

RESEARCH ARTICLE

The effects of two different biochars on the characteristics of saline acid sulfate soil

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Abstract

Biochar can be a potential bio-amendment for remediating saline acid sulfate soil and its effects may be dependent on its properties. The current study sought to assess the effects of two different biochars on the properties and quality of saline acid sulfate soil. The experiment was implemented by mixing soil with biochars made from longan branches (LBs) and coconut coir biochar (CB) at five rates of 0%, 0.7%, 1.5%, 3%, and 6% (w/w). After 100 days of incubation in a greenhouse, soil samples from experimental pots were taken and analyzed for 11 parameters. The results showed that biochar significantly enhanced pH while declining the concentration of SO_4^{2-} and exchangeable Al and Fe. Mechanisms responsible for these effects could be due to the high alkaline properties of the added biochar. Coconut biochar raised the concentration of exchangeable Na, K, and Mg more strongly than LB. Consequently, coconut biochar greatly increased the soil electrical conductivity (EC) value, while longan biochar exhibited no significant effect. The soil quality index of the 6%-LB-added soil increased by 64% and that of the 6%-CB-added soil increased by 45%, compared with the zero-biochar-added soil. Lower soil quality induced by CB compared with LB may be attributed to CB's initial properties, which had higher EC, Cl^- , and Na levels than LB. The findings suggested that biochar addition can improve overall quality but alter individual properties of saline acid sulfate soil in different directions, depending on the properties of the added biochar, which requires more studies to clarify its ameliorative effects.

KEYWORDS

coconut biochar, longan biochar, soil acidity, soil quality, soil salinity

1 | INTRODUCTION

Acid sulfate soil occupies a large area mostly in coastal regions all over the world (Karananidi et al., 2022). The soil can have a high concentration of sulfide, which can be oxidized to produce a large quantity of sulfuric acid as well as toxic elements, leading to the formation of some major crop-restricting characteristics of the soil, such as a high concentration of total sulfur, iron, and aluminum, as well as low phosphorus concentration and low pH (Nguyen, Dinh, Nguyen, et al., 2022). The soil also exhibited poor activities of microorganisms, slow decomposition of organic matter, limited release of nutrients,

and consequently poor plant growth (Nam et al., 2014). Many areas of acid sulfate soils, which are located close to the coast, may also be affected by seawater intrusion, which could be accelerated by climate change and subsequent sea-level rise. Furthermore, the soil may be salinized due to various reasons such as salt-affected groundwater, saltwater irrigation, fertilization, and weathering of salt-bearing rocks (Rengasamy, 2010; Shrivastava & Kumar, 2015), forming saline acid sulfate soil. Consequently, the soil also contains a high concentration of dissolved salts, which adversely affects the growth and yield of plants (Hailu & Mehari, 2021). As a result, saline acid sulfate soil may have saline-soil-related features and acid-sulfate-soil-related features,

leading to the depletion of agricultural productivity and subsequent global food security.

Many studies have been conducted to reclaim the salt-affected soil in general and saline acid sulfate soil in particular. The lime application can be considered a traditional and widely used method of reclaiming acid sulfate soil that reduces soil acidity and provides calcium to plants (Azman et al., 2014; Palko & Wepppling, 1994). Thi et al. (2022) conducted a study to compare the effect of three soil amendments, lime, organic fertilizer, and biochar on the growth and yield of corn planted in acid sulfate soil and concluded that the last two amendments with a high rate could be used to treat the soil. Biochar was also used to examine its effects on saline-alkaline soil (Sánchez et al., 2022). The finding indicates that biochar can be a potential amendment for reclaiming saline acid sulfate soils. Biochar addition may introduce some potential benefits, including increased organic carbon concentration, a method of sequestering carbon from the atmosphere, reduced greenhouse gas emissions, and improved soil properties leading to enhanced crop yield (Knoblauch et al., 2021; Koide et al., 2018; Yang et al., 2020).

Many studies reported that biochar may improve soil quality and then plant growth in saline soil, and/or acid sulfate soils. According to Akhtar et al. (2015), biochar mitigates the effects of saline soil on the growth and yield of maize. The authors also demonstrated that biochar alleviates the effects of salts in saline soils by reducing the Na concentration in the xylem sap of maize and maintaining nutrient balance in the plant stem. When biochar was applied to moderately saline soils, wheat yield increased by 38% in 2 years compared with the nonbiochar treatment (Lashari et al., 2013). The authors also suggested that biochar reduced EC, pH, and other soil properties, which helped increase the yield of wheat. Another study by Lashari et al. (2015) showed that using biochar in saline soils increased the growth and yield of maize by 23%–95%, and some soil properties such as electrical conductivity (EC), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), and the concentration of exchangeable Na^+ in the soil were significantly reduced. According to Sun et al. (2016), biochar improved the quality of saline soils, thereby enhancing crop growth. Biochar was also found to enhance cation exchange capacity (CEC) and decline Al stress, leading to a higher yield of rice and maize crops planted in acid-sulfate soil (Manickam et al., 2015). Evy et al. (2019) found that biochar may enhance pH, soil organic carbon (SOC), and the concentration of some nutrients such as available P, total N, and exchangeable Ca and K, which lead to an increase in the filled grain weight of rice in acid-sulfate soil.

The above research results suggest that using biochar as a soil amendment could improve the fertility of saline acid sulfate soil. The reason for the improvement could be high capacity of biochar to adsorb salt and acidity from the soil (Hammer et al., 2015; Lashari et al., 2013; Thomas et al., 2013). Nevertheless, our search in the literature revealed that few studies have been conducted to examine the effects of biochar on saline acid sulfate soil (Gunarathne et al., 2020; Nguyen, Dinh, Nguyen, et al., 2022). This suggests that more studies are in need to remediate this problematic soil for better agricultural productivity. Therefore, the current study was conducted to assess

the effects of two different biochars on the properties and quality of saline acid sulfate soil. We hypothesize that the ameliorative effects of biochar on saline acid sulfate soil are dependent on the properties of the amendment and the lower biochar rates may lead to rapid improvement in soil quality than the greater biochar rates.

2 | MATERIALS AND METHODS

2.1 | Experimental materials

The soil used for the current study was collected at 10°37'52" N 106°45'47" E in Binh Khanh commune, Can Gio District, Ho Chi Minh City, Vietnam. The soil is classified as a salic thionic fluvisol (WRB, 2015) with some main properties shown in Table 1. Around 250 kg of soil from the surface layer (15 cm) was collected from a farmer's field having a rotation of a rice season and shrimp culture. The collected soil was transferred to a greenhouse, air-dried, ground to pass through a 2-mm sieve, and stored until it was used for analysis and pot experiment. Longan branches and coconut coir, which are widely available in Vietnam, were used to make longan biochar (LB) and coconut coir biochar (CB), respectively. The longan and coconut were collected, air-dried, and chopped into 3–5 cm segments before pyrolysis using a method described by Nguyen, Dinh, Dong, and Le (2022). The pyrolysis process was implemented using a steel sheet-made reactor at a temperature of around 350°C, and the resulting biochars were used in the current experiment a few weeks later.

2.2 | Experimental setup

The two biochars were weighed and mixed with sieved soil at five rates of 0%, 0.7%, 1.5%, 3%, and 6% (w/w) in four replicates, forming 40 experimental pots (2 biochars \times 5 rates \times 4 replicates). Each of the mixtures of the soil and biochar (hereafter referred to as experimental soil) was packed into a plastic pot with a diameter of 20 cm and a height of 35 cm (about 3–4 kg of the experimental soil was packed into one pot). The soil and biochar mixture was flooded with distilled water during the 100-day experiment. The 40 pots were randomly arranged in a greenhouse, making the experiment a completely randomized design.

2.3 | Sampling and chemical analysis

Soil samples were taken from individual pots after 100 days of the experiment using a stainless steel sampler. Sampling was conducted based on the procedure by Nguyen, Dinh, Nguyen, et al. (2022). The taken soil was air-dried, ground to pass through a 2-mm sieve, and stored until analysis. Additionally, the soil and biochars before the experiment were subsampled in four replicates for analyzing the same as the soil samples after the experiment. All the soil and biochar samples were analyzed for pH, EC, the concentration of Cl^- ,

TABLE 1 Properties of saline sulfate soil and two biochars.

| Parameter | Unit | Longan biochar (LB) | Coconut biochar (CB) | Tested soil |
|-------------------------------|---------------------|-----------------------------|-------------------------------|-----------------------------|
| pH | None | 7.23 ^b ± 0.10 | 9.39 ^a ± 0.11 | 3.80 ^c ± 0.22 |
| EC | dS m ⁻¹ | 0.19 ^b ± 0.03 | 3.64 ^a ± 0.04 | 3.87 ^a ± 0.66 |
| Cl ⁻ | mg kg ⁻¹ | 1.81 ^c ± 0.13 | 27.54 ^a ± 0.25 | 2.09 ^b ± 0.09 |
| SO ₄ ²⁻ | mg kg ⁻¹ | 0.66 ^b ± 0.10 | 0.65 ^b ± 0.20 | 13.15 ^a ± 0.66 |
| Exchangeable Na | mg kg ⁻¹ | 1381.9 ^b ± 197.2 | 23848.8 ^a ± 1057.5 | 1893.3 ^b ± 34.0 |
| Exchangeable K | mg kg ⁻¹ | 966.0 ^b ± 58.4 | 64335.5 ^a ± 3911.1 | 889.2 ^b ± 60.7 |
| Exchangeable Ca | mg kg ⁻¹ | 3117.3 ^a ± 458.6 | 2744.8 ^a ± 758.6 | 1574.2 ^b ± 230.7 |
| Exchangeable Mg | mg kg ⁻¹ | 283.2 ^c ± 26.6 | 1112.4 ^a ± 159.9 | 703.2 ^b ± 75.8 |
| Exchangeable Al | mg kg ⁻¹ | 29.11 ^a ± 6.79 | 16.59 ^b ± 1.08 | 3.83 ^c ± 0.10 |
| Exchangeable Fe | mg kg ⁻¹ | 69.53 ^b ± 2.40 | 79.96 ^a ± 5.25 | 21.67 ^c ± 0.50 |
| Exchangeable Mn | mg kg ⁻¹ | 48.43 ^b ± 2.63 | 98.05 ^a ± 0.68 | 20.49 ^c ± 0.24 |

Note: Data are presented as mean ± SD (standard deviation of the mean). Superscripts (a, b, and c) indicate the significant difference within the same row for each parameter ($p < 0.05$).

SO₄²⁻, and exchangeable Al, Ca, Fe, K, Mg, Mn, and Na. The samples were added with distilled water in a 1:5 (w/w) ratio, and the extracts were measured for pH and EC with a pH meter and an EC meter, respectively. The concentrations of exchangeable cations were determined using the barium chloride method (Carter & Gregorich, 2008), and the extract was quantified using inductively coupled plasma optical emission spectrometry (ICP-OES). The concentration of Cl⁻ was quantified using the titration method (Hajrasuliha et al., 1991), and that of SO₄²⁻ was determined using the turbidimetric method (Rice et al., 2017).

2.4 | Statistical analyses

All experimental data were statistically analyzed using a two-way analysis of variance (ANOVA) for a completely randomized design with four replicates. Multiple regression analysis was conducted to quantify the contributive percentage of individual soil parameters on the soil quality index (SQI). The SQI was computed based on the principal component analysis/factor analysis (PCA/FA) approach (Mukherjee & Lal, 2014; Nguyen et al., 2021) using Equation (1).

$$SQI = \sum_{i=1}^n w_i s_i, \quad (1)$$

where n denotes the number of soil parameters; w_i is the weightage of the i th parameter, and s_i is the score of the i th parameter. The w_i is calculated using the result from PCA/FA, and s_i is determined using Equations (2 and 3). The 11 soil parameters were classified as “more is better” or “less is better.” The “more-is-better” parameters included pH, Ca, K, and Mg, whereas the others were the “less-is-better” parameters. For the “more-is-better” parameters, s_i is calculated using Equation (2).

$$s_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}}, \quad (2)$$

For the less-is-better parameters, s_i is calculated using Equation (3).

$$s_i = \frac{x_{\max} - x_i}{x_{\max} - x_{\min}}, \quad (3)$$

where x_i , x_{\min} , and x_{\max} represent the analyzed, minimum, and maximum values of parameter i , respectively. The PCA/FA method was used to identify latent factors that represented the key soil features and to calculate the weightage (w_i) of individual soil parameters (Table 1). The PCA/FA was applied to the entire dataset following the approach described by Mukherjee and Lal (2014). Factors with an eigenvalue greater than one were retained for further analysis and weightage estimation of soil parameters, which had a high loading value (>0.5) with the associated factor. The estimation of factor weightage and SQI are shown in Nguyen et al. (2021). The computed SQI was also statistically analyzed using the two-way ANOVA procedure the same as the other soil parameters.

3 | RESULTS

3.1 | Initial properties of experimental materials

The initial properties of the tested soil and biochars are presented in Table 1. LB and CB had neutral to alkaline pH values of 7.23 (LB) and 9.39 (CB). The tested soil was acidic (pH 3.8). The EC values of CB (3.64 dS m⁻¹) and experimental soil (3.89 dS m⁻¹) were significantly higher than that of LB (0.19 dS m⁻¹). Coconut biochar also had the highest concentration of Cl⁻ (27.54 mg kg⁻¹) and LB and the tested soil had similar Cl⁻ concentrations of 1.81 and 2.09 (mg kg⁻¹), respectively. The SO₄²⁻ concentration of the tested soil (13.15 mg kg⁻¹) was significantly higher than that of the two biochars (0.66 mg kg⁻¹ for LA and 0.65 mg kg⁻¹ for CB). Of the three experimental materials, CB had the highest concentration of exchangeable Na (23848.8 mg kg⁻¹), K (64335.5 mg kg⁻¹), Ca (2744.8 mg kg⁻¹), Mg

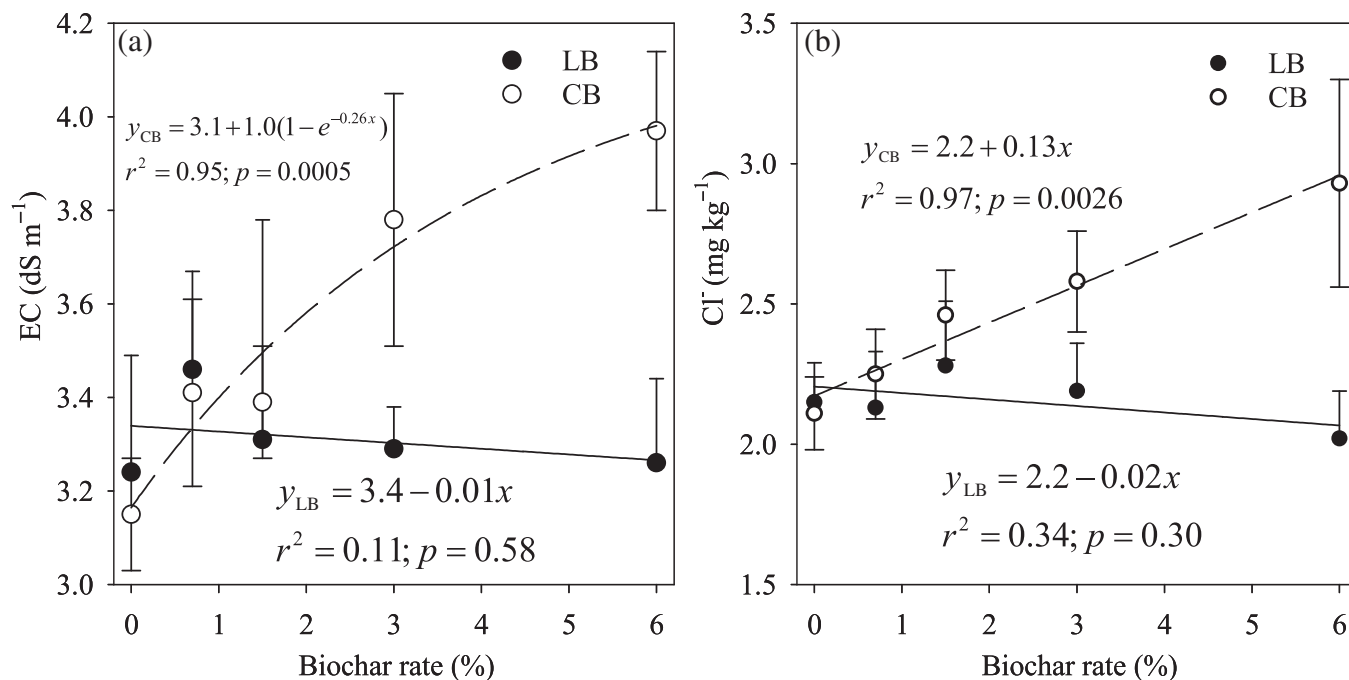


FIGURE 1 Change in the electrical conductivity (a) value and Cl⁻ (b) concentration of biochar-added soil over the biochar rates. Error bars indicate the standard deviation of the mean. CB, coconut coir biochar; LB, longan biochar. $p < 0.05$ indicates the relationship is statistically significant.

(1112.4 mg kg⁻¹), Fe (79.96 mg kg⁻¹), and Mn (98.05 mg kg⁻¹). Meanwhile, the experimental soil exhibited the lowest concentration of exchangeable K (889.2 mg kg⁻¹), Ca (1574.2 mg kg⁻¹), Al (3.83 mg kg⁻¹), Fe (21.67 mg kg⁻¹), and Mn (20.49 mg kg⁻¹).

3.2 | Changes in properties of biochar-added soil

Figure 1a shows that the addition of CB significantly increased the EC value of the biochar-added soil, whereas that of LB did not raise the EC value. Change in EC of soil added with CB followed an exponential rise model with the lowest EC value in soil added with no biochar (3.15 dS m⁻¹) and the highest value in soil added with 6% CB (3.97 dS m⁻¹). Soil amended with 6% LB had an EC value of 3.26 (dS m⁻¹), which was comparable to soil amended without biochar, which had an EC value of 3.24 (dS m⁻¹). Similarly, the concentration of Cl⁻ varied significantly in the five treatments applied with CB but not in the five treatments added with LB (Figure 1b). While CB greatly elevated the Cl⁻ concentration, following a linear regression model, LB led to similar Cl⁻ concentrations irrespective of biochar rates. Coconut biochar enhanced Cl⁻ concentration from 2.11 to 2.93 (mg kg⁻¹) and LB changed the Cl⁻ concentration from 2.15 to 2.02 (mg kg⁻¹) in the 0% and 6% biochar treatment, respectively.

The addition, CB significantly increased the concentration of exchangeable Na by about 17% across the range of CB rates, from 2905 (mg kg⁻¹) to 3421 (mg kg⁻¹) in the 0% and 6%-CB treatments, respectively (Figure 2a). In contrast, soil added with LB had exchangeable Na concentration reduced from 2921 to 2576 (mg kg⁻¹) in the

0% to 6% LB treatments, respectively. Likewise, soil added with 6% CB had the greatest exchangeable K concentration of 6174 (mg kg⁻¹), compared with 1567 (mg kg⁻¹) in the zero-C-added soil. The addition of CB significantly increased the exchangeable K concentration, following a linear regression model with an increasing rate of 745 mg kg⁻¹ for every percent of added CB. The addition of LB did not significantly enhance the exchangeable K concentration of the biochar-added soil. When compared with the zero-biochar treatment, soil treated with 6% CB increased the exchangeable K concentration by 294% and that added with 6% LB increased by 3.3%. The addition of two biochars significantly increased the concentration of exchangeable Ca in the tested soils, following an exponential rise model (Figure 2c). The concentration of exchangeable Ca increased from 1806 to 2037 when using LB, and from 1774 to 2027 (mg kg⁻¹) when using CB, corresponding to the 0% and 6% rates, respectively. When the biochar rate was increased from 0% to 6%, LB significantly increased the exchangeable Mg concentration from 1185 to 1228 (mg kg⁻¹) and CB insignificantly raised the exchangeable concentration from 1203 to 1379 (mg kg⁻¹), respectively.

The pH value of the tested soil greatly increased with the addition rates of both biochars (Figure 3a). Soil added with LB had pH values ranging from 4.52 to 4.83 and that added with CB ranged from 4.55 to 5.10 associated with biochar rates of 0% and 6%, respectively. The coconut biochar significantly elevated soil pH more than longan biochar. The SO₄²⁻ concentration of soil was significantly affected by biochar addition (Figure 3b). An increase in biochar rate resulted in a reduction of the SO₄²⁻ concentration, which ranged from 9.48 in the zero-biochar treatment to 7.97 and 8.08 (mg kg⁻¹) in the 6% LB and

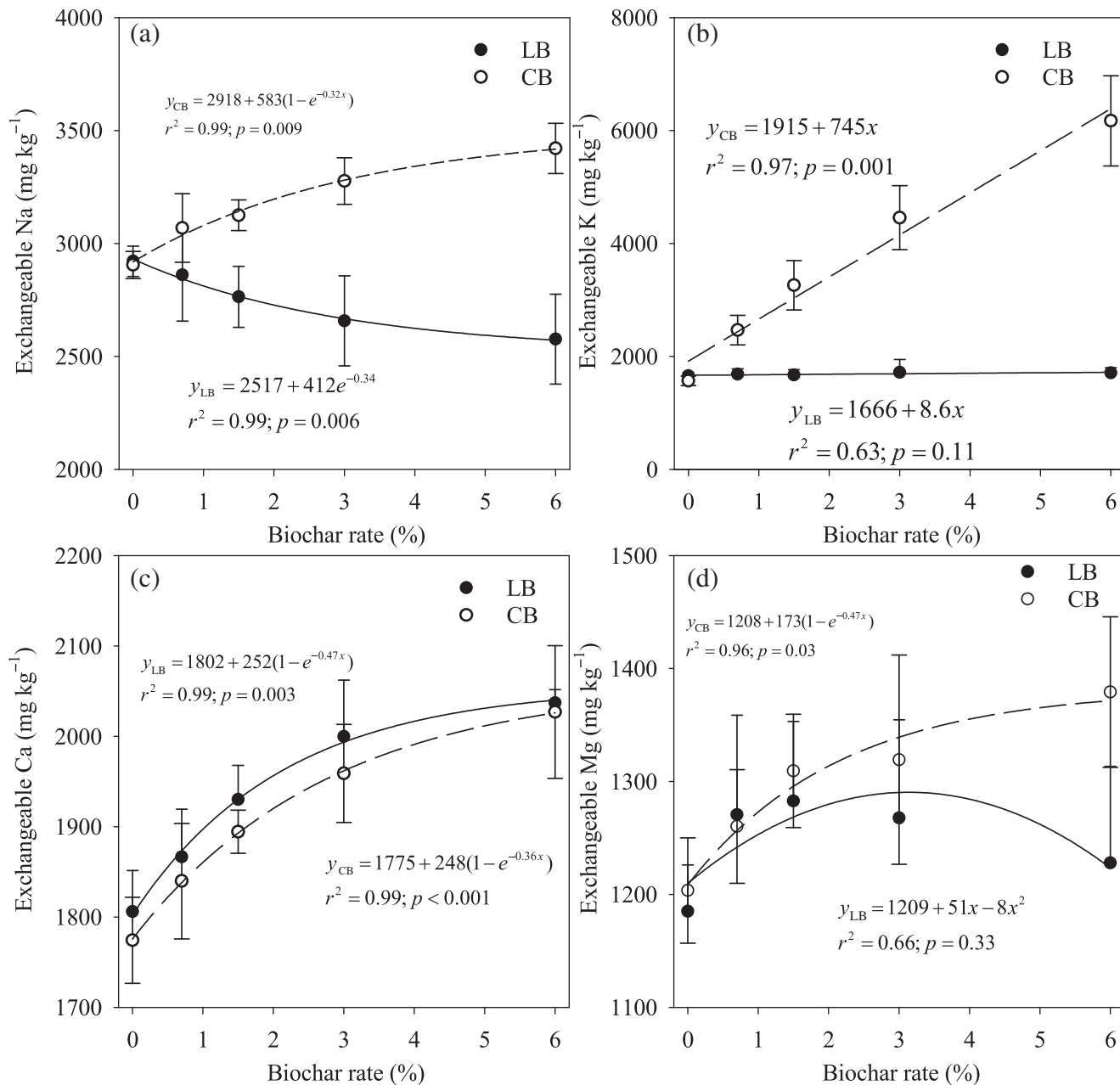


FIGURE 2 Change in the concentration of exchangeable Na (a), K (b), Ca (c), and Mg (d) of biochar-added soil over the biochar rates. Error bars indicate the standard deviation of the mean. CB, coconut coir biochar; LB, longan biochar. $p < 0.05$ indicates the relationship is statistically significant.

6% CB treatments, respectively. The decrease in the SO_4^{2-} concentration as affected by biochar addition followed an exponential decay model.

The concentration of exchangeable Al and Fe significantly declined with an increase in the addition rate of both biochars (Figure 4a,b). When the biochar addition rate rose from 0 to around 3%, the exchangeable concentration of these two elements dropped rapidly and then leveled off. Over the range of the biochar rate, the exchangeable Al concentration reduced from 34.6 to 21.5 ($mg\ kg^{-1}$) in the LB-added soil and from 33.2 to 11.9 ($mg\ kg^{-1}$) in the CB-added soil. The LB addition decreased the exchangeable Fe concentration from 98.6 to 74.8 ($mg\ kg^{-1}$), while the CB addition declined the

concentration from 95.1 to 55.6 ($mg\ kg^{-1}$), when the biochar rate increased from zero to 6%, respectively. The CB lowered the concentration of exchangeable Al and Fe more greatly than the LB. The biochar addition had no significant effect on the exchangeable Mn concentration, which varied from 47.0 to 52.9 ($mg\ kg^{-1}$) (Figure 4c).

3.3 | Soil quality index

The whole dataset was divided into two factors, of which factor 1 included five soil parameters of Cl^- , exchangeable Na, K, Mn, and EC, and factor 2 had a strong connection with pH, SO_4^{2-} ,

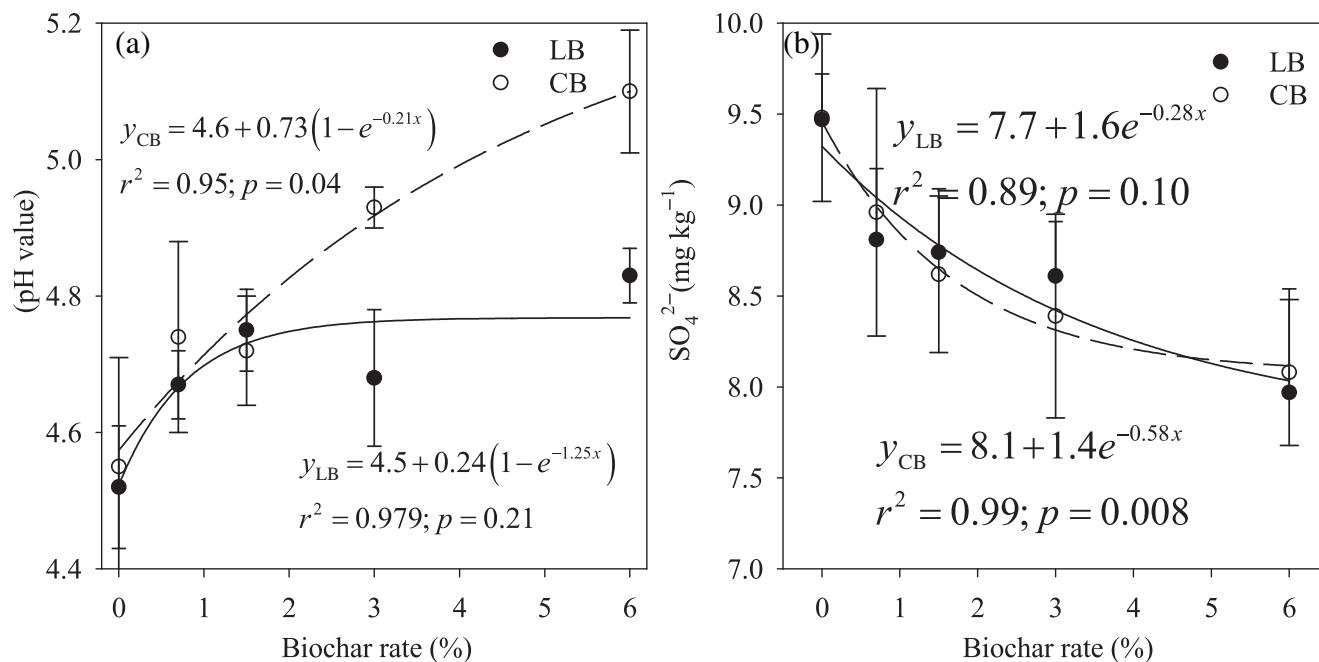


FIGURE 3 Change in the pH (a) value and the SO_4^{2-} (b) concentration of biochar-added soil over the biochar rates. Error bars indicate the standard deviation of the mean. CB, coconut coir biochar; LB, longan biochar. $p < 0.05$ indicates the relationship is statistically significant.

exchangeable Ca, Fe, Al, and Mn (Supplementary Table 1). Factor 1 explained 54.01% of the total variance of the entire dataset, while factor 2 accounted for 22.54%. The two factors together were responsible for 76.55% of the total variance of the 11 soil parameters.

The SQI was computed based on the PCA/FA method and is shown in Figure 5. With an increase in biochar addition rate, the SQI of soil added with the two tested biochars increased exponentially. When the biochar rate rose from 0 to less than 3, the SQI increased rapidly and then leveled off. At the higher biochar rates of 3% and 6%, the SQI of soil added with LB was greater than that added with CB. The SQI was significantly correlated with 11 soil parameters (Supplementary Table 2). The most important soil property in determining the SQI was EC, which explained 27.4% of the total variance in the SQI. Exchangeable Mg, K, and Na were the other three soil properties that explained more than 10% of the total variance in the SQI. The exchangeable Al concentration was the least important soil parameter in explaining the total variance of the SQI. The effects of two biochars on soil properties and quality are summarized and shown in Figure 6. The addition of the two biochar improved the acidity-related features, while CB lowered and LB enhanced the salinity-related features of the tested soil.

4 | DISCUSSION

The PCA/FA showed that 11 soil parameters can be grouped into two factors, which explained 76.55% of the total variance of the whole dataset (Supplementary Table 1). The first and most important factor could be linked to the salinity of the tested soil because factor 1 had

high loading values with Cl^- , EC, and exchangeable Na, K, and Mg. These parameters had a positive loading value with factor 1, indicating that an increase in these parameters may raise the salinity of the tested soil. Coconut biochar significantly increased the EC value while LB did not show the same effect (Figure 1a). The EC value is an important soil property in explaining as much as 27.4% of the total variance of the SQI (Supplementary Table 2). The EC of soil increased from 59.3 (mS m⁻¹) to 69.5 (mS m⁻¹) when adding 3.3% biochar made from rice husk to the soil (Abrishamkesh et al., 2015). In a meta-analysis review, Singh et al. (2022) pointed out that biochar made from wood may not significantly change the EC of tested soils, whereas that produced from herbaceous residues may significantly increase the EC of tested soils, and the change in EC could also be depending on soil properties. In the current study, longan biochar had a much lower EC value than the tested soil, while CB had a similar EC to the tested soil, responsible for the finding. Similarly, longan biochar contained a significantly lower Cl^- concentration than the tested soil (Table 1), leading to a reduction in the Cl^- concentration of the LB-added soil (Figure 1b). Meanwhile, the addition of CB, which had the greatest Cl^- concentration (Table 1), resulted in a significant increase in Cl^- concentration of the experimental soil (Figure 1b). Likewise, Danish et al. (2015) found that the addition of cotton-sticks-derived biochar to sandy soil significantly enhanced the Cl^- concentration of the soil, which could be due to the higher Cl^- concentration of the tested biochar than the tested soil.

The two biochars exhibited contrastive results in changing the concentration of exchangeable Na, K, and Mg (Figure 2). While CB significantly raised the concentration of exchangeable Na, K, and Mg, the LB did not show the same effect. Because biochar may weakly

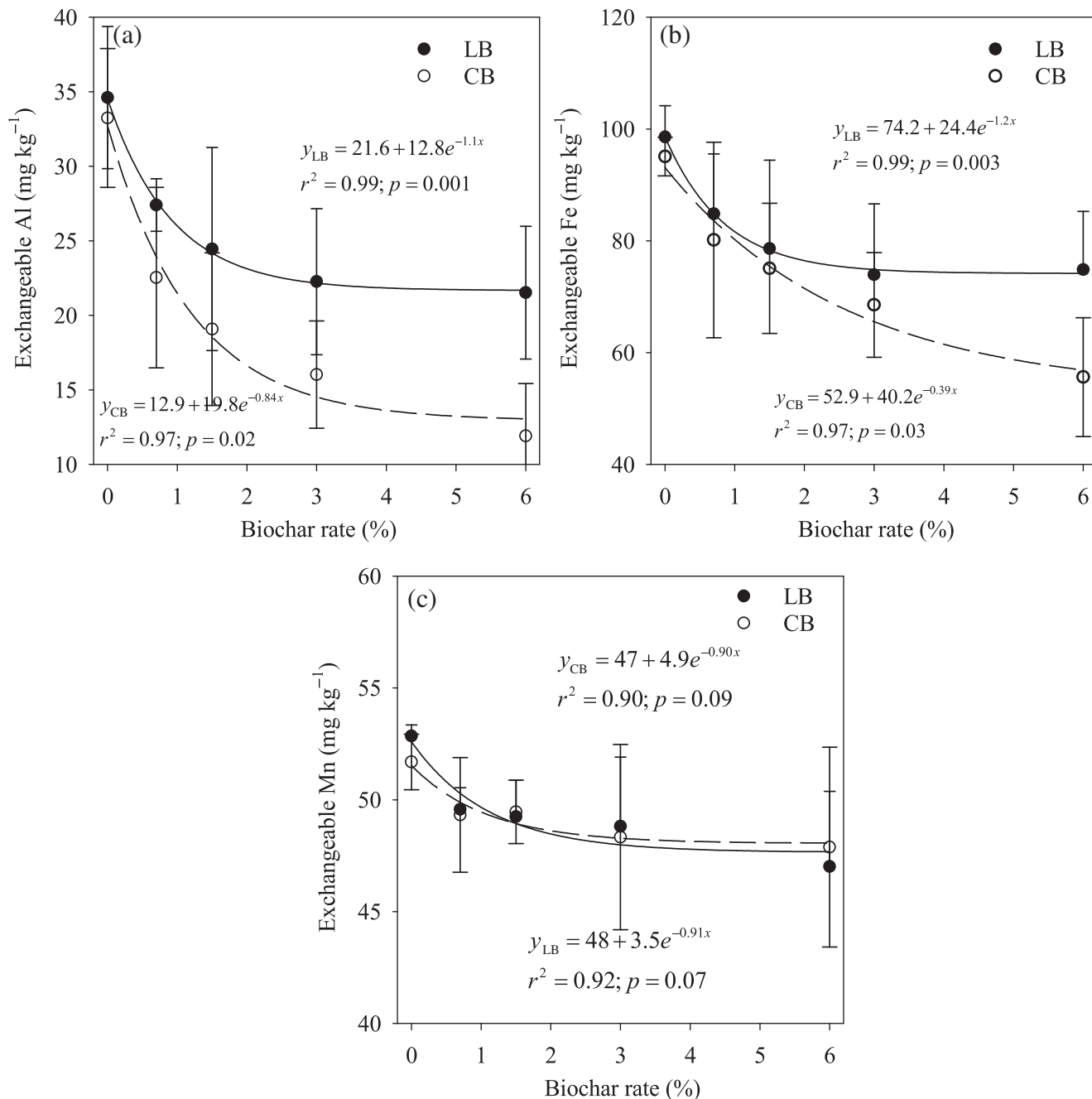


FIGURE 4 Change in the concentration of exchangeable Al (a), Fe (b), and Mn (c) of biochar-added soil over the biochar rates. Error bars indicate the standard deviation of the mean. CB, coconut coir biochar; LB, longan biochar. $p < 0.05$ indicates the relationship is statistically significant.

hold cations via electrostatic forces (Chintala et al., 2014), the cations contained in biochar may be dissolved into the soil solution, elevating their concentration. Nevertheless, the changing magnitude could be determined by the relative concentration of the tested biochars and the tested soil. Coconut biochar had a significantly higher concentration of exchangeable Na, K, and Mg than LB and tested soil (Table 1), resulting in a great enhancement of those elements in the biochar-added soil. With a similar explanation, applying cotton-sticks-derived biochar to sandy soil greatly was found to significantly raise the Na

concentration in the biochar-added soil (Danish et al., 2015). In contrast, a decline in the exchangeable Na concentration of the tested soil added with LB after the experiment in the current study could be attributed to a low concentration of the element in the amendment, relative to the tested soil. Many previous studies also found that biochar addition increased the K concentration in soil (Rasuli et al., 2021; Wang et al., 2018). Especially, the concentration of exchangeable K in the CB-added soil greatly increased compared with the no-biochar-added soil, which could be explained by the high concentration of the

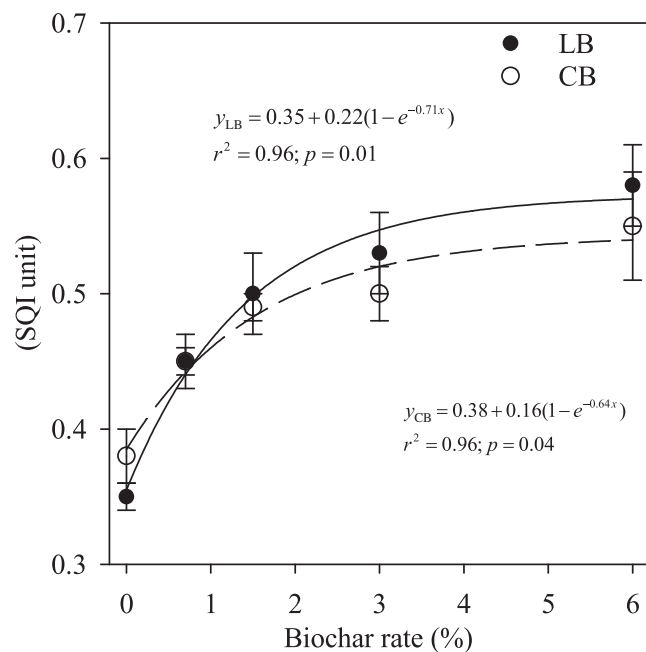


FIGURE 5 The dynamics of soil quality index of saline acid sulfate soil added with two tested biochars over the rate range.

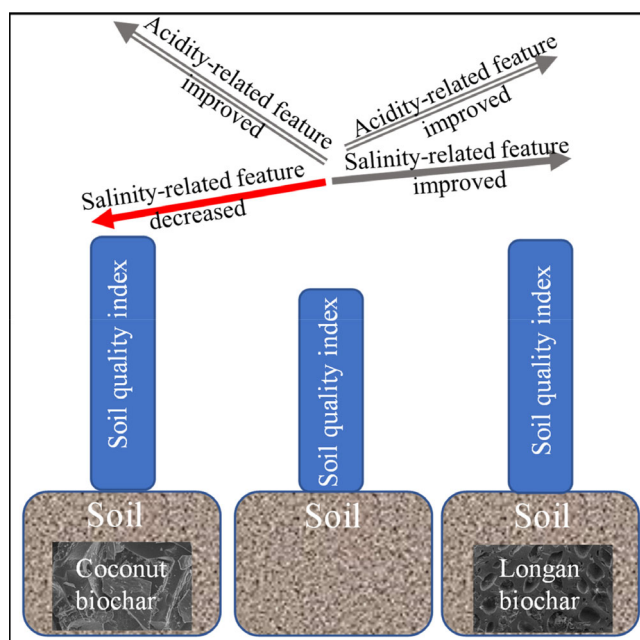


FIGURE 6 Conceptual figure reflecting the effects of two biochars on the properties and quality of saline acid sulfate soil.

element in CB. CB was found to have a great concentration of potassium (Hungwe et al., 2020, 2021), which was also reflected through a great concentration of exchangeable K in the coconut biochar (Table 1). These findings indicate that the initial properties of feedstocks and their consequent biochars are important in determining the properties of the biochar-added soil. For salt-affected soils, biochar made from coconut coir may be ineffective in remediating the

salt-related features of the tested soil, while that made from LB may have positive effects (Figure 6).

The second factor identified through PCA/FA could be involved in the acidity of the tested soil because it had strong correlation coefficients with pH, SO_4^{2-} , and exchangeable Ca, Fe, Al, and Mn (Supplementary Table 1). Both biochars greatly improved the pH of saline acid sulfate soil, which could be attributed to the alkalinity of the amendments (Fidel et al., 2017). The greater pH value of the two biochars (Table 1) may be responsible for the improved pH of the tested soil. When compared with the tested soil, the two biochar had a greatly higher content of alkaline elements, such as K and Ca (Table 1), which could be dissolved into the soil solution to remediate the acidity of the tested soil. The finding is consistent with previous studies, especially in acidic soils (Geng et al., 2022; Nguyen, Dinh, Nguyen, et al., 2022). Nevertheless, Zhang et al. (2019) found in the same study that biochar addition significantly enhanced the pH of acidic soils while decreasing the pH of the black soil and having a neutral effect on the Lou soil. The authors attributed varying effects of biochar to the relative pH values of tested soils and tested biochar. Similarly, the current study found that CB with a higher pH value resulted in a greater pH improvement in the biochar-added soil than LB.

As a result of improved pH due to biochar addition, some potential phytotoxic elements, such as Al and Fe (Figure 4a,b), which are abundant in acid sulfate soils (Manickam et al., 2015; Shamsuddin et al., 2004), may be reduced. The availability of these metals in the soil is greatly dependent on the pH of the surrounding environment (Bojorquez Quintal et al., 2017; Fageria & Nascente, 2014). An increase in soil pH may lead to the fixation and/or precipitation of Al and Fe, resulting in the conversion of these two elements into unexchangeable forms. Additionally, the improved pH caused by biochar addition may lead to an increase in plant-available SO_4^{2-} concentration in the tested soil due to the reduced sulfate adsorption (Martinson & Alveteg, 2004; Zhao et al., 2019). Nonetheless, the current study found that an increase in biochar rate resulted in a reduction of SO_4^{2-} concentration in the biochar-added soil (Figure 3b). Although the real reasons could be unclear, some causes could be linked to the low SO_4^{2-} concentration of biochars compared with the tested soil (Table 1) and the formation of the poorly insoluble compound with Ca (Zhao et al., 2019), which increased following biochar addition (Figure 2c).

The findings and discussion above indicate that the two tested biochars have different effects on the salt-related features and acid-related features of saline acid sulfate soil (Figure 6). CB may not be suitable for ameliorating the salt-related features, but it could be relevant for improving the acid-related features of the tested soil. Meanwhile, longan biochar may be suitable for both features of the tested soil, although its remediation effects on the acid-related feature (pH, exchangeable Fe, and Al) were relatively weaker than those of CB. Consequently, saline acid sulfate soil applied with LB tended to have a better SQI than that applied with CB (Figure 5). This confirms our first hypothesis that the ameliorative effects of biochar on saline acid sulfate soil are dependent on the properties of the amendment.

Although higher biochar rates led to a better SQI, rates of around 2%–3% may be optimal for the remediation of the tested soil. This is because a further significant increase in biochar rate to 6% may produce a relatively small enhancement in SQI, making the significant increment in biochar rate costly for small benefits gained. The findings are consistent with our second hypothesis that the lower biochar rates may lead to rapid improvement in soil quality than the greater biochar rates.

Although two different biochars exhibited different effects on remediating some characteristics of saline acid sulfate soil (Figure 6), the current study was implemented in a greenhouse, which may show some limitations. Biochar may additionally produce a porous soil environment, which may facilitate the leaching of salt- and acid-related elements such as Na, Cl, and SO_4^{2-} (Saifullah et al., 2018). The leaching effect was unable to test in the current study because it is a pot experiment setup without leaching. The current study was established without rice although the soil used was taken from a paddy field, planted with rice. Using agricultural wastes to make biochar, which is then used to remediate saline acid sulfate soil, could provide dual benefits for treated agricultural wastes and remediated soil constraints. These indicate that more studies should be implemented in the fields to validate the findings and test the other feedstocks, which are available in many countries, for sustainable management.

5 | CONCLUSIONS

The current study revealed that adding biochar to saline acid sulfate soil can have positive effects on some soil properties. Specifically, the pH value was found to increase while the concentration of SO_4^{2-} and exchangeable Al and Fe decreased. This could be attributed to the high alkaline properties of the biochar used in the current study. These findings suggest that biochar may strongly ameliorate the acidity-related properties of saline acid sulfate soil. Additionally, biochar raised the exchangeable concentration of some alkaline elements, such as Na, K, and Mg, depending on the properties of the amendment. CB was found to have a stronger effect on these elements than longan biochar, likely due to a higher concentration of these elements contained in the coconut biochar than in the longan biochar. Consequently, the study suggests that the effects of adding biochar to saline acid sulfate soil can vary depending on the properties of the biochar used, with longan biochar having a neutral effect and CB having adverse effects on salinity-related features of the soil. Therefore, while the addition of biochar can improve soil quality overall, its impact on individual soil properties will depend on the specific properties of the biochar used.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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