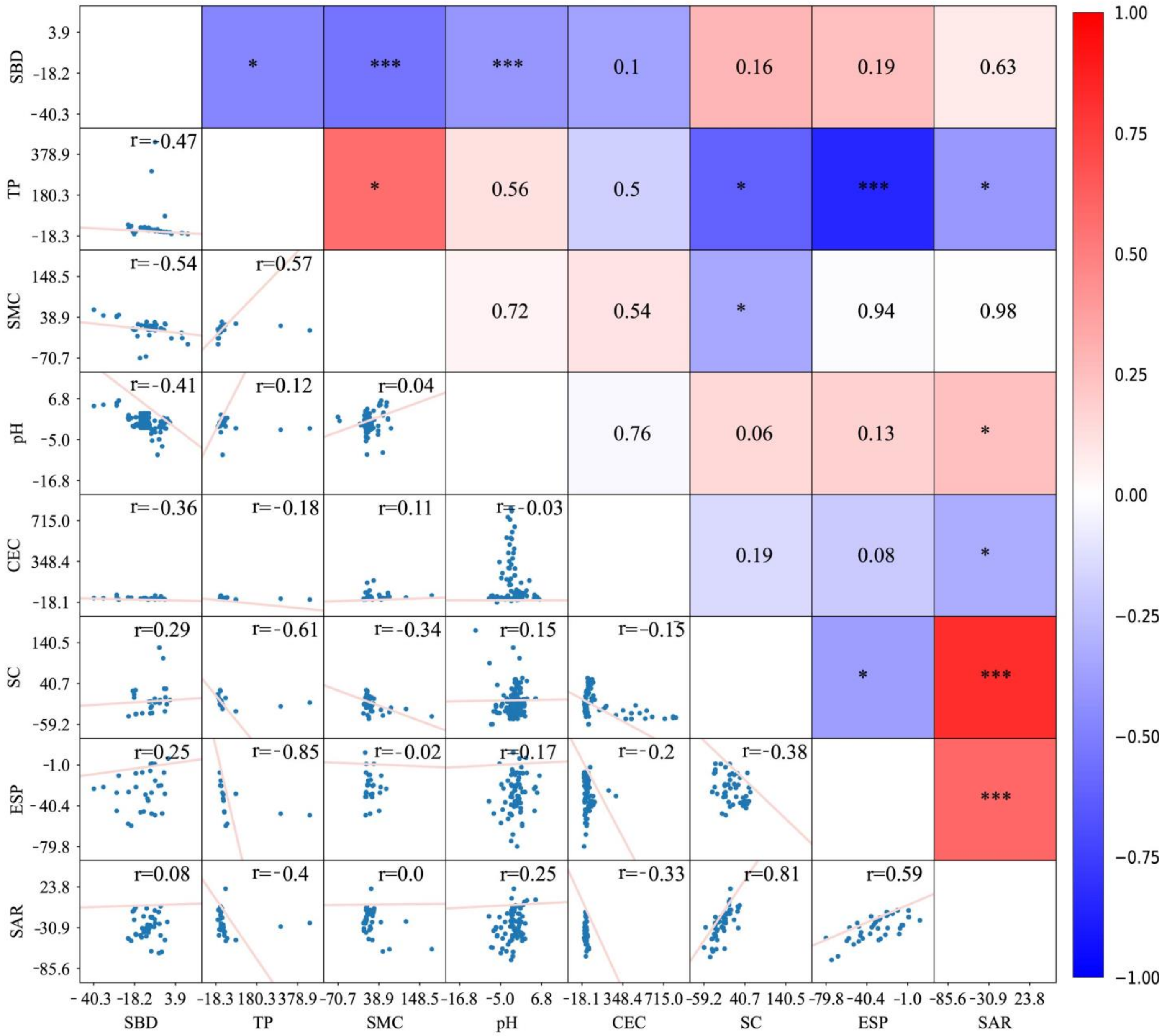

Figure 2. Spearman correlations between the effect size of soil bulk density (SBD), total porosity (TP), soil moisture content (SMC), soil pH, cation exchange capacity (CEC), soil salt content (SC), exchange sodium percent (ESP), and sodium adsorption (SAR). Correlation significance levels are displayed in the upper right triangle (above the diagonal line), with symbols * and *** denoting significance at $p < 0.05$ and $p < 0.001$, respectively, while non-significant values show their exact p values. Blue and red colors indicate negative and positive correlations, respectively. The lower left triangle shows the correlation coefficient (r) values (below the diagonal line).

3.3. Effect of Biochar on the Improvement of Soil Physicochemical Properties

The improvement of physicochemical properties in saline–alkali soil due to biochar application shows significant differences depending on the regional water balance, degree of soil salinization, and initial pH (Figure 3). Biochar application effectively improved soil physicochemical properties across initial soil conditions, resulting in significant decreases in pH, SC, and ESP, along with increases in CEC and TP. Notably, TP increased approximately fourfold in water deficit areas compared to water surplus areas (Figure 3b). Additionally, the application of biochar in mildly and moderately saline soils results in a greater reduction in SBD and increases in TP and SMC compared to heavily saline soils. The results also show that the increase in SBD decreased and TP increased with increasing soil pH, while the increase in CEC shows a decreasing trend with increasing soil pH. Notably, the reduction in soil SC in heavily saline soils is 4.9 times that in moderately saline soils (Figure 3f). This study also indicates that as soil pH increases, the reduction in SBD and the increase in TP become more pronounced, while the increase in CEC decreases with the increase in soil pH. Moreover, SMC exhibits the greatest increase at a soil pH baseline of 8.5–9.5, increasing by 16.74% compared to the control (Figure 3c); ESP shows similar reductions when soil pH is >9.5 and ≤8.5, decreasing by 30.63% and 30.35%, respectively, compared to the control (Figure 3g). SAR experiences the greatest reduction when soil pH ≤ 8.5, decreasing by 32.58% compared with the control (Figure 3h).

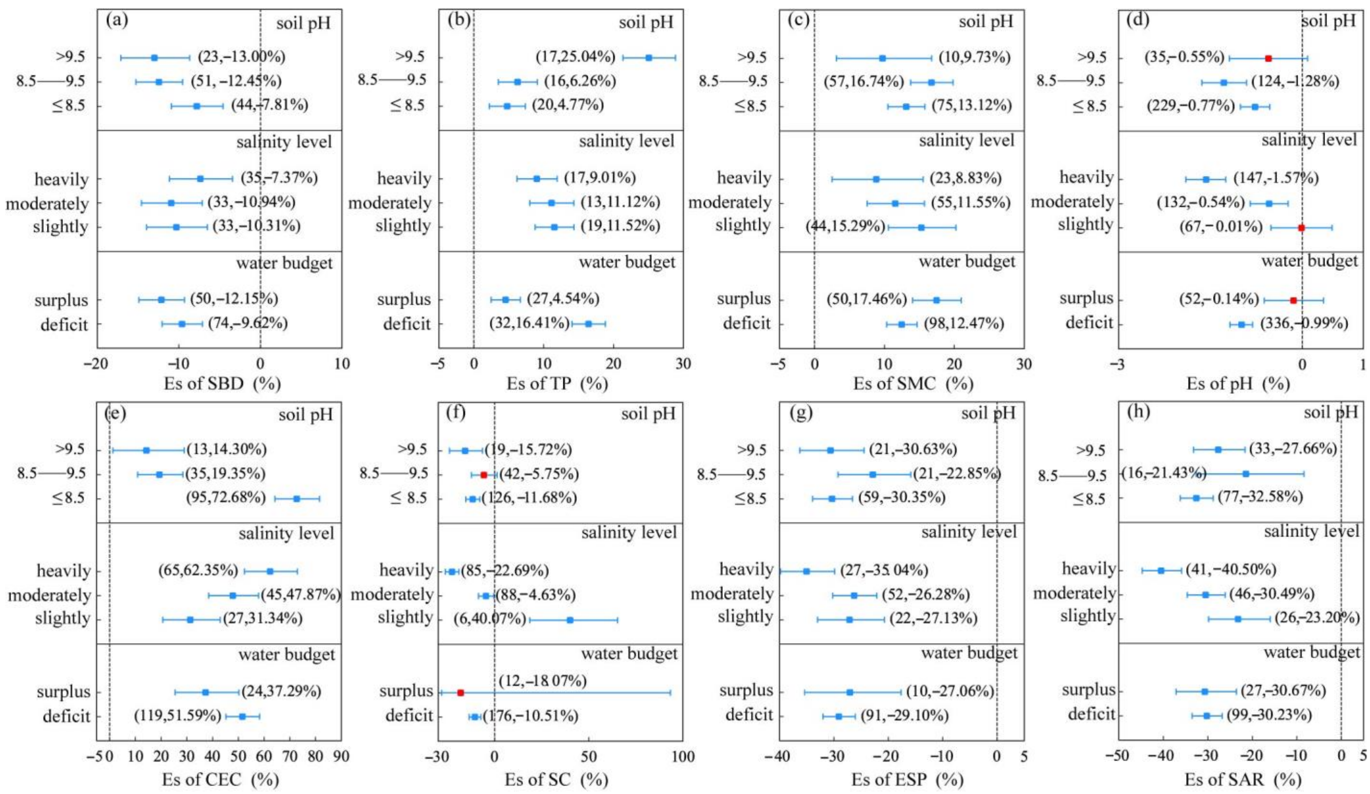

Figure 3. The influence of biochar application on physicochemical properties under different soil characteristics as follows: (**a**) soil bulk density (SBD), (**b**) total porosity (TP), (**c**) soil moisture content (SMC), (**d**) soil pH, (**e**) cation exchange capacity (CEC), (**f**) soil salt content (SC), (**g**) exchange sodium percent (ESP), and (**h**) sodium adsorption (SAR). The dots and error bars indicate the mean percentage change and 95% confidence interval (CI); the effect size was considered statistically significant if the CI did not include zero, with red dots representing no statistical significance. The numbers in parentheses indicate the number of response variables and the percentage change.

3.4. Influence of Different Types of Biochar on Saline–Alkali Soils

After the addition of different types of biochar, significant changes occurred in the physicochemical properties of saline–alkali soil (Figure 4). Overall, the effects of biochar characteristics on soil physicochemical properties showed significant changes. With the increase in biochar application rate, the reduction in SBD and the increase in TP and SMC became more significant, while the increase in CEC and the reduction in ESP were largest at high application rates. Additionally, when biochar with pH > 8 was applied, soil bulk density (SBD), soil conductivity (SC), and total phosphorus (TP) underwent significant changes compared to the control. Specifically, SBD and SC decreased by 10.61% and 12.37%, respectively (Figure 4a,f), while TP increased by 9.59% (Figure 4b). Meanwhile, the reduction in the ESP of soil also reached its maximum under these conditions, decreasing by 27.73% compared with the control (Figure 4g). The increases in the SMC and CEC of soil and the reductions in the pH and SAR of soil all reached their maximums when the pH value of biochar was between 6 and 8, especially the increase in CEC, which was about three times that of other biochar pH improvements (Figure 4e). When the pyrolysis temperature of biochar was between 401 and 500 °C, the reductions in ESP and SAR of soil and the increase in CEC reached their maximums compared to biochar pyrolyzed at other temperatures, decreasing by 39.57% and 42.40% (Figure 4g,h) and increasing by 44.64% (Figure 4e), respectively. For SMC, the increases at pyrolysis temperatures between 401 and 500 °C and 501 and 600 °C were similar (Figure 4c). For the reduction in soil pH, the pyrolysis temperature was directly proportional to it, with a reduction of 1.86% compared with the control when >600 °C (Figure 4d). Compared with the effects of biochar made from different raw materials on the improvement of saline–alkali soil physicochemical properties, it was found that mixed types had the greatest reductions in SBD, pH, and SC and the greatest increases in SMC and CEC. The wood category of biochar had the greatest reduction in SAR compared to the biochar produced from other raw materials. Only agricultural waste-derived biochar had a significant effect on reducing the ESP and increasing the TP of soil.

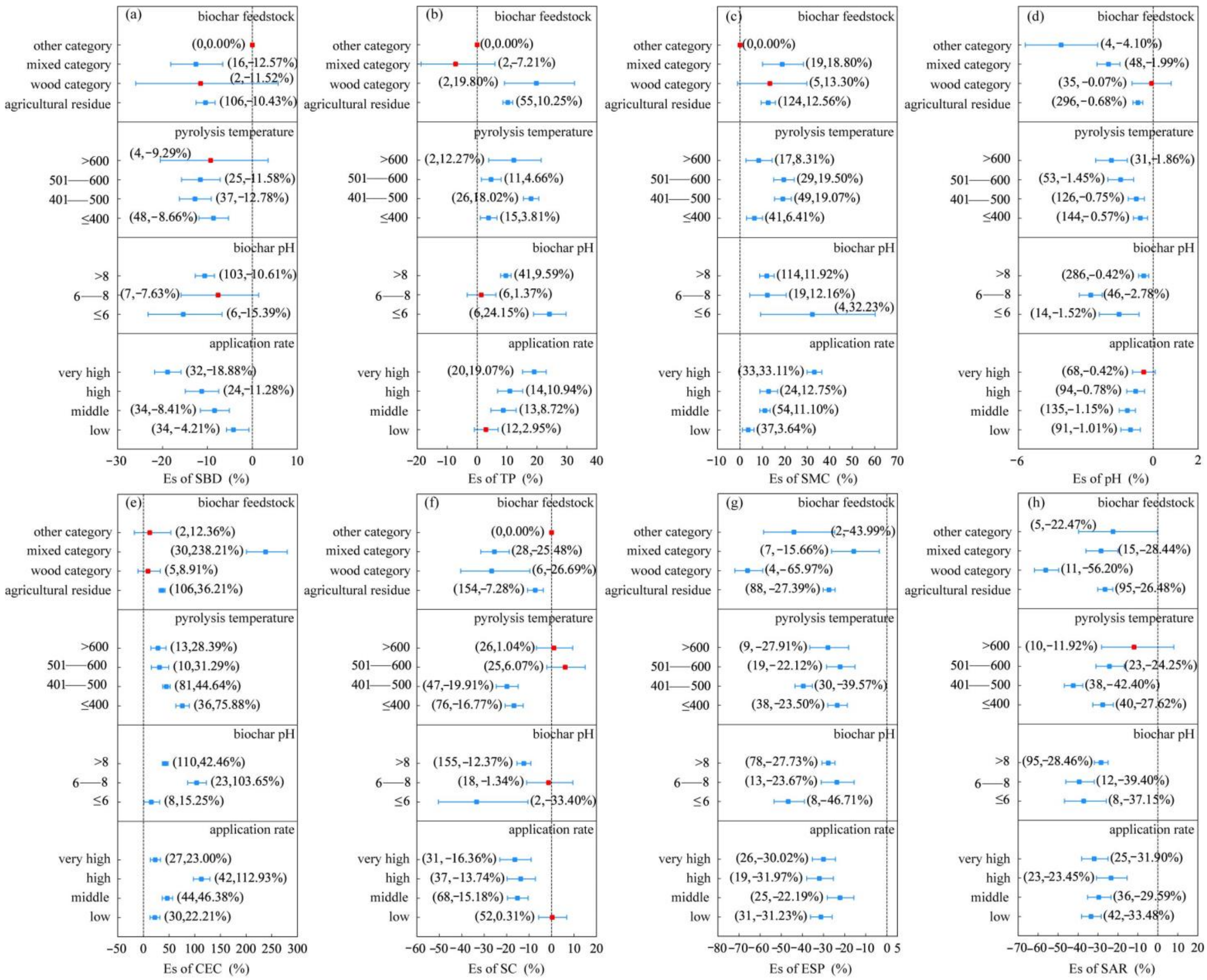

Figure 4. The impact of biochar with different characteristics on soil physicochemical properties as follows: (**a**) soil bulk density (SBD), (**b**) total porosity (TP), (**c**) soil moisture content (SMC), (**d**) soil

pH, (**e**) cation exchange capacity (CEC), (**f**) soil salt content (SC), (**g**) exchange sodium percent (ESP), and (**h**) sodium adsorption (SAR). The dots and error bars indicate the mean percentage change and 95% confidence interval (CI); the effect size was considered statistically significant if the CI did not include zero, with red dots representing no statistical significance. The numbers in parentheses indicate the number of response variables and the percentage change.

3.5. Key Driving Factors of Soil Physicochemical Property Changes

The aggregated boosted tree (ABT) method was used to analyze the relative importance of soil characteristics and biochar properties with regard to soil physicochemical properties. Biochar pH value (46.53%) was an important factor in explaining soil SBD changes (Figure 5a), salinization degree (36.60%), and biochar application rate (28.25%), and initial soil pH value (20.67%) had a greater impact on soil TP (Figure 5b). The pyrolysis temperature of biochar (37.25%) and biochar pH (21.53%) had a greater impact on soil SMC (Figure 5c). Salinization degree (36.68%) had significant influences on soil pH (Figure 5d). Compared with soil properties and other biochar characteristics, the type of biochar feedstock (86.90%) had a greater impact on CEC (Figure 5e), moisture deficit (26.62%), and soil salinization level (24.90%), and initial soil pH (20.43%) had a significant influence on soil SC (Figure 5f). Soil moisture deficit (43.87%) had a significant impact on soil ESP (Figure 5g), and pyrolysis temperature (21.83%) and moisture deficit (21.61%) had a significant influence on soil SAR (Figure 5h). In summary, biochar pH, salinization degree, type of biochar, pyrolysis temperature, and moisture deficit are the main driving factors for the changes in soil physicochemical properties when biochar is used to improve saline–alkali soil.

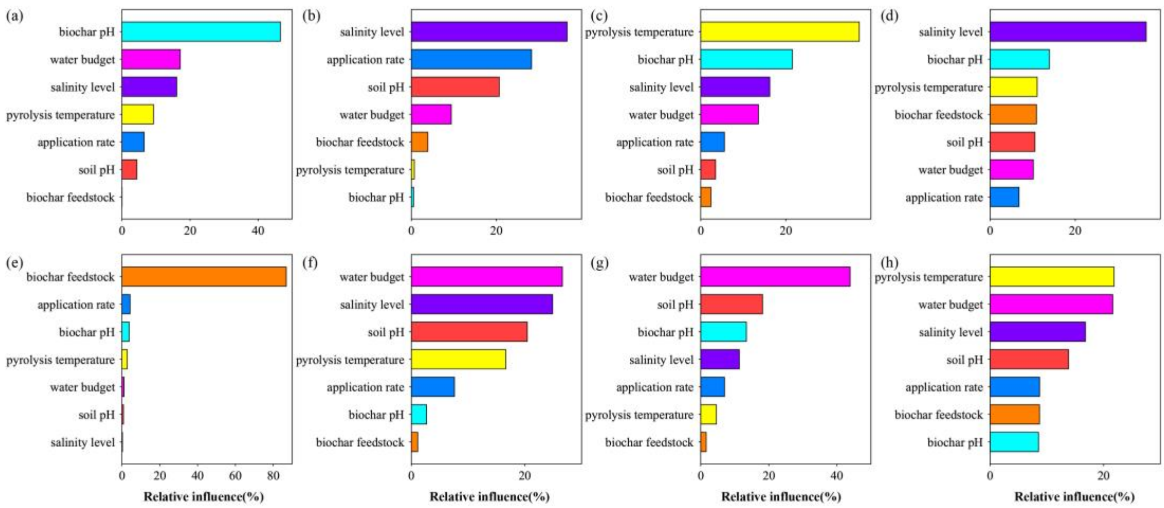

Figure 5. The relative influence of soil properties and biochar characteristic factors on soil physicochemical properties as follows: (**a**) soil bulk density (SBD), (**b**) total porosity (TP), (**c**) soil moisture content (SMC), (**d**) soil pH, (**e**) cation exchange capacity (CEC), (**f**) soil salt content (SC), (**g**) exchangeable sodium percentage (ESP), and (**h**) sodium adsorption ratio (SAR) based on the aggregated boosted tree model (ABT).

3.6. The Overall Impact of Biochar on Soil Physicochemical Properties

A comprehensive evaluation was conducted to assess the effects of various types of biochar on the physicochemical properties of saline–alkali soil with different characteristics. The optimal biochar characteristics for application under different soil characteristics were ultimately determined (Figure 6, Table 3). In this study, under all soil characteristics, the biochar produced at a pyrolysis temperature ranging from 401 to 500 °C was found to be the most effective for improving soil physicochemical properties (Table 3). This was especially true under conditions of water deficit, where the increase in soil physicochemical properties at 401–500 °C was twice that of >500 °C (Figure 6b). Under the condition of soil pH value of 8.5–9.5, the improvement effect of 401–500 °C on soil physicochemical properties is three times that of ≤400 °C (Figure 6g). Additionally, except for saline–alkali soils with pH > 9.5, where agricultural waste biochar was the most effective in improving soil physicochemical properties, other soil types showed the best improvement effects with mixed biochar (Table 3). Especially in heavily salinized soils, applying mixed biochar increased soil physicochemical properties by 69.56% compared to the control, significantly higher than other raw material biochar (Figure 6e). In areas with surplus moisture, lightly to moderately saline soils, and saline–alkali soils with an initial pH ≥ 8.5, extremely high application rates of biochar showed optimal improvement effects. In contrast, in areas with moisture deficits, heavily saline–alkali soils, or soils with pH ≤ 8.5, high application rates and neutral biochar were most effective in improving soil physicochemical properties (Table 3). Furthermore, lightly salinized soils saw the greatest increase with the application of alkaline biochar, increasing by 8.09% compared to the control (Figure 6c), while moderately saline soils or saline–alkali soils with an initial pH > 8.5 showed the most significant improvement effects with acidic biochar, increasing by 16.70%, 11.54%, and 14.50% compared with the control, respectively (Figure 6d,g,h).

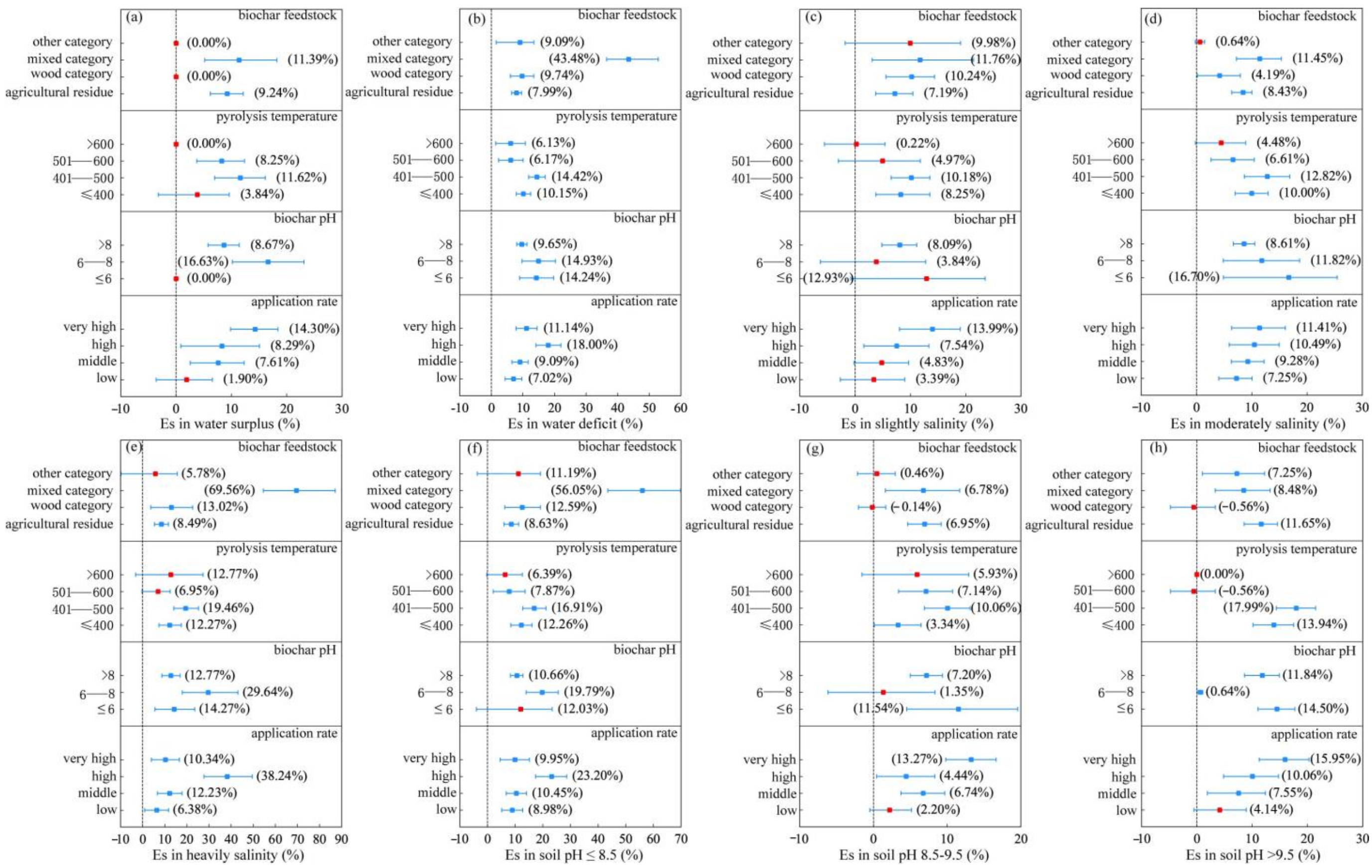

Figure 6. The overall impact of applying biochar with different characteristics on soil physicochemical properties under different soil characteristics as follows: (**a**) moisture surplus, (**b**) moisture deficit, (**c**) light salinization, (**d**) moderate salinization, (**e**) heavy salinization, (**f**) pH ≤ 8.5, (**g**) pH 8.5–9.5, and (**h**) pH > 9.5. The dots and error bars indicate the mean percentage change and 95% confidence interval (CI); the effect size was considered statistically significant if the CI did not include zero, with red dots representing no statistical significance. The numbers in parentheses indicate the number of response variables and the percentage change.

Table 3. The optimal characteristics of biochar application in different types of saline–alkali soils.

Different Soil Types		Feedstock				Pyrolysis Temperature				Biochar pH			Addition Rate			
		Agricultural Residue	Wood	Mixed	Other	≤400	401~500	501~600	>600	<6	6~8	>8	Low	Middle	High	Very High
Water Budget	Deficit			√			√				√				√	
	Surplus			√			√				√					√
Salinity	Slightly			√			√					√				√
	Moderately			√			√			√						√
	Heavily			√			√				√				√	
pH	<8.5			√			√				√				√	
	8.5~9.5			√			√			√						√
	>9.5	√					√			√						√

Note: √ represents the most suitable biochar properties in different types of saline soils.

4. Discussion

4.1. Impact of Biochar Application on the Physicochemical Properties of Saline–Alkali Soil

This study indicates that the application of biochar has varying effects on the physicochemical properties of saline–alkali soil, depending on the characteristics of the biochar and the type of saline–alkali soil. However, the application of biochar with a pyrolysis temperature of 401–500 °C or biochar derived from mixed materials significantly outperforms other types of biochar in improving these properties (Figure 6; Table 3). As the pyrolysis temperature increases (400–600 °C), the ash content of the biochar continuously increases, which becomes more alkaline [15,33,34]. Therefore, the biochar produced by <500 °C pyrolysis is neutral or weakly alkaline, which is more suitable for saline–alkali soil improvement [35,36]. Meanwhile, Lei et al. [37] used meta-analysis to find that biochar pyrolyzed at 401–500 °C resulted in a 29.55% increase in tomato yield compared to the control treatment without biochar. In addition, the improvement effect of mixed biochar is significantly better than that of other materials. This is mainly because biochar can reduce its pH value through modification methods such as acid (phosphoric acid, nitric acid, etc.) immersion and composting [38,39]. Or, in combination with acidic substance (such as wood vinegar, humic acid, and ammonium sulfate, etc.) co-application [40], it can increase many carboxyl and hydroxyl oxygen-containing functional groups, causing H^+ to replace the cations originally bound to -COO- in the biochar. Subsequently, the sites vacated by the neutralization reaction between the biochar and alkaline substances are occupied by Na^+, reducing the content of free Na^+ and thereby enhancing soil colloid aggregation and improving soil structure [41]. Concurrently, soil salt ion content is reduced through adsorption or complexation [42,43]. Furthermore, this study also found that the improvement effects on the physicochemical properties of saline–alkali soil were not proportional to the amount of biochar applied for all soil types (Figures 4 and 6). When the amount of biochar applied was higher than 80 t ha^{-1}, the improvement effect on the physical properties of saline–alkali soil was significant. And when the amount of biochar applied was 20–80 t ha^{-1}, it was more conducive to improving the chemical properties of saline–alkali soil (Figure 4), which is similar to the results of some studies [19,44]. The application of an extremely high amount of biochar can lead to an increase in the salt content of saline–alkali soil, and the direct input of salt ions is the main reason for this negative effect [19,44]. Moreover, the most suitable biochar pH for different types of saline–alkali soil varies, so it is necessary to adapt measures to local conditions when improving different types of saline–alkali soil. Appropriate biochar should be selected for different types of saline–alkali soil to ensure the restoration of saline–alkali land while minimizing harm to the soil.

4.2. Impact of Biochar on SBD, TP, and SMC of Saline–Alkali Soil

SBD and porosity are key factors that reflect and evaluate soil structure and texture [45], directly affecting the absorption and utilization of soil water and fertilizers by plant roots [46]. Biochar application significantly reduced bulk density and increased porosity of soils (Figure 1), and the increase in SBD was positively correlated with the decrease in TP (Figure 2). This is mainly due to the high porosity of biochar itself, which can directly increase the total porosity of the soil [19,47], and its own bulk density (0.09–0.74 g cm^{-3}) is much lower than that of saline–alkali soil (1.42–1.73 g cm^{-3}) [48]. Its dilution effect is the direct reason for improving SBD and TP [12]. However, with an increase in biochar application, the reduction in SBD becomes progressively smaller (Figure 4a), which is consistent with the studies by Leonard et al. [49] and Singh et al. [30]. The effect sizes of different biochar on these two soil properties may vary depending on the physical properties of biochar (which depends on feedstock types and pyrolysis temperatures) (Figure 5a,b). Biochar can differ in their physical properties, such as surface area and porosity, due to feedstock type and pyrolytic conditions, which affects the bulk density of soils [50]. The higher the porosity of the biochar, the larger its specific surface area, the lower its bulk density, and the more apparent its effect on soil improvement [51].

When the soil bulk density decreases and porosity increases, it facilitates the flow of soil moisture and air within the soil [46], thereby increasing soil SMC (Figure 1). Additionally, a reduction in SBD and an increase in TP can promote a positive increase in SMC (Figure 2). This can be attributed to the changes in soil structural characteristics due to the addition of biochar. Because the application of biochar not only increases the number of capillary pores in the soil but also, due to its rough surface, enhances the frictional interaction between the biochar and soil particles [52,53]. This improves the overall soil porosity while promoting the formation of soil aggregates, reducing its bulk density, and, consequently, increasing the water retention capacity and hydraulic conductivity of soils [50,52,53]. The increase in SMC is also influenced by the pyrolysis temperature of the biochar, pH, and the degree of soil salinization and moisture deficit (Figure 5c). Biochar with different pyrolysis temperatures and pH values, when applied to soils with varying degrees of salinization and moisture deficits, alters soil structure and soil humus components, thereby affecting the soil's water retention capacity. Under the treatment of biochar pyrolyzed at high temperatures (>500 °C), the increase in SMC is higher than that at lower temperatures (≤500 °C) (Figure 4c). This is mainly because, after aging in the soil, high-temperature biochar exhibits a decrease in hydrophobic alkyl functional groups and an increase in hydrophilic polar oxygen-containing functional groups (such as -OH and -COOH), coupled with its well-developed porous structure. It leads to changes in the soil moisture infiltration patterns, residence time, and flow paths, offering better moisture retention effects compared to low-temperature biochar [18,54,55]. Utilizing biochar to alleviate soil water scarcity in water-deficient regions holds significant importance [56]. In addition, biochar can reduce water diffusion rate by increasing soil porosity and improving soil's ability to intercept and retain precipitation [57]. The inherent abundant microporous structure and large specific surface area of biochar facilitate the maintenance of a greater amount of water in a capillary state, thereby effectively enhancing soil moisture retention and suppressing evaporation [58], and the SCM in the water surplus area was higher than that in the water deficit area (Figure 3c). Biochar application in light and moderate saline–alkali soils increased SMC more than in heavy saline–alkali soils (Figure 3c). Due to the high salt content of the soil, Liu et al. [59] stated the application of biochar may further increase the salt concentration, thus aggravating the accumulation of salt ions, and the increase in sodium ions will enhance the dispersion of soil particles, damaging the soil structure. The application of biochar in the medium saline soil promotes the infiltration of water but inhibits the infiltration of water in the heavy saline soil.

4.3. Impact of Biochar on pH and CEC of Saline–Alkali Soil

Recent studies have revealed variability in the impact of biochar application on soil pH levels. In this study, biochar treatment resulted in only a slight reduction in the pH of saline–alkali soils (Figure 1), which is consistent with Wang et al. [20]. Zheng et al. [15] and Cui [60] indicated that acidic oxygen-containing functional groups on the surface of biochar (such as -COOH, -OH) and its high CEC promote the absorption of cations (such as K^+, Ca^{2+}, and Mg^{2+}) by plants, leading to the release of H^+ in the process of hydrogen ion replacement to compensate for charge balance, thereby reducing pH. However, Kim et al. [22] and Manasa et al. [61] reported that the raw materials generate a large number of additional functional groups on the surface of the biochar during the pyrolysis process (such as carboxyl and ether groups), as well as cause the leaching of alkali metal ions and carbonates. The release of these ionic salts through the interaction of water and soil can exchange H^+ and Al^{3+} in the soil, causing the pH of most biochar to be alkaline, which leads to an increase in soil pH with increasing application rates (Figure 3d). These contradictions are closely related to the degree of salinization, biochar pH, pyrolysis temperature, and the type of biochar raw materials (Figure 5d). Sun et al. [62] and Xu et al. [34] believed that the difference between the low pH of biochar and the high pH of saline–alkali soil is also the key to the influence of biochar application on the pH of saline–alkali soil. In this study, biochar with a pH of 6–8 had the best effect on reducing soil pH (Figure 4d); when the baseline soil pH was between 8.5 and 9.5, the reduction effect on soil pH was significantly better than the other two baseline values (Figure 3d). The finding of Gao et al. [63] indicated that while the pH of most biochar increases with higher pyrolysis temperatures, the enrichment of inorganic elements persists. However, at elevated temperatures, these inorganic elements tend to form more stable and less soluble mineral crystals within biochar. At the same time, with the increase in preparation temperature, the polar functional groups on the surface of biochar gradually lysed and disappeared, forming a non-polar structure with higher stability and thereby reducing H/C and O/C and increasing the stability of biochar [64]. As a result, the decreasing effect of biochar on soil pH was gradually enhanced with the increase in pyrolysis temperature (Figure 4d). In addition, the effect of biochar on soil pH may also be related to the aging time of biochar. Jin et al. [65] conducted a 6-year biochar study on biochar application to saline soils and found that it initially increased soil pH, which subsequently decreased over the duration of biochar application. This may be due to the fact that biochar application breaks the alkaline soil structure, increases water content, enhances water circulation, and neutralizes soil alkalinity through functional groups such as carboxyl groups released by slow oxidation, which, in turn, reduces pH by decreasing alkaline groups in the soil [15,66].

Saline–alkali soil, characterized by low organic matter content and exchange sites dominated by salt ions such as Na^+, limits the ability to retain other cations, resulting in a low cation exchange capacity [67]. Biochar possesses a high specific surface area, abundant oxygen-containing functional groups (such as -OH and -COOH), and mineral components, which can directly increase the soil exchange sites [30,68,69]. Moreover, the addition of biochar may cause an increase in soil pH, leading to the deprotonation of soil colloids and an increase in net negative surface charges [48,70], thereby enhancing the CEC in the soil (Figure 1). However, this effect can be altered by both feedstock type and pyrolysis temperatures [30]. The results of this study found that mixed-type biochar significantly increased CEC more than other types of feedstock (Figure 4e). Wei et al. [19] and Al-Wabel et al. [47] pointed out that biochar produced from sewage sludge or livestock manure usually contains richer oxygen-containing functional groups and metal minerals compared to biochar from straw, and the CEC of sewage sludge or livestock manure biochar (about 73.9 cmol kg^{-1}) is significantly higher than that of wood and straw biochar (about 48.1 cmol kg^{-1}), thereby promoting an increase in soil CEC. As the pyrolysis temperature increases, the enhancement decreases (Figure 4). The possible reason for this is that with the increase in pyrolysis temperature, the complete decomposition of cellulose leads to a reduction in the number of oxygen-containing functional groups that can be generated, thereby causing a decrease in the cation exchange capacity of the biochar itself [19]. However, the meta-analysis results of this article indicate that pyrolysis temperature is not the key factor affecting CEC changes (Figure 5e). This may be related to the complex interactions between the raw materials used in different studies (modifications to the raw materials, mixed application of different raw materials) and pyrolysis methods. Zhao et al. [71] demonstrated that the impact of raw materials on the cation exchange capacity of biochar itself is greater than that of pyrolysis temperature. In addition, the aging of biochar with application time also affects the improvement of soil CEC. The aging of biochar will lead to an increase in oxygen-containing functional groups (e.g., -OH, -COOH) due to the oxidation of its surface, which will, in turn, increase the CEC of biochar; the improvement effect on soil CEC is better than that for un-aged biochar [72]. A current study [70] showed that the soil CEC improved by biochar with different application years also varied, which effectively improved by 17.0–45.0% in the first year, 22.5–82.0% in the second year, and 6.7–66.3% in the third year.

4.4. Impact of Biochar on SC, ESP, and SAR of Saline–Alkali Soil

Excessive salinity and alkalinity in the soil can lead to severe degradation of soil health, thereby inhibiting plant growth [73]. The application of biochar can enhance soil aeration and water permeability, thereby promoting the leaching of salts to the lower layers of the soil and reducing the accumulation of salts in the topsoil [48]. Additionally, He et al. [74] indicate that some acidic groups in biochar have electrostatic attractions with soil cations, absorbing many substances, including soluble salts, alleviating soil salinization, and thereby reducing soil salinity and alkalinity (Figure 1). In particular, biochar prepared by low-temperature pyrolysis (<500 °C) has a greater effect on reducing ESP and SC due to its neutral or weakly alkaline character (Figure 4f), which is more suitable for the improvement of SC and ESP in saline–alkali soil [33,36]. However, this study found that there is a significant inhibitory effect between SC and ESP. This may be because when the soil SC content is high, that is, the salt concentration in the soil solution is large, the exchange reaction of sodium ions in the soil will be inhibited. This is because high concentrations of salts compete with other cations for exchange sites, thereby reducing the value of ESP. This study also found that with an increase in the application rate of biochar, the degree of soil salinization may be exacerbated (Figure 4f,g), and the direct input of salt ions is the main reason for its negative effects [19,44]. Amini et al. [44] and Wang et al. [75] pointed out that biochar made from livestock manure, halophytic plants, and walnut shells can easily increase the salt and alkali content in the soil. The results of this study indicate that mixed-type biochar significantly reduces SC more than biochar from other raw materials (Figure 4f). It was possible that after the combined application of biochar and other acid amendments, the acidic functional groups in the amendments were related to the interaction with the surface of biochar, resulting in the neutralization or transformation of basic functional groups. The total amount of alkaline elements decreased by 88.78% and 26.53% compared with the original biochar, respectively [76]. Moreover, the specific surface area, porosity, and oxygen-containing functional groups (-COOH, -OH, etc.) of the biochar all increased, thereby enlarging the contact area with soil salinity and enhancing the surface complexation and adsorption capabilities with Na^+ [42,43]. Furthermore, the reduction in SC is more significant in water-deficient regions than in water-surplus areas (Figure 3f). Chen and Yu [77] pointed out that in water-deficient regions, soil evaporation is intense, and soil salts rise through capillary action, easily causing surface salt accumulation; hence, the ameliorative effect is more pronounced in these water-deficient areas. It is worth noting that the subgroup analysis of different raw material biochar in this study may have certain limitations. The reliability of the subgroup analysis may potentially be affected by a limited number of comparisons within certain categories of raw materials. Although they were discussed in the previous studies, the exact mechanisms still need to be more thoroughly explored in future research.

The application of biochar results in a very significantly positive correlation between SC and SAR, and ESP and SAR (Figure 2). Abbas et al. [78] and Jiang et al. [79] indicate that multivalent cations such as Ca^{2+} and Mg^{2+} on the surface of biochar displace excess Na^+ on soil particles through cation exchange, and it is then leached out of the soil by water, thereby reducing the soil SAR (Figure 1). However, the reduction in SAR is not only related to SC and ESP but also to soil moisture deficit, soil salinization degree, initial soil pH, and biochar pyrolysis temperature (Figure 5h). When the degree of soil salinization increases, the reduction in SAR also continues to increase (Figure 3h); as for the initial soil pH, the application of biochar has the best effect on reducing SAR in soils with pH < 8.5. The results of this study indicate that wood-based biochar more effectively improves SAR compared to biochar from other raw materials (Figure 4h). The high efficacy of this material may be due to its higher lignin content, specific surface area, porosity, and oxygen-containing functional groups. These properties work synergistically to enhance the biochar's ability to adsorb and remove Na^+ ions from the soil, thereby reducing SAR [80,81]. It is worth noting that with an increase in the amount of biochar applied, the water retention of biochar reduces the filtration rate of water, thereby decreasing the leaching of sodium ions [82], which poses a risk of increasing soil SAR (Figure 4h).

5. Research Gaps and Future Needs

This study analyzed the effectiveness of biochar with varying characteristics in improving the physicochemical properties of saline soils under different saline conditions. However, the subgroup analyses based on different soil types and feedstocks may have limitations. In particular, the limited number of comparisons in some feedstock categories may potentially affect the reliability of subgroup analyses. Although we propose some explanations, the exact mechanisms still need to be explored more thoroughly in future studies.

The potential risk of environmental pollution from biochar in amending saline soils is a major concern—the raw material, preparation, and aging of biochar may be accompanied by the generation of toxic substances, and the characteristics of particle size distribution, bulk density, porosity, compaction, and viscosity of different soils may have different toxicological effects. At the same time, factors such as the aging of biochar, climate, geology, and hydrology should be taken into account, and long-term dynamic tracking and monitoring should be carried out in conjunction with soil quality evaluation to assess the sustainability of biochar improvement effects and environmental risks.

Current research on the biochar improvement of saline soils is mostly limited to laboratory simulations and lacks long-term field trials to verify the applicability and mechanism of action for practical applications. Consideration of the long-term effects of biochar aging on soil physicochemical properties in subsequent studies will help to more accurately assess how biochar affects soil properties under different conditions and environments and how it affects agroecosystems, as well as the economic benefits of biochar application.

6. Conclusions

This study presents a global-scale meta-analysis to summarize the effect of biochar application on the improvement of saline–alkali soil. The application of biochar positively affects the physicochemical properties of saline–alkali soil, especially in reducing SAR and ESP, with a reduction of 30.31% and 28.88%, respectively. Additionally, biochar significantly enhances soil CEC. It is noteworthy that there is a significant inhibitory effect between the SC and ESP of soil, while all others exhibit synergistic effects. Among them, biochar pH, degree of salinization, type of biochar, pyrolysis temperature, and moisture deficit are the main driving factors influencing changes in the physicochemical properties of saline–alkali soils treated with biochar. The results indicate that the application of biochar in water-deficient regions is more conducive to enhancing soil chemical properties and TP. In mildly and moderately saline–alkali soils, the improvement in physical properties is superior to that in heavily saline–alkali soils, whereas the reverse trend is observed for chemical property enhancement. With an increase in the inherent soil pH, the amelioration of soil SBD and TP becomes increasingly pronounced. As the application rate of biochar increases, the improvement in soil physical properties becomes increasingly evident. Moreover, pH 6–8 biochar exhibits better efficacy in ameliorating soil chemical properties compared to biochar at other pHs. The different types of saline–alkali soils determine the different types of biochar used. However, the biochar obtained by pyrolysis at 401–500 °C is generally suitable for improving the physicochemical properties of various saline–alkali soils. In soil with pH < 8.5, water surplus, and mild salinity, mixed biochar (pH 6–8) at 41–80 t ha^{-1} has the most significant effect on soil improvement. Conversely, in soil with pH ≥ 8.5 located in water-deficit areas and classified as moderate and heavy saline–alkali, the application of biochar with pH ≤ 6 at >80 t ha^{-1} yields the best results for soil improvement. The improvement of saline–alkali soil with pH ≥ 8.5 was most effective with biochar derived from agricultural waste, and the other soils showed the greatest enhancement with mixed biochar.

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