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ORIGINAL PAPER

The Potential of Biochar to Ameliorate the Major Constraints of Acidic and Salt-Affected Soils

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Abstract

High salinity and severe acidity are the two primary constraints of acidic and salt-affected soil, leading to phytotoxicity of sodium (Na), aluminum (Al), and iron (Fe), as well as phosphorous (P) deficiency. Biochar, having high alkalinity and adsorption capacity, can be a potential bio-amendment to ameliorate these constraints. The current study aimed to assess the impacts of biochar addition on these constraints and the quality of the soil. A pot experiment was set up in a greenhouse using acidic and salt-affected soil mixed with five biochar rates (0 (T1), 2.5 (T2), 5 (T3), 10 (T4), and 20 (%, w/w, T5)); and experimental soil samples were taken on days 5, 15, 30, 60, and 100 to analyze for 11 parameters. The results showed that biochar addition (T5) enhanced electrical conductivity (EC), pH, and the concentration of exchangeable Na and potassium (K) by 24, 90, 13, and 1064 (%), whereas it reduced the concentration of Al and Fe by 93 and 66 (%), as compared to T1. The non-occluded P of the biochar-added soil was raised by 109 (%) in T5, relative to T1. The increased amount of exchangeable Na and K could originate from the added biochar, which may re-absorb Na after 2 months. The reduced magnitude of exchangeable Al and Fe could be involved in the increased pH, leading to the enhanced non-occluded P. In brief, biochar may worsen soil EC but mitigate the acidity-related constraints, leading to an enhancement of soil quality, eventually.

Keywords Acidity · Biochar · Exchangeable concentration · Salt-affected soil · Phosphorous fraction

1 Introduction

In general, the acidic and salt-affected soil had two primary constraints of high salinity and strong acidity, which can lead to unbalanced nutrients, phytotoxicity of aluminum (Al), iron (Fe), sodium (Na), and deficiency of phosphorous (P) (Kamran et al. 2019; Mayakaduwage et al. 2021; Sahab et al. 2021; Tian et al. 2021). Biochar, a carbon-rich substance, having some important features such as high alkalinity and great surface adsorption capacity (Duwiejuah et al. 2020; Shetty and Prakash 2020), can potentially be used as a bio-amendment to ameliorate these soil constraints. Nevertheless, limited studies have been conducted to examine the potential of using biochar to improve the quality of acidic and salt-affected soil.

Salt-affected soil refers to the soil that contains soluble salts sufficient to impair crop productivity. Saline soil, sodic soil, acid sulfate soil, and deteriorated sodic soil are the four main soil groups classified as salt-affected soil (FAO 1988). Salt-affected soil covers a large area, about 400 million ha, equal to 6% of the total world land area (Arora 2017). The

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soils can be formed through various anthropogenic and natural processes (Machado and Serralheiro 2017; Shrivastava and Kumar 2014). The salt-affected soil can be acidified to have a low pH if it is situated over a sulfidic soil layer. The oxidation of sulfides existing in the sulfidic layer can form sulfuric acid (Michael 2013; Shamshuddin et al. 2004), acidifying the salt-affected soils. The acidification may solubilize iron (Fe), aluminum (Al), and some other metals (Shetty et al. 2021), further salinizing the salt-affected soil. Hereafter, the acidic and salt-affected soils are defined as the salt-affected soil low in pH due to the oxidation of sulfides from the sulfidic layer.

Consequently, high salinity and strong acidity of the acidic and salt-affected soil are the two primary constraints, leading to depletion of crop productivities. The former can be considered as a major limiting factor of the salt-affected soil, which induces adverse impacts on plant growth through limited water uptake, toxic effects of ions such as Na^+ and Cl^-, and nutritional imbalance (Kamran et al. 2019; Otlewska et al. 2020; Sahab et al. 2021). The latter can be characterized by low pH, resulting in an elevated concentration of phytotoxic metals such as Al, Fe, and others (Zhang et al. 2020). In addition, phosphorous, an essential macronutrient, can be a limiting factor for crop growth because of its majority bound to oxides or hydroxides of Fe and Al, which are abundant in the acid sulfate soil (Mayakaduwa et al. 2019; Tian et al. 2021). In brief, two primary constraints of the acidic and salt-affected soils may lead to secondary constraints, which are high in electrical conductivity (EC), Na concentration, Al, Fe, and low in pH, and available P. These constraints need to be remediated for better soil quality and subsequent productivity.

With high alkalinity (Fidel et al. 2017), biochar addition was well-reported to raise the soil pH and improve the adverse impacts of Al toxicity (Shi et al. 2019). The addition of biochar was shown to increase the available P of soil (Novak et al. 2018). In acid sulfate soil, biochar was reported to increase the yield of rice and maize crops, mostly due to the improvement of cation exchange capacity (CEC) and reduction of Al stress (Manickam et al. 2015). On the other hand, the addition of biochar to reclaim the adverse impacts of salt-affected soil was studied frequently (Amini et al. 2016; Vasconcelos 2020). Crop productivity of the salt-affected soil can be improved due to the improvement of the physical, chemical, and biological properties of the biochar-added soil (Alkharabsheh et al. 2021; Hammer et al. 2015). Furthermore, Saifullah et al. (2018) demonstrated that biochar addition can reduce the EC of the salt-affected soil by facilitating leaching and adsorption of Na. Nonetheless, Singh et al. (2018) found that adding biochar to the salt-affected soil increased its EC. These indicated that the effects of biochar on the salinity-related properties of the salt-affected soil are inconsistent.

In summary, biochar could be a promising amendment for ameliorating the acidity and salinity of the two soils (acidic soil and salt-affected soil) separately. Nevertheless, few studies have been conducted to simultaneously alleviate the two constraints of the acidic and salt-affected soil. Recently, Gunarathne et al. (2020) used biochar as an organic amendment to reclaim the acidic and salt-affected soil in Sri Lanka. Although the authors pointed out that biochar produced at 500 °C from *Gliricidia Sepium* was a potential amendment for soil reclamation, the authors did not specifically discuss or reach any conclusion about the main constraints of the tested soil. This necessitates more studies to address the knowledge gap. As a result, the current study was conducted to assess the effects of biochar addition on these constraints (salinity and acidity) as well as the quality of acidic and salt-affected soil. It was hypothesized that adding biochar to the acidic and salt-affected soil would improve soil quality through remediating some major constraints such as EC, pH, toxic elements (Na, Al, Fe), and nutrient availability (K and P) of the tested soil.

2 Materials and Methods

2.1 Experimental Materials

The soil used for the current study was taken in Ly Nhon commune, Can Gio District, Ho Chi Minh City, Vietnam at 10° 28′ 39.8″ N 106° 45′ 59.6″ E. The soil is classified as a *Sali Thionic Fluvisols* (WRB 2015) with some main properties shown in Table 1. A total of around 100 kg of surface layer (0–15 cm) soil was collected from 20 points across four rice paddy fields. The bulk 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 the pot experiment.

Biochar was produced from rice straw, which is abundant in Vietnam due to the intensive rice production of the country. Although the rice husk was widely available, the rice straw was chosen because of the higher alkalinity of the rice straw-derived biochar (pH = 9.5) than that of the rice husk-derived biochar (6.31). The rice straw was collected, air-dried, and chopped into 3–5-cm segments before pyrolysis using a method by Nguyen et al. (2018) with some modification. The kiln reactor was constructed from a steel sheet that was rolled into a 0.8 × 1.5-m cylinder (width × height). The biochar was characterized and its properties were shown in Table 1.

2.2 Experimental Setup

The sieved soil was mixed with the biochar at five different rates: 0.0, 2.5, 5.0, 10, and 20% (w/w). Each of these mixtures was placed in three plastic pots to form soil columns

Table 1 Initial properties of experimental materials. *SE*, standard deviation of the mean; *wt*, weight; (*) particle size distribution

Parameters	Unit	Soil		Biochar	
		Mean	SE	Mean	SE
Clay content*	wt%	50.2	0.6		
Silt content*	wt%	22.8	1.2		
Sand content*	wt%	27.0	1.2		
Ash content	wt%			19.10	0.23
Organic carbon	wt%	4.06	0.13	46.1	0.96
Organic P	mg kg^{-1}	414.4	33.2	532.4	67.5
Non-occluded P	mg kg^{-1}	590.8	49.0	5301.0	332.4
Total P	wt%	0.23	0.01	1.13	0.04
Cl^-	mg kg^{-1}	32,857	3796	10,871	753
SO_4^{2-}	mg kg^{-1}	5336	1748	0	0
pH		4.25	0.10	9.48	0.02
EC	dS m^{-1}	6.70	0.28	3.79	0.17
Exchangeable Al	mg kg^{-1}	89.8	4.5	12.3	1.1
Exchangeable Ca	mg kg^{-1}	860.9	3.2	731.7	27.9
Exchangeable Fe	mg kg^{-1}	18.1	0.9	5.8	1.4
Exchangeable K	mg kg^{-1}	252.4	2.1	13,988.2	289.0
Exchangeable Mg	mg kg^{-1}	587.7	6.4	404.0	45.4
Exchangeable Mn	mg kg^{-1}	23.3	0.3	5.0	1.0
Exchangeable Na	mg kg^{-1}	5864.3	8.6	3945.8	219.2
K:Na ratio		0.043	0.0003	3.56	0.13

about 15 cm tall. The 15 soil pots (5 biochar rates × 3 replicates) were randomly arranged in a greenhouse to establish the pot experiment, which was set up as a completely randomized design with 3 replicates. To start the experiment, the soil in individual pots was watered to around 3–5 cm above the soil surface with tap water. The same water level was maintained throughout the experiment by adding tap water to simulate the real conditions of flooded rice fields.

2.3 Sampling and Chemical Analysis

Soil samples were taken from individual pots on days 5, 15, 30, 60, and 100 after the experiment began using a stainless-steel sampler. Sampling was carried out by inserting the sampler down to the bottom of individual pots, and six samplings were taken to obtain enough soil for chemical analysis. The taken soil was air-dried, ground to pass through a 2-mm sieve, and stored until analysis. Furthermore, the soil and biochar before the experiment were sub-sampled in three replicates for analyses the same as the soil throughout the experiment.

All the soil samples and biochar samples were analyzed for pH, EC, and the concentration of exchangeable Al, Ca, Fe, K, Mg, Mn, Na, and P fractions. These materials were added with distilled water in a 1:5 (w/w) ratio, and the extracts were measured for pH and EC using a pH meter and an EC meter, respectively. The concentrations of exchangeable cations were determined using the barium chloride method (Carter and Gregorich 2008), and the extract was quantified using inductively coupled plasma-optical emission spectrometry (ICP-OES). The P fractions were determined using the sequential extraction method by Chen et al. (2015). The non-occluded P was calculated as the total of inorganic P extracted using NH_4Cl, NH_4F, and NaOH-I solutions. The organic fraction was composed of organic P extracted using NH_4F, NaOH-I, and NaOH-II solutions (Chen et al. 2015). Furthermore, the before-experiment soil and biochar were analyzed for organic carbon content using the Walkley–Black method (for soil samples) and the dry combustion method (for biochar samples) with an elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany), chloride using the titration method (Hajrasuliha et al. 1991), and SO_4^{2-} using the turbidimetric method (Rice et al. 2017). In addition, the particle size distribution of the pre-experiment soil was determined (Carter and Gregorich 2008), and the ash content of the pre-experiment biochar was measured using the combustion method at 550 °C.

2.4 Statistical Analyses

All experimental data were statistically analyzed using one-way analysis of variance (ANOVA) for a completely randomized design with three replicates. A simple linear regression analysis was performed to examine the inter-relationships between the measured soil properties (Supplementary Table 1). Additionally, the soil quality index (SQI) was computed based on the principal component analysis/factor analysis (PCA/FA) approach (Mukherjee and Lal 2014) using Eq. 1 (Eq. 1).

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

where n denoted the number of soil parameters; w_i was the weightage of the ith parameter, and s_i was the score of the ith parameter. The w_i was calculated using the result from PCA/FA, and s_i was determined through Eqs. 2 and 3. The eleven soil parameters measured were divided into two groups of "more is better" and "less is better." The more-is-better parameters included pH, Ca, K, Mg, organic P, and non-occluded P, whereas the others were the "less-is-better" parameters. For the more-is-better, s_i was determined with the following Eq. 2 (Eq. 2).

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

For the less-is-better parameters, s_i was calculated using the following Eq. 3 (Eq. 3)

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

where x_i, x_{min}, and x_{max} represented 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 attributes and to calculate the weightage (w_i) of individual soil parameters (Table 2). 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 kept for latent factor determination and weightage estimation of soil parameters having a high loading value (> 0.5) with the relevant factor. The factor weightage (FW) was calculated as that $\frac{e_i}{\text{Sum}}$, where e_i was the eigenvalue of factor *i*, and Sum was the total of all eigenvalues retained after PCA/FA. The parameter weightage was computed as that $\frac{FW_i}{\sum_{i=1}^{n} FW_i}$; where FW_i was the factor weightage of *i*th parameter; *n* was the total number of parameters. The computed SQI was also statistically analyzed using the one-way ANOVA procedure.

3 Results

3.1 Dynamics of Salt-Related Properties (EC, Na, K, and K:Na Ratio)

Biochar addition significantly increased the EC value of the examined soil from 1.4 (no-biochar treatment, T1) to 3.9 (dS m^{-1}) (20% biochar treatment, T5) after 5 days and from 4.4 (T1) to 7.3 (dS m^{-1}, T5) after 100 days (Fig. 1a).

Table 2 Loading values of individual soil parameters of two factors from PCA/FA. The bold numbers were greater than 0.5. *PR.weightage*, parameter weightage

Soil parameters	Factor 1	Factor 2	PR.weightage
Organic P	**0.96**	−0.01	0.11
Echangeable Ca	**0.95**	0.18	0.11
Echangeable Fe	**0.76**	**−0.54**	0.11
Echangeable Al	**0.70**	**−0.54**	0.11
Echangeable Mn	**0.60**	**0.59**	0.11
Echangeable Mg	−0.04	**0.84**	0.05
Echangeable K	−0.46	**0.82**	0.05
pH	0.16	**0.77**	0.05
EC	**−0.86**	0.25	0.11
Non-occluded P	**−0.89**	0.17	0.11
Echangeable Na	**−0.79**	−0.21	0.11
Eigenvalue	5.86	2.86	
Percent	53.28	26.04	
Cumulative percentage	53.28	79.32	
Factor weightage	0.67	0.33	

Over the five measurements, soil EC was also raised with biochar rates, with the EC measured on day 100 of T5 being the highest. Biochar significantly raised the concentration of exchangeable Na of the studied soil in the first three measures (Fig. 1b) but decreased its concentration in the final measurement, from 5725 (T1) to 3809 (mg kg^{-1}, T5). Biochar addition greatly increased the exchangeable K concentration by 1.9 to 10.6 times when compared to the non-biochar treatment, depending on biochar rates. The exchangeable K concentration was decreased slightly over the course of the five measurements. The K:Na ratio, which was established to assess the relative role of K and Na concentration, was increased dramatically with biochar rates while it was slightly decreased during the five measurements (Fig. 1d).

3.2 Dynamics of Acidity-Related Properties (pH, Ca, Mg, Al, Fe, Mn)

The pH of the examined soil was increased significantly from 5.1 to 6.2 in the first measurement and from 4.5 to 5.5 in the last measurement from T1 to T5, respectively (Fig. 2a). Over the five measures, the pH of the five treatments was slightly decreased from 5.1 to 4.5 for T1 and from 6.6 to 5.0 for T5 in the first and the last measurements, respectively. While the concentration of exchangeable Ca was declined, that of Mg was increased over the biochar rates and five measurements (Fig. 2b, c). The concentration of exchangeable Al and Fe was declined significantly with biochar rates and with measurements (Fig. 2d, e). The exchangeable Al concentration was dramatically reduced from 68.0 (T1) to 4.8 (mg kg^{-1}, T5) in the first measurement and from 27.6 (T1) to 3.0 (mg kg^{-1}, T5) in the final measurement. The exchangeable Fe concentration fell from 15.8 (T1) to 6.4 (mg kg^{-1}, T5) in the first measurement and from 14.1 (T1) to 2.7 (mg kg^{-1}, T5) in the last measurement. Unlike Al and Fe, the concentration of exchangeable Mn was not significantly changed by the biochar rate but it was slightly decreased across the five measurements, from 15.4 to 6.9 (mg kg^{-1}).

3.3 P Fractions

The concentration of non-occluded P was increased significantly with biochar addition rates and slightly increased during the five measurements, from 593 (T1) to 1500 (mg kg^{-1}, T5) in the first measurement and from 843 (T1) to 1639 (mg kg^{-1}, T5) in the last measurement (Fig. 3a). The absolute concentration of organic P was significantly increased with the biochar rates in all five measurements except for the fourth measurement (Fig. 3b). Consequently, the relative proportion of the non-occluded fraction over total P was increased significantly with biochar rates and

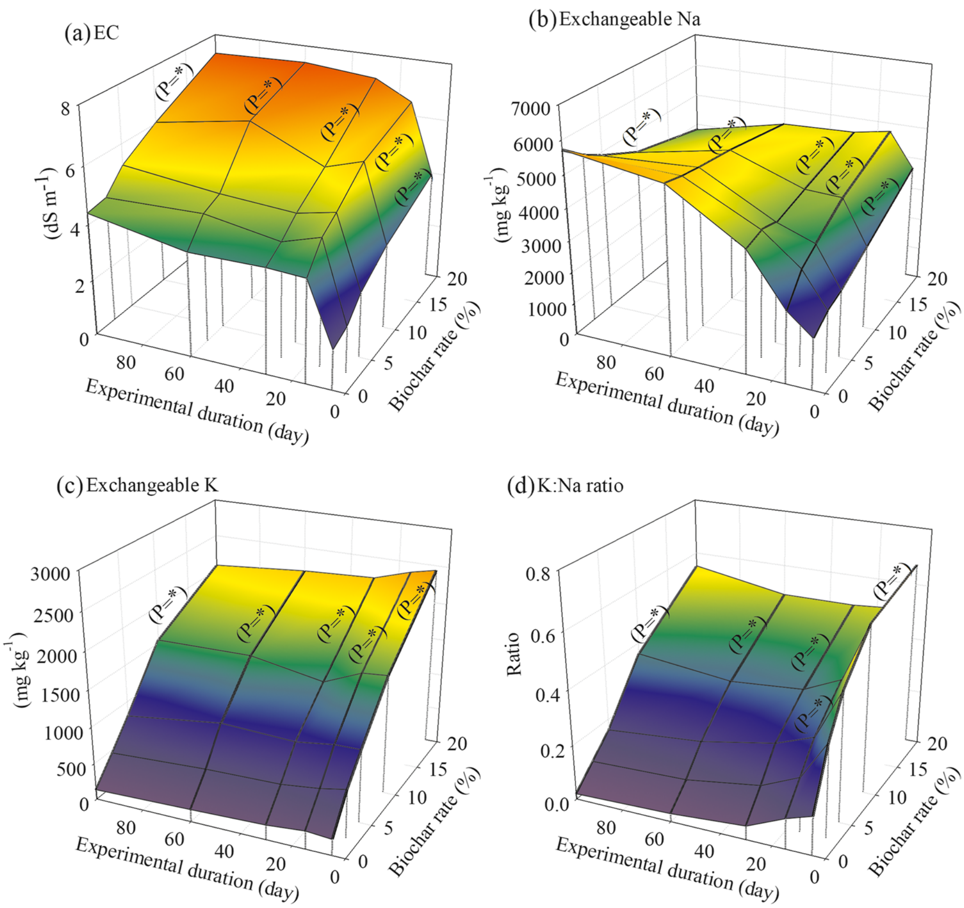

Fig. 1 Dynamics of salt-related parameters (EC, Na, K, and K:Na ratio) of acidic and salt-affected soil over the experimental duration (day) and five biochar application rates. Data from three replicates were averaged for the graph. ($P=*$) indicated that the difference among 5 treatments within one measurement was statistically significant at $P<0.05$

five measurements, ranging from 26 (T1) to 37 (%, T5) in the first measurement and from 33 (T1) to 39 (%, T5) in the last measurement (Fig. 3c). The relative proportion of the organic fraction was decreased significantly with biochar rates and five measurements (Fig. 3d).

3.4 Soil Quality And Assessment of Biochar Effects

Table 2 showed the results of the PCA/FA method, which was used to identify latent factors representative of all measured parameters and to determine the weightage of individual soil characteristics for SQI estimation. The eleven soil parameters were classified into two latent factors, with factor 1 explaining 53.3%, and factor 2 explaining 26% of the total variance of the entire dataset. Factor 1 was highly connected with 8 soil characteristics (organic P, Ca, Fe, Al, Mn, EC, non-occluded P, and Na) and factor 2 was greatly correlated with 6 soil parameters (Fe, Al, Mn, Mg, K, and pH). The SQI was calculated using the weightage of individual parameters (Table 2) and was shown in Fig. 4. The SQI was significantly increased from 0.45 (T1) to 0.82 (T5) in the first measurement and from 0.33 (T1) to 0.60 points (T5) in the last measurement. The index was rapidly declined from the first measurement to the second measurement and slightly decreased from the second measurement to the last measurement. Finally, the impacts of biochar on some major constraints of the tested soil were assessed by plotting EC against pH (Fig. 5a) and the K:Na ratio against the total of the exchangeable Al and Fe concentrations (Fig. 5b). Soil added without biochar was located in the bottom left corner and characterized with higher acidity and lower salinity (Fig. 5a). Soil added with higher biochar rates was located further to the upper right corner, characterized by lower acidity and higher salinity. Soil without biochar had the highest exchangeable Al and Fe content and the lowest K:Na ratio (Fig. 5b). Increased biochar rates decreased the total concentration of the two elements (Al and Fe) while increased the K:Na ratio.

4 Discussion

Two latent factors were identified through the PCA/FA method (Table 2). The first one, which explained 53.28% of the total variance and had a high loading value with EC and Na, could be representative of the salinity feature; and the second one, which explained 26% of the total variance and was well correlated with pH and K, could be a representative

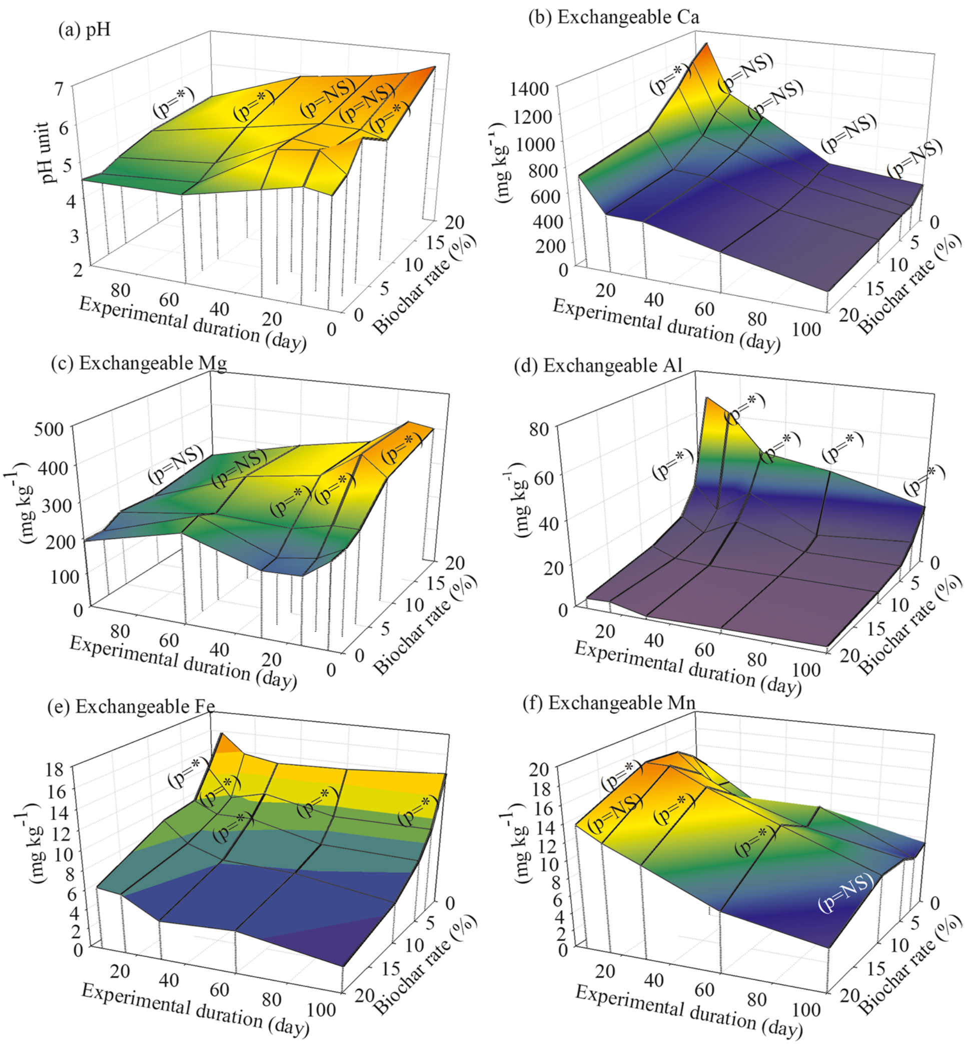

Fig. 2 Dynamics of acidity-related parameters (pH, Ca, Mg, Al, Fe, and Mn) of acidic and salt-affected soil over the experimental duration (day) and five biochar application rates. Data from three replicates were averaged for the graph. ($P=*$) and ($P=$NS) indicated that the difference among 5 treatments within one measurement was statistically significant and not statistically significant at $P<0.05$, respectively

of the acidity feature of the examined soil. These two latent factors reflected the two primary constraints of the acidic and salt-affected soil.

While many studies reported that biochar addition lowered the EC of the salt-affected soils (Hammer et al. 2015; Saifullah et al. 2018), the current study found that biochar addition increased the EC of the acidic and salt-affected soil, which was consistent with another study (Singh et al. 2018). Furthermore, the current study found that the biochar-added soil was significantly enhanced with the exchangeable K concentration. The increased K could be primarily derived from the added biochar, which had the exchangeable K concentration (13,988 mg kg^{-1}), 55 times greater than soil (253 mg kg^{-1}, Table 1). Similarly, the Mehlich K concentration of soil added with biochars made from various feedstocks was significantly higher than that of soil added without biochar, which was attributed to the K released by the added biochar (Novak et al. 2018). The increase in soil EC could be the consequence of the released K and Na from the added biochar, which can be reflected through the correlations between EC with K and Na concentration. For example, the correlation coefficient between EC and K concentration was greater than that between EC and Na concentration (Supplementary Table 1). This could imply that the rise in K concentration of the biochar-added soil could be more important in determining soil salinity and quality than the change in Na concentration.

It was interesting to note that the exchangeable Na concentration was increased with the biochar rates in the first measurement (5 days after the experimental began), from 1616 (T1) to 3670 (mg kg^{-1}, T5), but was decreased in the final measurement (100 days after the experimental began), from 5725 (T1) to 3809 (mg kg^{-1}, T5) (Fig. 1b). Sodium in this system could come from two main sources of the original soil and the added biochar (Table 1). In the first three measurements, the release of biochar-contained Na might enhance the exchangeable Na concentration of the biochar-added soil. Nonetheless, in the final measurement, the exchangeable Na concentration of the T5 (added with 20% biochar) was much higher than that of T1 (no biochar

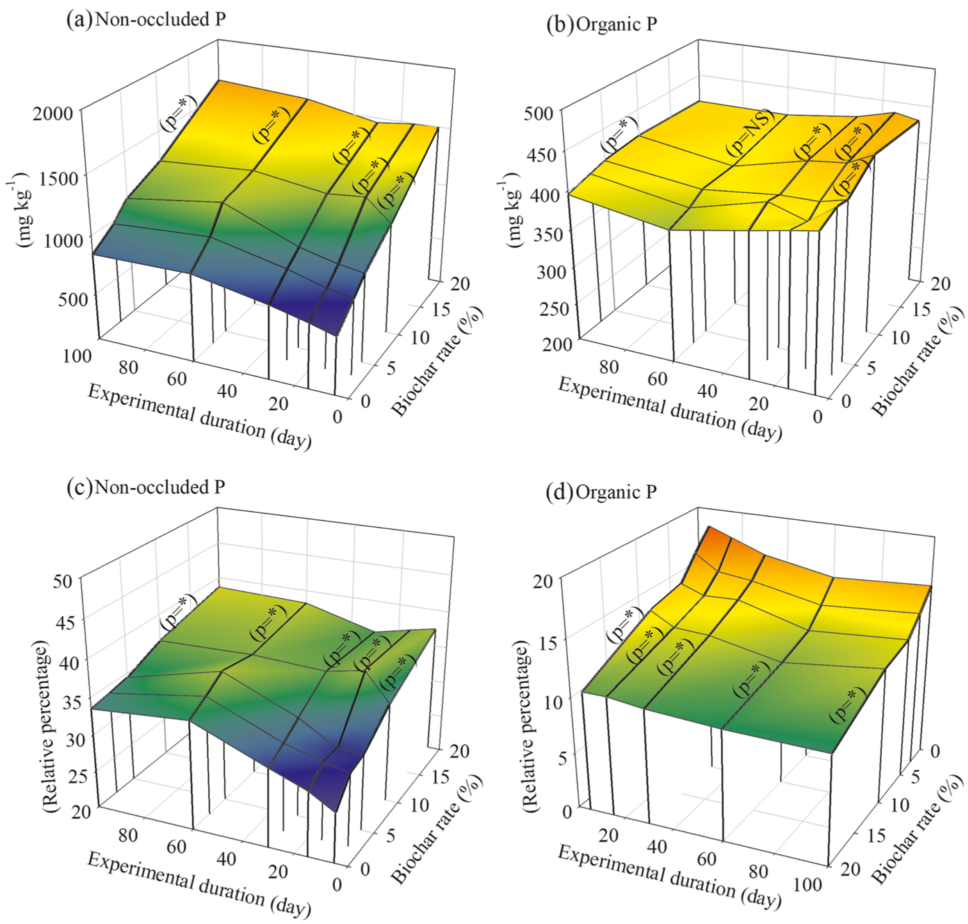

Fig. 3 Dynamics of two P fractions of acidic and salt-affected soil over the experimental duration (day) and five biochar application rates. Data from three replicates were averaged for the graph. ($P=*$) indicated that the difference among 5 treatments within one measurement was statistically significant at $P<0.05$

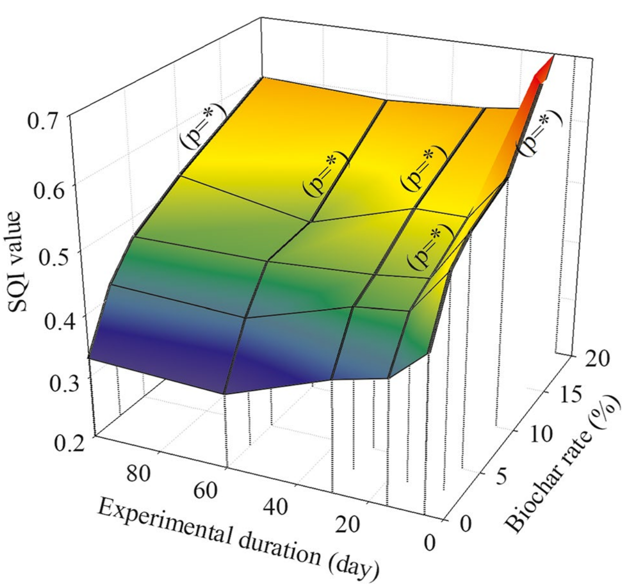

Fig. 4 Dynamics of soil quality index (SQI) over the experimental duration (day) and five biochar application rates. Data from three replicates were averaged for the graph. ($P=*$) indicated that the difference among 5 treatments within one measurement was statistically significant at $P<0.05$

added) (Fig. 1b). This may indicate that the added biochar re-adsorbed Na from the biochar-added soil (Rostamian et al. 2015), lowering the exchangeable Na concentration in the biochar-added soil.

Over the biochar rates, the increased K concentration greater than the changed Na concentration shown by the increased K:Na ratio (Fig. 1d) may be a good indicator of improved soil quality as a result of biochar addition. This is because increasing K concentration may reduce the plant's uptake for Na, a phytotoxic cation that has adverse impacts on plant growth (Wakeel 2013). Additional statistical analysis of the current study data revealed that the K and Na variables accounted for 82% and 11.5% of the total variance of the ratio, respectively. This suggests that the increased K concentration by biochar addition was more important in determining the ratio variation than the change in Na concentration.

The elevated pH of the tested soil (Fig. 2a) was entirely caused by the addition of alkaline cations (K and Na) from the added biochar. The significant and positive correlation between K concentration and pH (Supplementary Table 1) may imply that the additional K from the added biochar played an important role in enhancing soil pH. Nevertheless, the unusually negative correlation between Na concentration

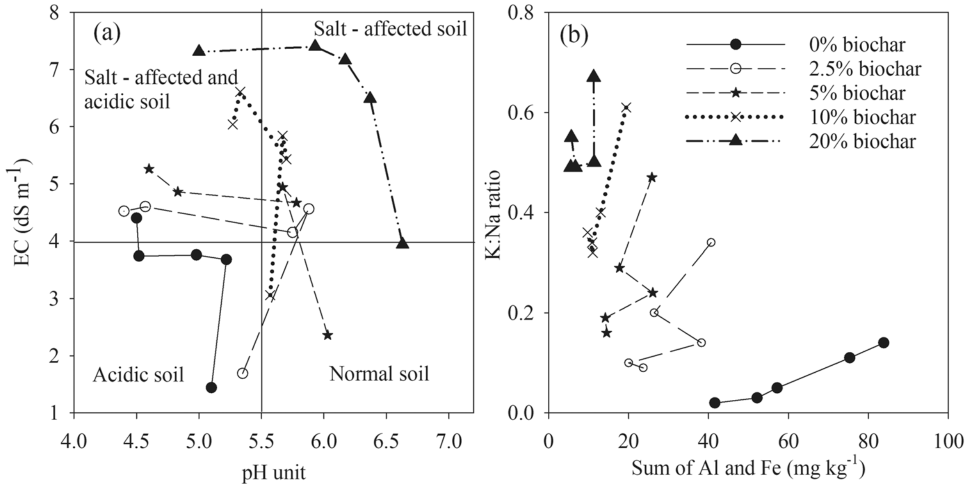

Fig. 5 The diagram of EC vs pH (**a**) and the sum of Al and Fe vs K:Na ratio (**b**) to assess the effects of biochar application rates on properties of the acidic and salt-affected soil

and pH (Supplementary Table 1) could be attributed to Na re-adsorption on biochar in the last two measurements, as explained in the preceding section. These could indicate that the increase in K concentration caused by biochar addition was the primary explanation for the elevated soil pH while the change in Na concentration played a minor impact.

Furthermore, the increased soil pH can be explained by the change in Ca concentration, which had a strong and positive inter-relationship with soil pH (Supplementary Table 1). Nonetheless, the reduction of Ca concentration by biochar addition (Fig. 2b) was an important and interesting finding in the current study. A similar finding was reported by Miranda et al. (2017), attributing the reduction to the leaching of the element after translocation from the exchange sites to the soil solution. This mechanism may not be present in the current study, which was conducted in plastic pots protected from leaching. The current study also found that the mineral fraction of P bound with Ca was increased with biochar rates (data not shown). This may suggest that precipitation of calcium with phosphorous (Cerozi and Fitzsimmons 2016; Karunanithi et al. 2016) could be a possible mechanism responsible for the reduction of exchangeable Ca.

Al and Fe, which are typically abundant in the acid sulfate soils (Manickam et al. 2015; Shamshuddin et al. 2004), can be toxic to plants. The exchangeable concentration of the two elements in the soil was significantly declined with an increase in biochar addition rates (Fig. 2d, e), indicating that biochar could be a suitable amendment to alleviate these soil constraints. The increased soil pH (Fig. 2a) could be the main cause of the reduction reported by other authors (Jha et al. 2016; Sanchez 2019). Moreover, the non-occluded P composed of soluble P, Al-bound P, and Fe-bound P rose dramatically with biochar rates (Fig. 3a, c), suggesting that the reduction of the exchangeable Al and Fe concentration could be additionally involved in soil P transformation under the influence of the biochar addition. A negative and significant relationship between the non-occluded P fraction and Al and Fe concentration (Supplementary Table 1) could be considered as an indicator of P binding to reduce the exchangeable fraction of the two metals. Different from these two elements, Mn concentration was slightly affected by biochar addition rates (Fig. 2f), indicating that the changed pH had a minor influence on the Mn exchangeability. In addition, the weak relationship between the Mn concentration and non-occluded P fraction (Supplementary Table 1) may suggest that the Mn proportion bound to P may be minor that was similarly reported by Pedas et al. (2011).

The current study found that biochar addition greatly raised the fraction of non-occluded P (Fig. 3a), which may be explained by three seasons. The first one could be related to the amount of P in the added biochar. The total P and the non-occluded P fraction of biochar (1.13% and 5301 mg kg^{-1}) were higher than those of the examined soil (0.23% and 591 mg kg^{-1}, respectively) (Table 1), leading to a higher non-occluded P fraction of the biochar-added soil than the non-biochar added soil. A similar finding was reported by Novak et al. (2018) who found that the concentration of total P in biochar greater than that in their tested soils led to an increase in the Mehlich-P concentration of the biochar-added soil. The second reason could be involved in Al and Fe fixation varying with pH. The significant and positive inter-relationship between soil pH and the non-occluded P concentration (Supplementary Table 1) could indicate that the increased soil pH could enhance this P fraction, which is composed of three inorganic forms of soluble P, Al-P, and Fe–P, sequentially extracted by NH_4Cl, NH_4F, and NaOH solution (Chen et al. 2015). The elevated pH caused by biochar addition can immobilize Al and Fe as oxides or hydroxides, providing a background for temporarily adsorbing P to form Al-P and Fe–P. The final reason could be connected to organic matter decomposition, which could be influenced by biochar addition (Minamino et al. 2019; Wang et al. 2015).

The fraction of non-occluded P comprised soluble P as well as P associated with Al and Fe oxides and hydroxides (Kwesi 2020; Schubert et al. 2020), which might be considered as a possible source of plant-available P, depending on the plant type (Schubert et al. 2020). The enhancement of this P fraction by biochar addition was also reported from a 5-year field experiment (Cao et al. 2021). These may suggest that biochar can be used as an organic amendment to ameliorate the P deficiency of acidic soils.

Biochar addition reduced the exchangeable form of two phytotoxic metals, Al and Fe, while increasing the K:Na ratio (Fig. 5b). The decline in the exchangeable form of the two metals may create a healthier environment for plant growth. The improved K:Na ratio may provide the plant more opportunities to take up K while restricting Na uptake, thereby ameliorating the adverse impacts of ionic Na (Munir et al. 2019). Furthermore, the increased ratio was found to enhance plant-available water and subsequently improve maize growth (Farahani et al. 2020). To improve the examined soils even further, the added biochar should be washed out to remove the salts contained in the material before application. Moreover, the current study was conducted in a greenhouse and leaching did not happen. This may restrict salt leaching from the biochar-added soil, alleviating the impacts of biochar, compared to the on-field application.

The current study used a very high biochar rate (20%) equal to 240 (tone ha^{-1}) (assuming bulk density equal 1.2 (gram cm^{-3}) and 10-cm soil depth) to test its effects, which can be impractical or uneconomic. The biochar rate of 2.5% (equivalent to 30 tones ha^{-1}) or less may be economically feasible which was applied in many studies (El-Naggar et al. 2019; Joseph et al. 2021). We used the highest biochar rate to examine the extreme effects of the material on this typical soil, having a lot of agronomic constraints. The addition of biochar to the acidic and salt-affected soil resulted in two different consequences, which were a reduction of soil acidity (improved pH) and an increase of soil salinity (increased EC) (Fig. 5a). The highest biochar rate (20% biochar) significantly increased soil EC and pH, bringing the soil to the salt-affected soil-classified zone (Fig. 5a). Of the five treatments, the one added with 2.5% biochar was seen to be optimal as the treatment can balance the soil's two opposite tendencies of increased salinity and declined acidity. The additional benefits of this treatment may include a declined concentration of exchangeable Al and Fe and an increased K:Na ratio in return for the greater EC.

Finally, biochar addition significantly increased SQI typically during the first few weeks from its application (Fig. 4). Other studies reported similar findings on different soils (Mensah and Frimpong 2018; Oladele 2019). The current study measured main characteristics indicative of the acidic and salt-affected soil, such as EC, pH, Na, K, Ca, Mg, Al, Fe, Mn, organic P, and non-occluded P, and used them for SQI estimation to test the biochar's effects. Following biochar addition, some parameters got worse, such as EC and Na, but the others got better, such as pH, Al, Fe, and non-occluded P. Although SQI can be computed using many soil properties, such as physical, chemical, and biological properties that vary with studies and soil types (Mukherjee and Lal 2014), the current study used a set of the above parameters to emphasize on the two main constraints (strong acidity and high salinity) of the acidic and salt-affected soil. More studies focusing on various soil properties and on-field setup using the 2.5% biochar treatment should be implemented to test the comprehensive impacts of biochar on this problematic soil.

5 Conclusions

The examined soils have two major constraints, which were strong acidity (reflected by low soil pH) and high salinity (reflected by great soil electrical conductivity, EC), which can restrict crop productivity. Biochar addition can raise the pH and EC of the examined soil. The concentration of exchangeable sodium (Na) and potassium (K) was significantly increased whereas that of aluminum (Al) and iron (Fe) was decreased with biochar rates and with the experimental duration of 100 days. The increased concentration of Na and K could originate from the added biochar, while the reduced magnitude of exchangeable Al and Fe could be involved in their immobilization due to the increased soil pH. The added biochar may re-adsorb Na to reduce its exchangeable fraction in the examined soil after several months. The absolute concentration of non-occluded P (total inorganic P extracted using NH_4Cl, NH_4F, and NaOH-I solutions) was significantly improved with biochar rates, while that of the organic P (total organic P extracted from NH_4F, NaOH-I, and NaOH-II solutions) was slightly changed. The increased magnitude of non-occluded P could be related to Al and Fe immobility, as well as a considerable amount of P in the added biochar. Although biochar increased soil EC, the amendment improved the other soil constraints related to the acidity, leading to an enhancement of soil quality, eventually.

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Declarations

Conflict of Interest The authors declare no competing interests.

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