

RESEARCH ARTICLE

Amelioration of salt-affected soil using combined amendments for synergistic effects: Impacts and management implications

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Abstract

Saline acid sulphate soils are commonly ameliorated using traditional amendments like lime and cow manure. Biochar, derived from crop residues, is another potential remedy for this type of soil. Their combined use may create synergistic effects, necessitating further investigation. This study aims to assess the combined impacts of biochar with traditional amendments on soil quality, properties and rice yield. A field experiment was established with six treatments: no-amendment (control), lime, cow manure, biochar, combined lime and biochar, and combined cow manure and biochar with rice (*Oryza sativa*) planted in four replicates. The study revealed that the effects of these amendments on soil properties were driven by their inherent characteristics and secondary processes, such as neutralization. Combining biochar with lime significantly increased soil pH (6.2), and exchangeable calcium ($648.6 \text{ cmol}(+) \text{ kg}^{-1}$), while reducing exchangeable aluminium ($11.83 \text{ cmol}(+) \text{ kg}^{-1}$) and iron ($37.5 \text{ cmol}(+) \text{ kg}^{-1}$), compared to the control. Meanwhile, combining biochar with cow manure notably enhanced Mehlich-1 phosphorous (3.4 mg kg^{-1}), organic carbon (4.99%), ammonium (27.0 mg kg^{-1}) and cation exchange capacity ($17.2 \text{ cmol}(+) \text{ kg}^{-1}$). Biochar combined with cow manure exhibited greater synergetic effects on soil quality than when combined with lime. Consequently, these combinations improved the soil quality index, which exhibited a strong correlation with rice yield and biomass when its value was below 0.4. This finding indicates that these combinations exhibit insignificant synergistic effects on rice yield and growth. Further research is needed to elucidate these findings and explore the optimal application rates concerning soil properties for improved management practices.

KEYWORDS

biochar, cow manure, rice yield, salinity, soil acidity, soil quality

1 | INTRODUCTION

Salt-affected soils are defined as soils with elevated salt levels, which can adversely impact crop growth and yield (FAO, 2023). Notably, salt-affected soils encompass

acid-sulphate soils, which result from the oxidation of pyrite into sulfuric acid (FAO, 1988). Mainly located in coastal regions, acid-sulphate soils may become saline acid-sulphate soils due to seawater intrusion (Morton et al., 2023). These soils are characterized by low pH, high

acidity, excessive salt content, potential toxicity of aluminium (Al) and iron (Fe) and deficiencies in essential nutrients such as phosphorus (P) (Morton et al., 2023; Nguyen, Dinh, et al., 2022; Nguyen & Nguyen, 2023b). Given the increasing global demand for food (van Dijk et al., 2021), it is imperative to reclaim the soil for better agricultural productivity.

Some amendments have been commonly used to reclaim the soils, including lime and animal manure (Farooqi et al., 2023; Islam et al., 2021; Loan et al., 2022). Lime is a traditional amendment with a proven track record in addressing acidic soils (Gomes et al., 2002; Shangguan et al., 2019). Its high alkalinity content can effectively mitigate acidity-related issues, including aluminium (Al) and iron (Fe) toxicity, which are major challenges in saline acid-sulphate soils (Nguyen, Dinh, et al., 2022; Rosilawati et al., 2014). In addition, the soils are deficient in some essential nutrients such as available P, and micronutrients, such as zinc and copper (Sarangi et al., 2022). In response, animal manure is applied to provide nutrients to the soils, leading to improved crop productivity (Kalanaki et al., 2020). However, a potential risk associated with the use of animal manure is the salinization of the treated soils (Li-Xian et al., 2007), exacerbating the challenges posed by saline acid-sulphate soils.

Recently, biochar, a carbon-rich material produced from crop residues, has gained attention for its use in reclaiming salt-affected soils (Amini et al., 2016; Liu et al., 2023). The addition of biochar can offer multiple benefits, including lowered exchangeable Na, increased organic carbon (OC) content, increased soil pH, reduced acidity, and improved soil properties resulting in enhanced crop yields (Knoblauch et al., 2021; Koide et al., 2018; Nguyen et al., 2019; Yang et al., 2020). These findings indicate that biochar, alongside lime and animal manure, can be valuable amendments to ameliorate the constraints of saline acid-sulphate soil, depending on their specific characteristics. These insights lead to our first hypothesis that biochar, lime and cow manure can exert varying effects on the properties and quality of saline acid sulphate soil, driven by their unique characteristics.

Biochar is known for its low nutrient content, especially nitrogen, relative to its high carbon content (Phillips et al., 2022). Consequently, its positive effects on crop yield are amplified when used in conjunction with nitrogen fertilizers (Sun et al., 2023). Meanwhile, animal manure, like cow manure, is commonly rich in nutrients (Almeida et al., 2019). A combination of biochar and cow manure may lead to synergistic effects, the phenomenon where the combined impact of two or more factors is greater than the sum of their individual effects, for remediating the constraints of salt-affected soils. However, leaching salts from the soil is a common method to reclaim salt-affected soils

(Shaygan & Baumgartl, 2022). The effectiveness of this method relies on how water migrates through the topsoil layer, carrying salts downward. Lime, with its great calcium content, competes with H^+ and some toxic elements such as Al and Fe for binding sites in soil components such as organic matter and clay materials. This competition pushes these elements into the soil solution when lime is applied. Meanwhile, biochar, a porous material, can increase porosity and reduce the bulk density of the soil (Singh et al., 2022), promoting salt leaching from saline soil (Xiao & Meng, 2020; Yue et al., 2016). The combined application of lime and biochar can potentially exhibit synergistic effects in ameliorating salinity and mitigating the availability of toxic elements. The synergistic effects can be achieved through the displacement of exchangeable H^+ , Al, and Fe by lime, followed by the subsequent leaching of these displaced elements facilitated by biochar. The above findings indicate that combining biochar with lime or cow manure is a promising strategy for improving soil quality and addressing the challenges of saline acid-sulphate soils. This leads to our second hypothesis that the combination of biochar with lime or cow manure exhibits synergistic effects in enhancing the quality of the saline acid-sulphate soil.

The soil quality typically correlates positively with rice (*Oryza sativa* L.) yield (Liu et al., 2015) but this relationship can vary, depending on the characteristics of the tested soil and amendments (Behera et al., 2012). Enhancing soil quality and properties through the combination of biochar, lime, and cow manure can lead to improved crop yields. For example, combining lime with biochar led to a substantially higher corn yield than single amendments in acid-sulphate soil (Loan et al., 2022). Similarly, the combination of biochar and lime was found to enhance corn yield, relative to sole lime application (Mosharrof et al., 2021). Consequently, our third hypothesis posits that the synergistic effects of combining various soil amendments are evident in enhanced rice yield and growth in saline acid sulphate soil. Therefore, the current study was conducted to assess the combined impacts of biochar with lime or cow manure on quality, properties and rice yield in saline acid sulphate soil.

2 | MATERIALS AND METHODS

2.1 | Study site and experimental materials

The research was conducted on a 500-square-meter area of paddy field located at 10°38'19" N, 106°46'5" E, in Binh Khanh commune, Can Gio District, Ho Chi Minh City, Vietnam. The land falls within a coastal region with a sub-equatorial tropical monsoon climate, characterized by

two distinct seasons: a rainy season spanning from May to October and a dry season extending from November to April of the following year. The average monthly temperatures range from 25°C to 29°C, with the highest recorded at 38.2°C and the lowest at 14.4°C. The soil in the experimental paddy field, which undergoes a rotation of one rice crop and one shrimp crop, falls under the classification of salic thionic fluvisols (WRB, 2015). The biochar used in the current study was produced from rice husk using slow pyrolysis at 400°C a few weeks before the experiment. Other materials, such as cow manure, quick lime and the local rice variety (Ba Bui), were obtained from nearby stores in Binh Khanh commune. Lime was generated by heating limestone at elevated temperatures, converting calcium carbonate into calcium oxide, which has a high level of alkalinity (pH=13). The properties of biochar, cow manure, and the examined soil are shown in Table 1.

2.2 | Experimental setup

Lime and organic manure can be considered as traditional amendments for the reclamation of salt-affected soils because they are commonly used to treat such soils (Shaygan & Baumgartl, 2022). Meanwhile, crop residue-derived biochar has been identified as a promising amendment for mitigating salt-affected soils (Liu et al., 2023). The combination of these two types of soil amendments may yield

synergistic impacts, leading to improved soil quality and enhanced productivity. The current study was set up as a randomized complete block design with two experimental factors and four replicates. Factor 1 was a biochar-related factor, which was applied at two levels of 0 and 10 tons ha⁻¹ (Linh et al., 2023) and factor 2, referred to as the traditional amendment, included no amendment, lime, and cow manure. Lime was applied at 1 ton ha⁻¹ and cow manure was applied at 10 tons ha⁻¹ (Nguyen, Sasaki, et al., 2021). The combination of these two experimental factors resulted in six treatments, which included: no-amendment (control), lime, cow manure, biochar, biochar combined with lime and biochar combined with cow manure. The experiment consisted of 24 experimental plots (six treatments×4 replicates), each having a size of 12 m² (4 m×3 m) (Nguyen, Tran, et al., 2022). Between the field plots, a drainage ditch (about 1 m wide) was built to separate the field plots and serve for rice irrigation. Biochar, lime and cow manure were weighed following the specific treatment requirements, evenly distributed over the experimental plots, and then manually incorporated into the top 15 cm of soil layer. These amendments were applied once at the beginning of the rice crop for a season. The germinated rice grains were directly sown into experimental plots in July 2022. No inorganic fertilizers were utilized in the experiment, and all other agricultural practices, including weeding, pest management, and irrigation, were carried out by the local farmers' traditional methods.

TABLE 1 Some basic properties of the experimental materials (saline acid sulphate soil-SASS, biochar and cow manure).

Soil parameter	Unit	Biochar	Cow manure	SASS
pH	N/A	8.15±0.03	7.11±0.02	4.98±0.03
SO ₄ ²⁻	g kg ⁻¹	5.53±0.21	594.58±42.34	3.18±0.14
Exchangeable acidity	cmole(+) kg ⁻¹	1.38±0.30	5.21±0.11	2.43±0.10
Exchangeable H ⁺	cmole(+) kg ⁻¹	1.17±0.29	3.46±0.09	1.76±0.16
EC	dS m ⁻¹	0.40±0.01	1.41±0.03	1.43±0.05
Cl ⁻	g kg ⁻¹	1.52±0.04	5214.79±53.95	0.26±0.02
Mehlich-1 P	mg kg ⁻¹	231.59±8.91	692.63±23.29	5.69±0.31
OC	%	37.83±0.48	34.91±0.66	4.39±0.09
NH ₄ ⁺	g kg ⁻¹	3.57±0.08	145.94±8.33	110.65±17.96
CEC	cmole ⁽⁺⁾ kg ⁻¹	21.38±0.32	36.09±0.70	15.49±0.22
Exchangeable Al	mg kg ⁻¹	20.44±2.03	331.10±12.08	27.16±1.31
Exchangeable Fe	mg kg ⁻¹	49.65±3.13	62.05±2.43	70.19±2.84
Exchangeable Mn	mg kg ⁻¹	64.14±1.05	8890.08±399.6	35.14±1.25
Exchangeable Ca	mg kg ⁻¹	2780.02±86.55	622.66±34.43	572.63±26.02
Exchangeable K	mg kg ⁻¹	11,094.03±94.78	9094.87±152.42	921.54±20.30
Exchangeable Mg	mg kg ⁻¹	447.75±3.23	21.38±3.51	1044.72±32.22
Exchangeable Na	mg kg ⁻¹	1968.30±70.70	934.49±18.27	1598.74±51.84

Note: Data are presented as mean±SE (standard error of the mean) of four replicates.

Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity; OC, organic carbon.

2.3 | Measurements and chemical analysis

At the end of the rice season in December 2022, grain yield, straw, and root in individual basic plots were determined. Rice grain yield was measured over the entire area (12 m²) of each basic plot. Rice straw was collected from four 1-m² frames (1 m × 1 m), which were placed randomly across each field plot after grain harvest. The above-ground biomass within each frame was collected, washed, air-dried, and weighed for assessment. Root biomass from each field plot was obtained using eight 0.04-m² frames (0.2 m × 0.2 m), two of these smaller frames placed within each of the 1-m² frames. Bulk soil was gathered from the top 0.2 cm layer within individual 0.04-m² frames (Chen et al., 2019). The root mass obtained from this bulk soil was carefully washed with tap and distilled water, air-dried and subsequently weighed for assessment. Soil samples were taken from each of the experimental plots at the end of the crop season using a stainless steel sampler for the top 0–20 cm layer (Jayasekara et al., 2022). For each of the 24 experimental plots, 10 sub-soil samples, taken from 10 points randomly distributed over one experimental plot, were mixed well into one composite sample. A total of 24 composite soil samples from 24 experimental plots were air-dried, passed through a 2-mm sieve, and then stored for subsequent chemical analyses. In addition, before the experiment, four composite soil samples were collected from the experimental paddy field, which was divided into four sections. Each section had one composite soil sample collected from ten randomly distributed points.

The four pre-experiment soil samples and the 24 soil samples collected after the experiment were analysed for various parameters, including pH, electrical conductivity (EC), Mehlich-1 phosphorous (P), organic carbon (OC), ammonium (NH₄⁺), chloride (Cl⁻), sulphate (SO₄²⁻), exchangeable acidity, exchangeable hydrogen (H⁺), cation exchange capacity (CEC), exchangeable aluminium (Al), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn) and sodium (Na). These soil properties were selected to be analysed for assessment because they effectively reflect the primary attributive constraints of saline acid sulphate soils, including acidity (pH, SO₄²⁻, exchangeable acidity and exchangeable H⁺), salinity (EC, Cl⁻ and Na⁺) toxicity (Al, Fe and Mn) and nutrient status (Mehlich-1 P, OC, NH₄⁺, CEC, Ca, K and Mg) (Morton et al., 2023; Nguyen, Dinh, et al., 2022; Nguyen & Nguyen, 2023b). To determine pH and EC values, the sieved soil was added with distilled water in a 1:5 (w/w) ratio and the resulting extracts were measured using a pH meter and an EC meter after 1 h of shaking (Carter & Gregorich, 2008). The concentrations of exchangeable

cations were determined using the barium chloride method (Carter & Gregorich, 2008), and the extracts were 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 the level of SO₄²⁻ was determined using the turbidimetric method (Rice et al., 2017). Other parameters, such as Mehlich-1 P, OC, NH₄⁺, exchangeable acidity, exchangeable H⁺ and CEC, were determined using the associated methods described in Chapter III-Soil Chemical Analysis of Soil Sampling and Methods of Analysis book (Carter & Gregorich, 2008).

2.4 | Statistical analyses

All experimental data were subjected to statistical analyses using a two-way analysis of variance (ANOVA) for a randomized complete block design with four replicates. The ANOVA model is represented as $\gamma_{ije} = \mu + \beta_i + \alpha_j + \alpha\beta_{ij} + \varepsilon_{ije}$, where γ_{ije} denotes the response of individual combinations of two experimental factors (biochar and traditional amendment); μ signifies the overall mean of the entire dataset; β_i symbolizes the effect of the *i*th biochar level; α_j embodies the effect of the *j*th traditional amendment treatment; $\alpha\beta_{ij}$ indicates the interaction effect between biochar and traditional amendment; ε_{ije} signifies the random error with a mean of zero and normal distribution (Akhtar & Memon, 2009). When ANOVA results yielded a significant effect with $p \leq .05$, the Tukey's Honest Significant Difference test was employed to categorize mean values.

The soil quality index (SQI) was computed based on the principal component analysis/factor analysis (PCA/FA) approach using Equation (1).

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

where *n* represents the number of soil properties; *w_i* stands for the weightage of the *i*th parameter; and *s_i* represents the score of the *i*th parameter. *w_i* was calculated using the result from PCA/FA, and *s_i* was determined based on the measured data of individual properties after transformation (Nguyen, Le, et al., 2021). PCA/FA was implemented to reduce the multiple dimensions of variation in the data set, which contained numerous interrelated variables, into a few primary dimensions known as latent factors. These latent factors represented the key soil features and were used to calculate the weightage (*w_i*) for individual soil properties (Nguyen, Le, et al., 2021). All 17 measured soil properties were incorporated into the PCA/FA model already built in JMP pro 17 (SAS Institute Inc, North Carolina, USA) to identify

and isolate the latent factors. Factors having an eigenvalue greater than one were retained for weightage estimation of soil parameters, which had a high loading value (>0.5) with the associated factor (Nguyen & Nguyen, 2023b). The estimated factor weights are shown in Table 2 and more details about the PCA/FA method can be found in Mukherjee and Lal (2014). The computed SQI was also subjected to statistical analysis using the same two-way ANOVA procedure as the other soil parameters. The relationship between SQI with rice yield and total biomass was examined using a non-linear exponential-rise-to-maximum model.

3 | RESULTS

3.1 | Properties of the tested soil and amendments

3.1.1 | The properties of the soil and amendments before the experiment

The initial properties of biochar, cow manure and the tested soil are summarized in Table 1. The pH values of

biochar, cow manure and soil were 8.15, 7.11 and 4.98 respectively. The EC values of biochar (0.40 dS m^{-1}) were much lower than those of cow manure (1.41 dS m^{-1}) and the soil (1.43 dS m^{-1}). Cow manure had the highest concentration of Mehlich-1 P ($692.63 \text{ mg kg}^{-1}$), followed by biochar ($231.59 \text{ mg kg}^{-1}$) and the soil (5.69 mg kg^{-1}). The concentrations of OC in biochar and cow manure were similar, varying from 34.91% to 37.83%, which were notably higher than that in the soil, 4.39%. The NH_4^+ concentration varied considerably, with biochar having 3.57 g kg^{-1} , cow manure at 145.94 g kg^{-1} and the soil at 110.65 g kg^{-1} . The SO_4^{2-} concentration in cow manure (594.58 g kg^{-1}) was much higher than that in the other materials (5.53 g kg^{-1} for biochar and 3.18 g kg^{-1} for the tested soil). Cow manure had the highest value of CEC ($36.09 \text{ cmole}(+) \text{ kg}^{-1}$), followed by biochar ($21.38 \text{ cmole}(+) \text{ kg}^{-1}$), and the soil ($15.49 \text{ cmole}(+) \text{ kg}^{-1}$). For the other soil properties, biochar had the highest contents of exchangeable Ca ($2780.02 \text{ mg kg}^{-1}$), exchangeable K ($11,094.03 \text{ mg kg}^{-1}$), and exchangeable Na ($1968.30 \text{ mg kg}^{-1}$), while cow manure exhibited the highest level of exchangeable Al ($331.10 \text{ mg kg}^{-1}$) and exchangeable Mn ($8890.08 \text{ mg kg}^{-1}$). The concentration of exchangeable Fe in the tested soil

TABLE 2 Loading value and weightage of measured parameters estimated using PCA/FA.

Soil parameter	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Weightage of parameters
Exchangeable Fe	0.87	-0.17	0.08	-0.11	-0.02	0.07	0.097
Exchangeable acidity	0.78	0.08	0.31	0.04	-0.01	-0.26	0.097
Exchangeable Al	0.64	-0.64	0.05	-0.02	0.22	-0.10	0.097
Exchangeable Ca	-0.86	0.17	-0.08	0.39	0.02	-0.03	0.097
pH	-0.75	0.20	0.21	-0.37	-0.23	-0.17	0.097
OC	-0.16	0.80	0.16	-0.14	0.26	0.21	0.058
CEC	-0.03	0.79	-0.38	0.10	-0.14	0.17	0.058
Exchangeable K	-0.26	0.75	-0.14	0.04	-0.23	-0.13	0.058
NH_4^+	0.15	0.63	0.55	0.15	0.11	-0.05	0.058
Mehlich-1 P	-0.38	0.54	0.21	0.37	-0.20	0.05	0.058
Cl^-	0.08	-0.08	0.92	-0.01	-0.10	0.07	0.039
Exchangeable H^+	0.08	-0.19	0.59	0.00	0.59	0.19	0.039
Exchangeable Mg	-0.25	-0.01	-0.13	0.88	-0.12	-0.13	0.034
Exchangeable Mn	0.14	0.34	0.48	0.64	0.02	0.02	0.034
Exchangeable Na	0.11	-0.08	0.42	0.51	-0.49	0.26	0.034
SO_4^{2-}	0.08	-0.06	-0.04	-0.09	0.84	-0.01	0.024
EC	-0.03	0.15	0.10	-0.05	0.01	0.93	0.022
Eigenvalue	4.85	2.92	1.97	1.69	1.20	1.08	
Percent	28.51	17.16	11.60	9.97	7.03	6.37	
Cumulative percent	28.51	45.67	57.27	67.23	74.26	80.64	
Factor weightage	0.354	0.213	0.144	0.124	0.087	0.079	

Note: Bold numbers are those having absolute values greater than 0.5.

Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity; OC, organic carbon.

was the highest (70.19 mg kg^{-1}), followed by cow manure (62.05 mg kg^{-1}) and biochar (49.65 mg kg^{-1}).

3.1.2 | Soil properties after the experiment

An interaction between biochar and the traditional amendments was observed in the levels of pH and exchangeable acidity of the tested soil after the experiment (Figure 1a,c). In the two treatments where no traditional amendments (cow manure and lime) were applied, soil added with biochar exhibited a higher pH value (6.04) than that added without biochar (5.24). In the three treatments without biochar, soil added with traditional amendments had higher pH values compared to soil without these additives. Figure 1a also showed that soil applied with either biochar or traditional amendments had considerably higher pH levels than unamended soil after the experiment. Similarly, soil without biochar and no traditional amendment displayed the highest exchangeable acidity ($2.30 \text{ cmol}(+) \text{ kg}^{-1}$), while the soil with lime and no biochar had the lowest exchangeable acidity ($1.44 \text{ cmol}(+) \text{ kg}^{-1}$) (Figure 1c). In the two treatments with cow manure, the soil added with biochar presented much lower

exchangeable acidity ($1.68 \text{ cmol}(+) \text{ kg}^{-1}$) than the soil without biochar ($2.26 \text{ cmol}(+) \text{ kg}^{-1}$). Soil added with biochar and traditional amendments, except for that added with cow manure and no biochar, had a lower exchangeable H^+ concentration than the control (Figure 1d). The biochar and the two traditional amendments did not show significant effects on the levels of SO_4^{2-} (Figure 1b), EC (Figure 1e) and Cl^- (Figure 1f). After the experiment, the tested soil had SO_4^{2-} levels varying from 1.67 to $2.13 \text{ (g kg}^{-1})$, EC values between 1.02 to $1.11 \text{ (dS m}^{-1})$ and Cl^- concentrations ranging from 1.27 to $1.39 \text{ (g kg}^{-1})$.

Biochar addition showed no significant effect on the Mehlich-1 P concentration, while traditional amendments exhibited great influences on the level of this soil parameter (Figure 2a). On average, the two treatments without traditional amendment showed the lowest Mehlich-1 P concentration, averaging 2.42 mg kg^{-1} , while the two treatments with added cow manure showed the highest Mehlich-1 P concentration, averaging 3.26 mg kg^{-1} . Figure 2b showed that adding biochar to the soil increased the OC concentration of the tested soil, compared to the soil without biochar. Soil treated with both biochar and cow manure showed the highest OC concentration (4.99%), while that with no biochar and no traditional amendment had the

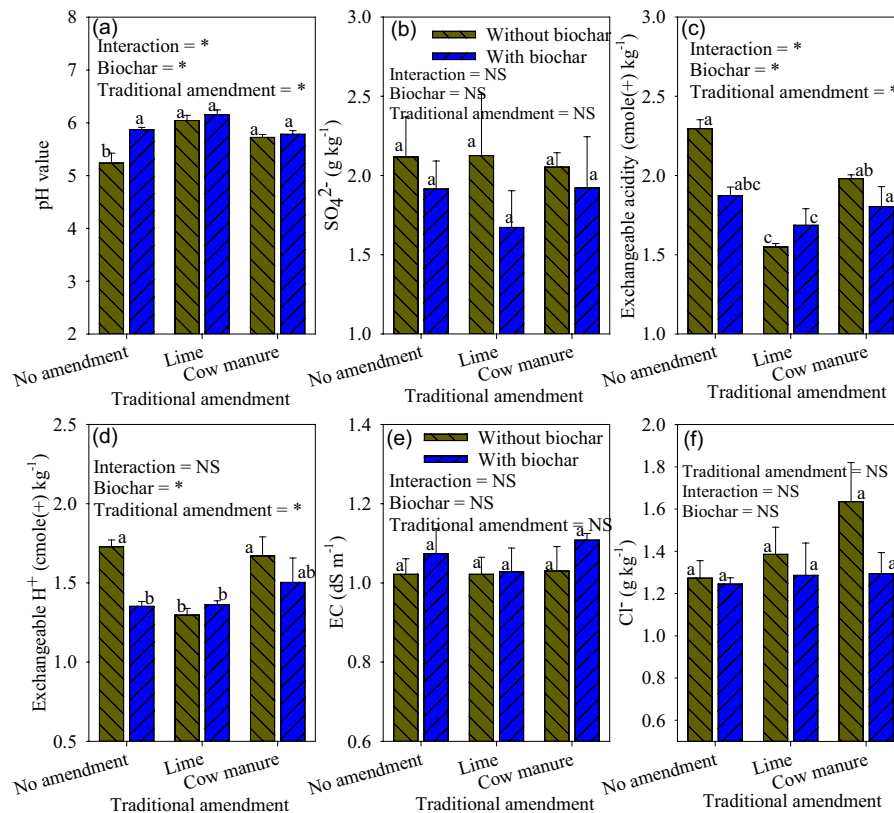


FIGURE 1 The levels of pH (a), SO_4^{2-} (b), exchangeable acidity (c), exchangeable H^+ (d), electrical conductivity (EC, e) and Cl^- (f) in the soil after the experiment as affected by two experimental factors, biochar and traditional soil amendment (lime and cow manure). Error bars indicate the standard error of the mean calculated from four replicates. * and NS indicate the associated effects are statistically significant and insignificant at $p \leq .05$ respectively.

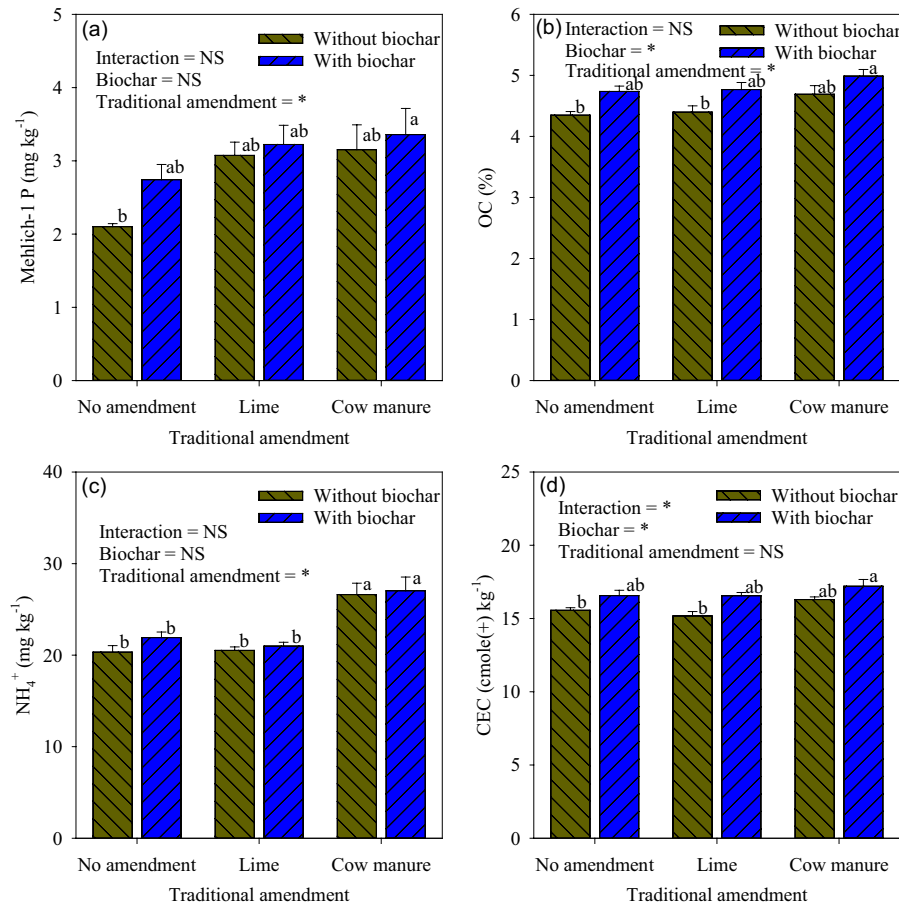


FIGURE 2 The levels of Mehlich-1 P (a), organic carbon (OC, b), NH_4^+ (c) and CEC (cation exchange capacity, d) in the soil after the experiment as affected by two experimental factors, biochar and traditional soil amendment (lime and cow manure). Error bars indicate the standard error of the mean calculated from four replicates. * and NS indicate the associated effects are statistically significant and insignificant at $p \leq 0.05$ respectively.

lowest OC concentration (4.35%). The concentration of NH_4^+ in the soils was greatly affected by the traditional amendment, but not by the biochar (Figure 2c). The two treatments with cow manure showed the greatest NH_4^+ concentration (26.8 mg kg⁻¹), while the other four treatments had lower NH_4^+ concentration, varying from 20.3 to 21.9 (mg kg⁻¹). CEC value was strongly influenced by the interaction between biochar and traditional amendments (Figure 2d). The treatment of biochar combined with cow manure resulted in the highest CEC level (17.21 cmol(+) kg⁻¹), and the treatment of lime alone led to the lowest CEC value (15.18 cmol(+) kg⁻¹).

The concentrations of exchangeable Al and Fe were notably influenced by the addition of biochar and the traditional amendments (Figure 3a). Soil without biochar and no traditional amendment had the highest exchangeable Al concentration (19.44 mg kg⁻¹), while soil treated with both biochar and lime or cow manure exhibited the lowest exchangeable Al concentration (11.8 and 11.7 mg kg⁻¹ respectively). The two treatments with lime exhibited the lowest levels of exchangeable Fe, with values of 48.01

and 37.54 mg kg⁻¹, while the two treatments without traditional amendment had the highest concentrations of this soil parameter, ranging from 70.19 to 66.61 mg kg⁻¹. Biochar addition strongly lowered the exchangeable Fe concentration of the tested soil, compared to the no biochar treatment. On average, the three no-biochar treatments had an exchangeable Fe concentration of 60.90 (mg kg⁻¹), while the three biochar-added treatments showed a concentration of 51.65 (mg kg⁻¹). The addition of biochar and traditional amendment had no significant effect on the exchangeable Mn concentration, which varied from 28.38 to 30.24 (mg kg⁻¹) (Figure 3c).

Overall, biochar addition greatly increased the concentration of exchangeable Ca (Figure 4a) and K (Figure 4b), compared to soil added with no biochar. The exchangeable Ca concentration increased from 543.18 (mg kg⁻¹) in the control treatment to 559.46 (mg kg⁻¹) in the treatment with no traditional amendment but with biochar. In the two treatments with lime, the exchangeable Ca concentration increased from 639.9 (mg kg⁻¹) when applied without biochar to 648.6 (mg kg⁻¹) when combined with biochar.

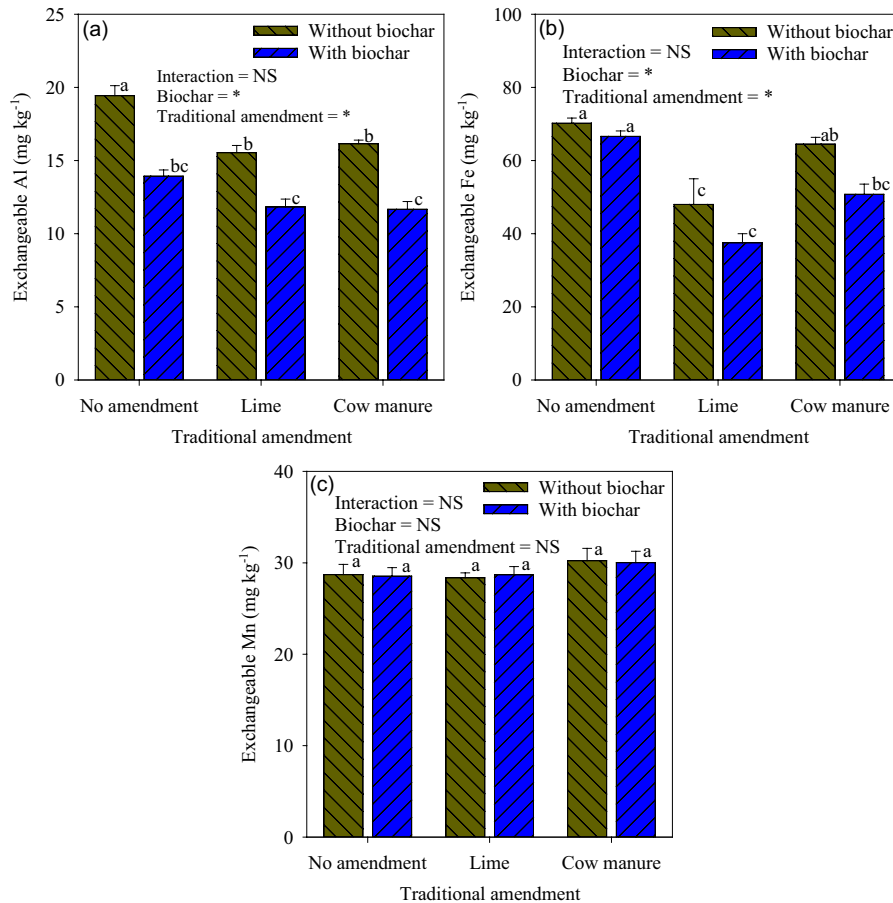


FIGURE 3 The levels of exchangeable Al (a), Fe (b) and Mn (c) in the soil after the experiment as affected by two experimental factors, biochar and traditional soil amendment (lime and cow manure). Error bars indicate the standard error of the mean calculated from four replicates. * and NS indicate the associated effects are statistically significant and insignificant at $p \leq .05$ respectively.

Particularly, in the two treatments with cow manure, the addition of biochar strongly increased this soil parameter from 550.6 to 646.0 (mg kg^{-1}). The exchangeable Ca concentrations were the highest in the two treatments with the lime application (averaged 644.2 mg kg^{-1}), but the lowest in the two treatments without traditional amendment (averaged 551.3 mg kg^{-1}). Similarly, the exchangeable K concentration increased from 726.64 to 885.76 (mg kg^{-1}) in the two treatments without traditional amendments, from 761.51 to 898.89 (mg kg^{-1}) in the two treatments with lime, and from 791.19 to 936.41 (mg kg^{-1}) in the two treatments with cow manure if the soil added without and with biochar respectively. Both biochar and traditional amendments had no considerable effects on the levels of exchangeable Mg, varying from 834.8 to 909.0 (mg kg^{-1}) (Figure 4c), and exchangeable Na, ranging from 1818 to 1918 (mg kg^{-1}) (Figure 4d).

3.2 | Rice growth and yield

The addition of three soil amendments alone exhibited statistically similar root weights compared to the control

treatment (Figure 5a). The three treatments without biochar had root weights varying from 0.09 to 0.10 kg m^{-2} , while the other three treatments with biochar exhibited root weights ranging from 0.12 to 0.15 kg m^{-2} . The combination of biochar and the traditional amendments had strong interactive effects on straw weight (Figure 5b), grain weight (Figure 5c) and total biomass of rice (Figure 5d). In the two treatments without any traditional amendment, the addition of biochar led to a great enhancement in straw weight (0.28 kg m^{-2}), grain weight (0.47 kg m^{-2}) and total biomass (0.87 kg m^{-2}), compared to 0.21, 0.36, 0.65 kg m^{-2} , respectively, in treatments without biochar. The application of any amendments resulted in a significant increase in the weight of straw, grain and total biomass, compared to the control treatment. The treatments using only biochar, or only lime, or cow manure resulted in statistically similar outcomes in terms of root weight, grain weight and total biomass of rice. Combining biochar with lime or cow manure also did not significantly enhance straw weight (Figure 5b), grain weight (Figure 5c) and total biomass (Figure 5d), compared to their single applications.

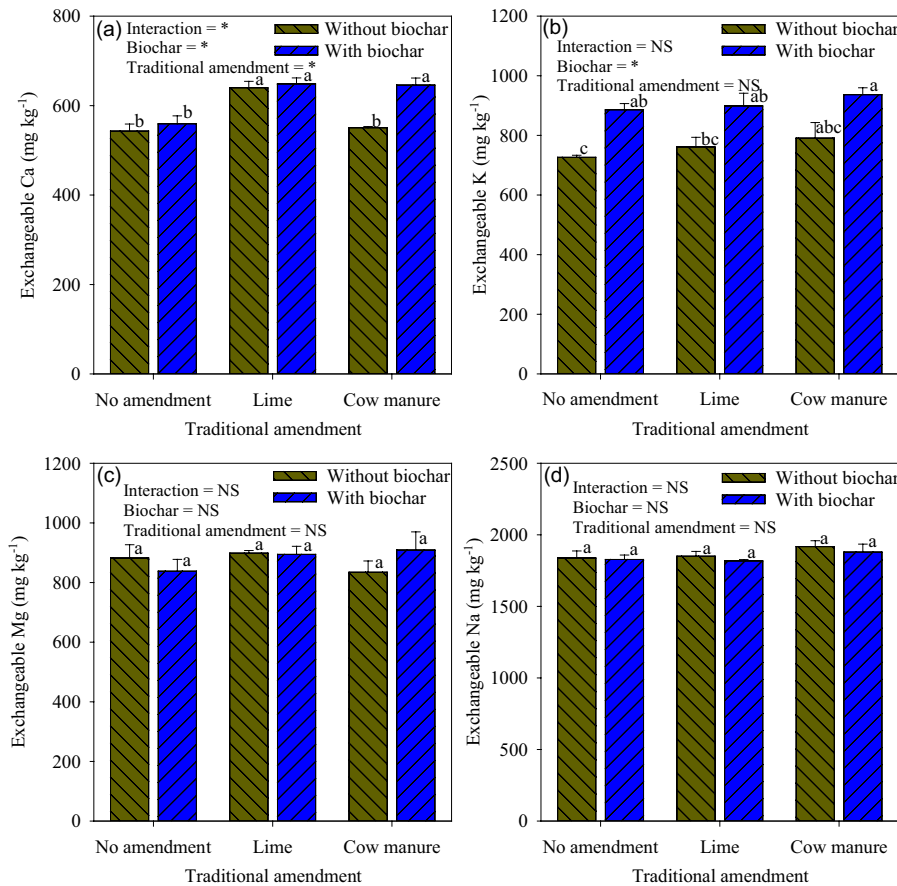


FIGURE 4 The concentration of exchangeable Ca (a), K (b), Mg (c) and Na (d) in the soil after the experiment as affected by two experimental factors, biochar and traditional soil amendment (lime and cow manure). Error bars indicate the standard error of the mean calculated from four replicates. * and NS indicate the associated effects are statistically significant and insignificant at $p \leq .05$ respectively.

3.3 | The soil quality index (SQI) and its correlation with grain weight and total biomass of rice

The PCA/FA grouped the whole data set into six factors, of which factor 1 had high loading values with five soil parameters, including exchangeable Fe, acidity, Al, Ca and pH (Table 2). Factor 2 exhibited a strong relationship with five other soil parameters, namely OC, CEC, exchangeable K, NH_4^+ and Mehlich-1 P. Factor 3 displayed a considerable connection with Cl^- and exchangeable H^+ . Factor 4 had notable loading values with exchangeable Mg, Mn and Na, while Factor 5 was most strongly related to SO_4^{2-} , and Factor 6 was primarily associated with EC. Factor 1 explained 28.51% of the total variance of the entire data set, while factors 2 to 6 contributed 17.16%, 11.60%, 9.97%, 7.03% and 6.37% respectively. Collectively, six factors were responsible for 80.64% of the total variance of the 17 soil parameters.

Based on the results from the PCA/FA, the SQI was calculated and shown in Figure 6a. The highest SQI values

were observed when biochar was used in combination with lime (0.69 units) or when biochar was combined with cow manure (0.66 units). The lowest SQI was recorded for soil without any amendments SQI (0.25 units). The addition of biochar led to a significant increase in SQI from 0.24 to 0.50 units for the two treatments without traditional amendment, from 0.54 to 0.69 units for the two treatments with lime, and from 0.41 to 0.66 units for the two treatments with cow manure, as compared to cases where no biochar was added. Moreover, the application of traditional amendments greatly enhanced SQI compared to the unamended soil. Figure 6b showed a strong relationship between SQI and both grain weight and the total biomass of paddy rice. As SQI increased from 0.22 to 0.75 units, grain weight and total biomass of rice exhibited substantial growth, following an exponential model with a coefficient of determination (r^2) of .48 and .69 respectively. Within the range of SQI below 0.4, the grain weight and total biomass rose more rapidly than for the SQI values above 0.4. The increasing rate in grain weight and total biomass of rice started to level off when SQI reached a value greater than 0.4.

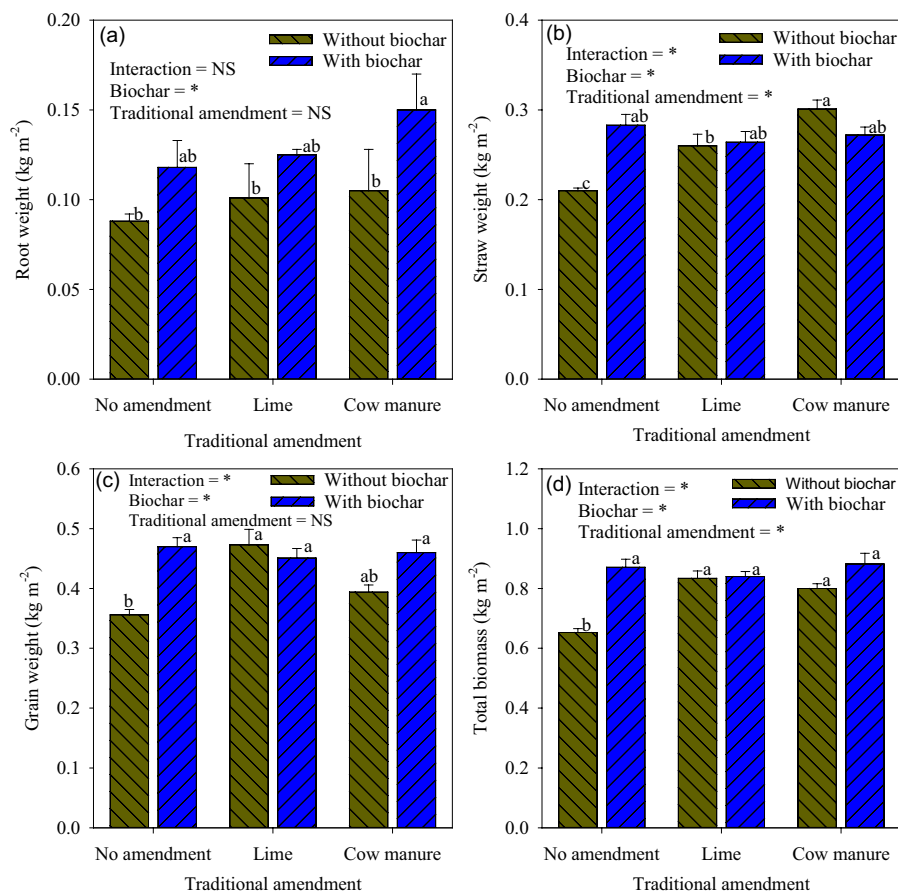


FIGURE 5 Root weight (a), straw weight (b), grain weight (c) and total biomass (d) of rice after the experiment as affected by two experimental factors, biochar and traditional soil amendment (lime and cow manure). Error bars indicate the standard error of the mean calculated from four replicates. * and NS indicate the associated effects are statistically significant and insignificant at $p \leq .05$ respectively.

4 | DISCUSSION

4.1 | Single effects of individual soil amendments

The application of biochar, which exhibited the highest levels of OC and exchangeable potassium, yielded the greatest increases in OC, cation exchange capacity (CEC) and exchangeable potassium when compared to the treatments involving the sole application of lime or cow manure. Nevertheless, the concentration of exchangeable Al was found to be lowest in the soil treated with only biochar, compared to the soil added solely with lime or cow manure, as well as the control (no amendment added). The lowered concentration of exchangeable Al in soil due to biochar addition has been reported by various studies (Geng et al., 2022; Wang et al., 2023). The change in exchangeable Al in the soil is primarily driven by a few factors, such as pH and complexation with organic matter in the soil matrix (Li et al., 2022; Li & Johnson, 2016). High alkalinity, large surface area and great porosity of biochar (Shetty et al., 2021) could be the reason for the

greatest reduction of exchangeable Al in the sole biochar treatment compared to the sole lime or cow manure treatments. These typical features promote surface adsorption of cations, such as Al, thereby lowering its soluble concentration in the soil.

Meanwhile, lime is frequently applied to remediate the acidity of acidic soils due to its high alkalinity and rich Ca cations (Hume et al., 2023). With a high Ca level ranging from 93% to 95% and a pH value of 13, the application of only lime in the current study resulted in the greatest increase in pH value and exchangeable Ca concentration, surpassing the effects of biochar or cow manure additions, as well as the untreated control. The elevated soil pH by these three individual amendments can also be attributed in part to the initial low pH levels of the soil before the experiment. Lime and biochar contain substantial amounts of Ca and K cations, which may displace hydrogen ions in soil colloids and consequently elevate soil pH (Dang et al., 2022). Additionally, exchangeable acidity, exchangeable H⁺ and exchangeable Fe were also found to be at their lowest in the soil treated solely with lime, compared to soils treated with other single amendments.

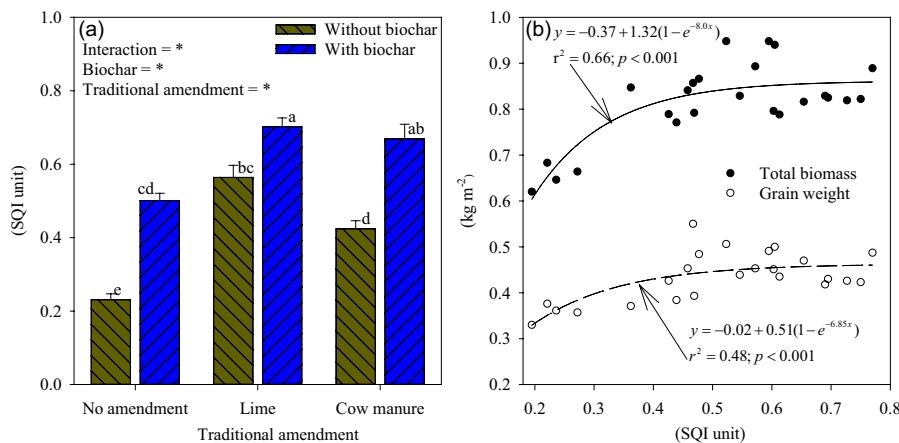


FIGURE 6 The SQI (a) and the relationship between SQI and grain weight as well as total biomass of rice (b) after the experiment. Error bars indicate the standard error of the mean calculated from four replicates. * and NS indicate the associated effects are statistically significant and insignificant at $p \leq .05$ respectively.

Since exchangeable acidity comprises both exchangeable H^+ and Al^{3+} (Nair et al., 2019), the levels of exchangeable acidity exceeded those of exchangeable H^+ in the tested soil. Because two cations H^+ and Al^{3+} generally maintain a relatively stable ratio in soils (Li & Johnson, 2016), lime application to remediate one cation also influences the other, as observed in the current study.

Different from biochar and lime, cow manure is not only rich in nutrients but also possesses relatively high acidity and contains certain toxic elements. Consequently, soil added with only cow manure exhibited the highest levels of exchangeable acidity, H^+ , Mehlich-1 P concentration and NH_4^+ concentration after the experiment, compared to the other single-amendment treatments. Although the cow manure contained greater levels of Cl^- and SO_4^{2-} than the tested soil, its addition to the soil did not result in considerably increased levels of these two soil parameters. The reason could be related to the high mobility of the two anions, which can leach from the top soil layers (Miramontes-Gutierrez et al., 2021; Nenadović et al., 2011). Leaching could potentially account for the similar levels of these two anions in all six experimental treatments. The high level of CEC found in cow manure led to soil CEC akin to that in the soil added with sole biochar. This particular parameter is influenced by various factors, such as pH, organic matter and clay composition, in the soil. While the clay content remained consistent across all treatments, the addition of either single biochar or cow manure led to a similar improvement of soil pH and OC after the experiment, compared to the control treatment, explaining the observed CEC.

Therefore, these above findings provide strong support for our initial research hypothesis, which posits that biochar, lime and cow manure have distinct effects on the

properties and quality of saline acid sulphate soil, driven by their unique characteristics. This hypothesis typically holds when certain soil parameters respond directly to the effects of the amendments, such as soil pH, OC, exchangeable calcium and potassium. However, certain soil parameters influenced by secondary processes, like aluminium, manganese, available P, chloride ions and sulphate ions, may not be adequately explained solely based on the original properties of the amendments.

4.2 | Synergistic effects of the soil amendments

Combining biochar with lime or cow manure resulted in more substantial changes in Mehlich-1 P, OC, CEC, exchangeable Al, Fe, Ca and K than applying any single amendments. These findings support our second hypothesis that the synergistic effects of combining biochar with lime or cow manure enhance soil properties and the soil quality index. The highest level of Mehlich-1 P was observed in the soil amended with both biochar and cow manure, indicating their synergistic role in enhancing the availability of this soil parameter. While the addition of lime could potentially reduce soil P availability due to its adsorption or formation of less soluble compounds with P (Curtin & Syers, 2001; Liao et al., 2020), this effect was not distinctly observed in the current study. Elevating the pH and decreasing the exchangeable Al in the soil through the use of both biochar and cow manure, coupled with the high content of available P in these amendments, may explain the observed rise in Mehlich-1 P concentration in the soil of the present study. The finding is in line with the other studies (Johan et al., 2021; Qi et al., 2023). Although

cow manure had a higher exchangeable Al level than the tested soil, its addition to the soil led to a lower content of this soil parameter, compared to the control treatment. This suggests that the levels of exchangeable Al in the soil are co-affected by other factors. As mentioned above, exchangeable Al status in the soil is driven by the initial properties of the amendments and secondary processes, which are related to the neutralization of soil acidity and surface adsorption. The introduction of the three amendments notably elevated soil pH, which is the primary factor contributing to the decrease in exchangeable aluminium (Fan et al., 2022). When biochar was combined with cow manure or lime, the reduction of exchangeable Al persisted without an additional increase in soil pH. This observation suggests that other mechanisms, such as the formation of organo-aluminium complexes between biochar and aluminium (Paz-Ferreiro et al., 2020), may also co-influence its content in the soil. Likewise, the exchangeable Fe concentration may be co-determined by multiple factors such as the initial properties of the amendments, elevated pH of the soils (Nguyen, Le, et al., 2021; Pouangam Ngalani et al., 2022) and adsorption on biochar and organic matter (Kügler et al., 2019).

While the sole use of lime or biochar resulted in the lowest levels of exchangeable acidity and H^+ , combining biochar with lime did not lead to a further reduction in these two soil parameters, compared to the control. The finding indicates that the combination of biochar and lime did not exhibit synergistic effects on the reduction in these two soil acidity-related parameters. Biochar is known for its strong buffering capacity (Blok et al., 2016), which can resist changes caused by the addition of lime. This suggests that biochar, despite having relatively higher levels of exchangeable acidity, H^+ and a lower pH value compared to lime, could potentially counteract the strongly alkalizing impact of lime. Consequently, this might result in a modest rise in the exchangeable acidity and H^+ ion levels in the soil treated with biochar and lime, relative to the soil treated with sole lime. Consequently, the combination of biochar with lime or cow manure in two treatments notably enhanced the SQI to a greater extent than any single-amendment treatments, confirming our second hypothesis. The increased SQI results from the cumulative changes in individual parameters of the tested soil as discussed earlier. Biochar addition enhanced the SQI by 0.27 units, compared to the control, suggesting that the quality of the tested soil is substantially improved by biochar, in line with other studies (Munda et al., 2023; Nascimento et al., 2023). Meanwhile, biochar, in combination with lime, contributed to a 0.14-unit increase in SQI, and in combination with cow manure, biochar

boosted the SQI by 0.25 units. The observed results suggest a more significant enhancement in SQI when biochar is combined with cow manure compared to its combination with lime. Compared to cow manure, lime shares certain characteristics with biochar, such as high Ca content, elevated pH level and low nutrient contents such as NH_4^+ . Consequently, the combination of biochar and lime leads to relatively weaker synergistic effects on soil quality compared to biochar combined with cow manure. This finding is noteworthy, as it addresses a topic that has received limited attention in the existing literature. The potential synergistic effects of biochar and cow manure on SQI are of particular interest for future research, as they may hold the key to developing more effective soil amendment strategies.

Soil quality exhibited a strong correlation with rice yield and total biomass, following an exponential model, which is in line with other studies (Nguyen & Nguyen, 2023a). A rapid increase in rice yield or total biomass for the SQI range below 0.4 units suggests that SQI levels below 0.4 units are more effective in improving rice yield and total biomass. Beyond this threshold, further increases in SQI may not lead to considerable improvement in rice yield and growth. Moreover, rice yield and total biomass were not significantly different among the five treatments of amendments. These findings indicate that our third research hypothesis, which posited synergistic effects from the combination of soil amendments in enhancing rice yield and growth in saline acid sulphate soil, was not supported. This implies that the combination of biochar with lime or cow manure exhibits statistically similar effects on rice yield and growth as individual amendments. There can be numerous reasons responsible for the findings. For optimal yield and growth, rice requires balanced nutrients such as N, P, K and other micronutrients (Gao et al., 2023). The plateauing response of rice yield and total biomass, when the SQI exceeds 0.4, could be due to deficiencies in some yield-limiting nutrients, which requires more studies. Furthermore, among the 17 soil parameters measured in the present study, some that reflect the salinity of the tested soil, such as Na, Cl^- and EC, were not significantly influenced by the amendments. This suggests that rice yield and growth could be driven by these salinity-related parameters when SQI is greater than 0.4. Reducing the salinity can potentially be a solution to enhance rice yield and growth in saline acid sulphate soil.

4.3 | Implication for sustainable management

The three soil amendments were applied to remediate saline acid sulphate soil and the results varied with their

characteristics. The lime application increased soil pH, thereby reducing acidity and subsequently decreasing the presence of potentially phytotoxic elements such as Al and Fe. However, this amendment has a limitation of low nutrient content, particularly nitrogen, resulting in low improvement in soil nutrition. This suggests that lime application alone may not create favourable environmental conditions for plants to grow. Conversely, cow manure, with its high nutrient levels, enhances the nutrient status of the soil. Nevertheless, its capacity to remediate acidity-related properties of the soil is lower than that of lime. This suggests that the combination of cow manure and lime may balance the advantages and limitations of both amendments, optimizing their benefits, though this specific combination was not explored in the current study and requires more studies. Biochar possesses intermediate properties between lime and cow manure, with high pH levels and nutrient content, such as K, and Ca, as well as carbon content. Biochar is considered an eco-friendly environmental treatment material (Srivatsav et al., 2020), produced from agricultural organic wastes. The biochar contributes to correcting acidity-related, nutrient-related and toxicity-related properties in the saline acid sulphate soil, in addition to carbon sequestration and organic waste treatment. Nevertheless, these three amendments introduce negligible effects on salinity-related properties of the soil, necessitating further studies.

Combining biochar with lime or cow manure produces significant complementary effects on soil properties and quality but exhibits weak synergistic effects on rice yield and growth. The findings indicate that soil properties are directly influenced by the amendments, driven by the combined characteristics of the amendments. However, it appears that for crops like rice, its maximal yield and growth may not be achieved with the application of these combined amendments. This implies that substantial improvement in soil quality may not necessarily lead to a corresponding increase in rice yield and growth in the examined soil. Consequently, a single application of individual amendments, typically biochar, may be sufficient, and combining these amendments may not additionally enhance rice yield and growth. However, the improved soil quality resulting from a combination of three amendments may benefit other crops such as corn and vegetables, but further study is needed to explore their impacts. Furthermore, the outcomes of the amendments are greatly dependent on the specific characteristics of the saline acid sulphate soil, such as its pH, salinity levels and nutrient content, as well as the appropriate application rates of the amendment. The combination of these amendments may improve soil quality more than that required by rice. Therefore, it is required to examine the application rate of individual or combined amendments to ensure that

desired soil quality can be achieved for improved crop productivity while avoiding the over-application of nutrients or encountering potential issues.

5 | CONCLUSION

This study has revealed that the effects of biochar, lime and cow manure on soil properties were driven by their inherent characteristics, which directly improved specific soil properties such as pH, OC, exchangeable calcium and potassium. The combination of biochar and lime led to the greatest increases in soil pH and exchangeable calcium, and the largest reductions in exchangeable aluminium and iron, effectively improving acidity-related properties and reducing the toxicity of the soil. However, the combination of biochar and cow manure resulted in the greatest enhancements in Mehlich-1 P, OC, ammonium and cation exchange capacity, thereby improving the nutrient-related properties of the tested soil. Consequently, these two combinations of biochar with lime or cow manure led to the most sustainable improvement in the soil quality index. Interestingly, the synergistic effects of biochar on soil quality were more profound when combined with cow manure compared to its combination with lime, likely due to the close alignment of biochar properties with those of lime rather than cow manure. The applications of both individual and combined amendments resulted in substantial improvement in rice growth and yield. Rice yield and total biomass rapidly increased when the soil quality index rose to below 0.4, but thereafter, the rate of improvement stabilized. These findings suggested a weak synergistic effect of combining biochar with lime and cow manure on rice yield and growth. Further studies are necessary to elucidate these findings and explore the optimal application rates of the amendments tailored to soil properties to maximize the benefits of the amendments. Such investigations could pave the way for developing enhanced management practices that promote sustainable agriculture and improve crop yields in challenging soil conditions.

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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.

REFERENCES

- Akhtar, M., & Memon, M. (2009). Biomass and nutrient uptake by rice and wheat: A three-way interaction of potassium, ammonium and soil type. *Pakistan Journal of Botany*, *41*, 2965–2974.
- Almeida, R. F., Queiroz, I. D. S., Mikhael, J. E. R., Oliveira, R. C., & Borges, E. N. (2019). Enriched animal manure as a source of phosphorus in sustainable agriculture. *International Journal of Recycling of Organic Waste in Agriculture*, *8*, 203–210. <https://doi.org/10.1007/s40093-019-00291-x>
- Amini, S., Ghadiri, H., Chen, C., & Marschner, P. (2016). Salt-affected soils, reclamation, carbon dynamics, and biochar: A review. *Journal of Soils and Sediments*, *16*, 939–953. <https://doi.org/10.1007/s11368-015-1293-1>
- Behera, B., Sankar, G. R. M., Sharma, K. L., Mishra, A., Mohanty, S. K., Mishra, P. K., Rath, B. S., & Grace, J. K. (2012). Effects of fertilizers on yield, sustainability, and soil fertility under rainfed pigeon pea + rice system in subhumid oxisol soils. *Communications in Soil Science and Plant Analysis*, *43*, 2228–2246. <https://doi.org/10.1080/00103624.2012.701685>
- Blok, C., van der Salm, C., Hofland-Zijlstra, J., Streminska, M., Eveleens-Clark, B., Regelink, I., Visser, R., & Fryda, L. (2016). Biochar for horticultural rooting media improvement: Evaluation of biochar from gasification and slow pyrolysis. *Agronomy*, *7*, 6. <https://doi.org/10.3390/agronomy7010006>
- Carter, M. R., & Gregorich, E. G. (2008). *Soil sampling and methods of analysis* (2nd ed.). CRC Press, Taylor & Francis Group.
- Chen, Y., Li, S., Zhang, Y., Li, T., Ge, H., Xia, S., Gu, J., Zhang, H., Lü, B., Wu, X., Wang, Z., Yang, J., Zhang, J., & Liu, L. (2019). Rice root morphological and physiological traits interaction with rhizosphere soil and its effect on methane emissions in paddy fields. *Soil Biology and Biochemistry*, *129*, 191–200. <https://doi.org/10.1016/j.soilbio.2018.11.015>
- Curtin, D., & Syers, J. (2001). Lime-induced changes in indices of soil phosphate availability. *Soil Science Society of America Journal*, *65*, 147–152. <https://doi.org/10.2136/sssaj2001.651147x>
- Dang, L. V., Ngoc, N. P., & Hung, N. N. (2022). Effects of biochar, lime, and compost applications on soil physicochemical properties and yield of pomelo (*Citrus grandis* Osbeck) in alluvial soil of the Mekong Delta. *Applied and Environmental Soil Science*, *2022*, 1–10.
- Fan, B., Ding, S., Peng, Y., Yin, J., Liu, Y., Cui, S., Zhou, X., Mu, K., Ru, S., & Chen, Q. (2022). Supplying amendments alleviates aluminum toxicity and regulates cadmium accumulation by spinach in strongly acidic soils. *Journal of Environmental Management*, *324*, 116340. <https://doi.org/10.1016/j.jenvman.2022.116340>
- FAO. (1988). *Salt-affected soils and their management*. <http://www.fao.org/3/x5871e/x5871e00.htm#Contents>
- FAO. (2023). *Salt-affected soils*, *FAO soil portal*. <https://www.fao.org/soils-portal/soil-management/management-of-some-problem-soils/salt-affected-soils/more-information-on-salt-affected-soils/en/>
- Farooqi, Z. U. R., Sabir, M., Ahmad, H. R., Shahbaz, M., & Smith, J. (2023). Reclaimed salt-affected soils can effectively contribute to carbon sequestration and food grain production: Evidence from Pakistan. *Applied Sciences*, *13*, 1436.
- Gao, P., Zhang, T., Lei, X.-Y., Cui, X.-W., Lu, Y.-X., Fan, P.-F., Long, S.-P., Huang, J., Gao, J.-S., Zhang, Z.-H., & Zhang, H.-M. (2023). Improvement of soil fertility and rice yield after long-term application of cow manure combined with inorganic fertilizers. *Journal of Integrative Agriculture*, *22*, 2221–2232. <https://doi.org/10.1016/j.jia.2023.02.037>
- Geng, N., Kang, X., Yan, X., Yin, N., Wang, H., Pan, H., Yang, Q., Lou, Y., & Zhuge, Y. (2022). Biochar mitigation of soil acidification and carbon sequestration is influenced by materials and temperature. *Ecotoxicology and Environmental Safety*, *232*, 113241. <https://doi.org/10.1016/j.ecoenv.2022.113241>
- Gomes, B. P., Ferraz, C. C., Vianna, M. E., Rosalen, P. L., Zaia, A. A., Teixeira, F. B., & Souza-Filho, F. J. (2002). In vitro antimicrobial activity of calcium hydroxide pastes and their vehicles against selected microorganisms. *Brazilian Dental Journal*, *13*, 155–161.
- Hajrasuliha, S., Cassel, D. K., & Rezaiejad, Y. (1991). Estimation of chloride ion concentration in saline soils from measurement of electrical conductivity of saturated soil extracts. *Geoderma*, *49*, 117–127. [https://doi.org/10.1016/0016-7061\(91\)90095-B](https://doi.org/10.1016/0016-7061(91)90095-B)
- Hume, R., Marschner, P., Mason, S., Schilling, R. K., Hughes, B., & Mosley, L. M. (2023). Measurement of lime movement and dissolution in acidic soils using mid-infrared spectroscopy. *Soil and Tillage Research*, *233*, 105807. <https://doi.org/10.1016/j.still.2023.105807>
- Islam, M. R., Jahan, R., Uddin, S., Harine, I. J., Hoque, M. A., Hassan, S., Hassan, M. M., & Hossain, M. A. (2021). Lime and organic manure amendment enhances crop productivity of wheat-mungbean-T. Aman cropping pattern in acidic Piedmont soils. *Agronomy*, *11*, 1595.
- Jayasekara, A., Ekanayake, S., Premarathna, M., Warnakulasooriya, D., Abeysinghe, C., & Seneviratne, G. (2022). Organic material inputs are not essential for paddy soil carbon sequestration. *Environmental Challenges*, *8*, 100551. <https://doi.org/10.1016/j.envc.2022.100551>
- Johan, P. D., Ahmed, O. H., Omar, L., & Hasbullah, N. A. (2021). Phosphorus transformation in soils following co-application of charcoal and wood ash. *Agronomy*, *11*, 2010. <https://doi.org/10.3390/agronomy11102010>
- Kalanaki, M., Ritzema, H., Bamshad, R., Jones, E., & Fazilatnia, M. (2020). Application of bio-desalinization for reclamation of salt-affected soil under composted cow manure and deficit irrigation with saline water. *Paddy and Water Environment*, *18*, 469–479. <https://doi.org/10.1007/s10333-020-00795-7>
- Knoblauch, C., Priyadarshani, S. H. R., Haefele, S. M., Schröder, N., & Pfeiffer, E.-M. (2021). Impact of biochar on nutrient supply, crop yield and microbial respiration on sandy soils of northern Germany. *European Journal of Soil Science*, *72*, 1885–1901. <https://doi.org/10.1111/ejss.13088>
- Koide, R. T., Nguyen, B. T., Skinner, R. H., Dell, C. J., Adler, P. R., Drohan, P. J., Licht, M., Matthews, M. B., Nettles, R., Ricks, K., & Watkins, J. (2018). Comparing biochar application methods for switchgrass yield and C sequestration on contrasting marginal lands in Pennsylvania, USA. *Bioenergy Research*, *11*, 784–802. <https://doi.org/10.1007/s12155-018-9940-1>
- Kügler, S., Cooper, R. E., Wegner, C.-E., Mohr, J. F., Wichard, T., & Küsel, K. (2019). Iron-organic matter complexes accelerate

- microbial iron cycling in an iron-rich fen. *Science of the Total Environment*, 646, 972–988. <https://doi.org/10.1016/j.scitotenv.2018.07.258>
- Li, K.-W., Lu, H.-L., Nkoh, J. N., Hong, Z.-N., & Xu, R.-K. (2022). Aluminum mobilization as influenced by soil organic matter during soil and mineral acidification: A constant pH study. *Geoderma*, 418, 115853. <https://doi.org/10.1016/j.geoderma.2022.115853>
- Li, W., & Johnson, C. E. (2016). Relationships among pH, aluminum solubility and aluminum complexation with organic matter in acid forest soils of the northeastern United States. *Geoderma*, 271, 234–242. <https://doi.org/10.1016/j.geoderma.2016.02.030>
- Liao, P., Ros, M. B. H., Van Gestel, N., Sun, Y.-N., Zhang, J., Huang, S., Zeng, Y.-J., Wu, Z.-M., & Van Groenigen, K. J. (2020). Liming reduces soil phosphorus availability but promotes yield and P uptake in a double rice cropping system. *Journal of Integrative Agriculture*, 19, 2807–2814. [https://doi.org/10.1016/S2095-3119\(20\)63222-1](https://doi.org/10.1016/S2095-3119(20)63222-1)
- Linh, D. T. T., Khoi, C. M., Ritz, K., Sinh, N. V., Phuong, N. T. K., My, H. M. T., Linh, T. B., Minh, D. D., Linh, T. T., & Toyota, K. (2023). Effects of rice husk biochar and compost amendments on soil phosphorus fractions, enzyme activities and rice yields in salt-affected acid soils in the Mekong Delta, Viet Nam. *Agronomy*, 13, 1593.
- Liu, Q., Meki, K., Zheng, H., Yuan, Y., Shao, M., Luo, X., Li, X., Jiang, Z., Li, F., & Xing, B. (2023). Biochar application in remediating salt-affected soil to achieve carbon neutrality and abate climate change. *Biochar*, 5, 45. <https://doi.org/10.1007/s42773-023-00244-8>
- Liu, Z., Zhou, W., Li, S., He, P., Liang, G., Lv, J., & Jin, H. (2015). Assessing soil quality of gleyed paddy soils with different productivities in subtropical China. *Catena*, 133, 293–302. <https://doi.org/10.1016/j.catena.2015.05.029>
- Li-Xian, Y., Guo-Liang, L., Shi-Hua, T., Gavin, S., & Zhao-Huan, H. (2007). Salinity of animal manure and potential risk of secondary soil salinization through successive manure application. *Science of the Total Environment*, 383, 106–114. <https://doi.org/10.1016/j.scitotenv.2007.05.027>
- Loan, T. K., Yunusa, I. A. M., Rab, M. A., Zerihun, A., & Nguyen, H. M. (2022). Responses in growth, yield and cob protein content of baby corn (*Zea mays*) to amendment of an acid sulfate soil with lime, organic fertiliser and biochar. *Crop and Pasture Science*, 74, 90–100. <https://doi.org/10.1071/CP21812>
- Miramontes-Gutierrez, E. M., Ochoa-Rivero, J. M., Rubio-Arias, H. O., Ballinas-Casarrubias, L., & Rocha-Gutiérrez, B. A. (2021). Impact of cations (Na(+), K(+), Mg(+2)) and anions (F(-), Cl(-), SO(4)(2-)) leaching from filters packed with natural zeolite and ferric nanoparticles for wastewater treatment. *International Journal of Environmental Research and Public Health*, 18, 1–12. <https://doi.org/10.3390/ijerph18168525>
- Morton, L. W., Nguyen, N. K., & Demyan, M. S. (2023). Salinity and acid sulfate soils of the Vietnam Mekong Delta: Agricultural management and adaptation. *Journal of Soil and Water Conservation*, 78, 85A–92A. <https://doi.org/10.2489/jswc.2023.0321A>
- Mosharraf, M., Uddin, M. K., Sulaiman, M. F., Mia, S., Shamsuzzaman, S. M., & Haque, A. N. A. (2021). Combined application of biochar and lime increases maize yield and accelerates carbon loss from an acidic soil. *Agronomy*, 11, 1313. <https://doi.org/10.3390/agronomy11071313>
- Mukherjee, A., & Lal, R. (2014). Comparison of soil quality index using three methods. *PLoS One*, 9, e105981. <https://doi.org/10.1371/journal.pone.0105981>
- Munda, S., Nayak, A. K., Shahid, M., Bhaduri, D., Chatterjee, D., Mohanty, S., Tripathi, R., Kumar, U., Kumar, A., Khanam, R., & Jambhulkar, N. (2023). Soil quality assessment of lowland rice soil of eastern India: Implications of rice husk biochar application. *Heliyon*, 9, e17835. <https://doi.org/10.1016/j.heliyon.2023.e17835>
- Nair, K. M., Kumar, K. S. A., Lalitha, M., Shivanand, K. S. C. R., Srinivas, S., Koyal, A., Parvathy, S., Sujatha, K., Thamban, C., Mathew, J., Chandran, K. P., Haris, A., Krishnakumar, V., Srinivasan, V., Jessy, J. J., Nagaraj, J. S., D'Souza, M. V., Raghuramulu, Y., Hegde, R., & Singh, S. K. (2019). Surface soil and subsoil acidity in natural and managed land-use systems in the humid tropics of Peninsular India. *Current Science*, 116, 1201–1211.
- Nascimento, Í. V., Fregolente, L. G., Pereira, A. P. A., Nascimento, C. D. V., Mota, J. C. A., Ferreira, O. P., Sousa, H. H. F., Silva, D. G. G., Simões, L. R., Souza Filho, A. G., & Costa, M. C. G. (2023). Biochar as a carbonaceous material to enhance soil quality in drylands ecosystems: A review. *Environmental Research*, 233, 116489. <https://doi.org/10.1016/j.envres.2023.116489>
- Nenadović, S., Nenadovic, M., Kljajević, L., Ljesevic, M., Omerasević, M., & Matovic, B. (2011). Investigation of Cl⁻ and SO₄²⁻ anion absorption in natural soils. *Processing and Application of Ceramics*, 5, 85–89. <https://doi.org/10.2298/PAC1102085N>
- Nguyen, B. T., Dinh, G. D., Nguyen, T. X., Nguyen, D. T. P., Vu, T. N., Tran, H. T. T., Van Thai, N., Vu, H., & Do, D. D. (2022). The potential of biochar to ameliorate the major constraints of acidic and salt-affected soils. *Journal of Soil Science and Plant Nutrition*, 22, 1340–1350. <https://doi.org/10.1007/s42729-021-00736-1>
- Nguyen, B. T., Le, L. B., Pham, L. P., Nguyen, H. T., Tran, T. D., & Van Thai, N. (2021). The effects of biochar on the biomass yield of elephant grass (*Pennisetum Purpureum Schumacher*) and properties of acidic soils. *Industrial Crops and Products*, 161, 113224. <https://doi.org/10.1016/j.indcrop.2020.113224>
- Nguyen, B. T., & Nguyen, V. N. (2023a). Biochar addition balanced methane emissions and rice growth by enhancing the quality of paddy soil. *Journal of Soil Science and Plant Nutrition*, 23, 2998–3009. <https://doi.org/10.1007/s42729-023-01249-9>
- Nguyen, T. K. P., Khoi, C., Sinh, N., Chiem, N., & Toyota, K. (2019). Effects of rice husk biochar and calcium amendment on remediation of saline soil from rice-shrimp cropping system in Vietnamese Mekong Delta. *Journal of Experimental Agriculture International*, 39, 1–12. <https://doi.org/10.9734/jeai/2019/v39i230327>
- Nguyen, T. T., Sasaki, Y., Katahira, M., & Singh, D. (2021). Cow manure application cuts chemical phosphorus fertilizer need in silage rice in Japan. *Agronomy*, 11, 1483.
- Nguyen, T. T. T., Tran, T. A. T., Kristiansen, P., & Nguyen, V. T. (2022). Investigating the resistance of barnyard grass populations to pretilachlor in direct-seed rice in the Central Region of Vietnam. *African Journal of Agricultural Research*, 18, 542–554. <https://doi.org/10.5897/AJAR2022.16016>
- Nguyen, T. X. T., & Nguyen, B. T. (2023b). The effects of two different biochars on the characteristics of saline acid sulfate soil. *Land Degradation & Development*, 34, 3744–3754. <https://doi.org/10.1002/ldr.4717>

- Paz-Ferreiro, J., Álvarez-Calvo, M. L., Figueiredo, C. C., Mendez, A.-M., & Gascó, G. (2020). Effect of biochar and hydrochar on forms of aluminium in an acidic soil. *Applied Sciences*, *10*, 7843.
- Phillips, C. L., Meyer, K. M., Garcia-Jaramillo, M., Weidman, C. S., Stewart, C. E., Wanzek, T., Grusak, M. A., Watts, D. W., Novak, J., & Trippe, K. M. (2022). Towards predicting biochar impacts on plant-available soil nitrogen content. *Biochar*, *4*, 9. <https://doi.org/10.1007/s42773-022-00137-2>
- Pouangam Ngalani, G., Dzemze Kagho, F., Peguy, N. N. C., Prudent, P., Ondo, J. A., & Ngameni, E. (2022). Effects of coffee husk and cocoa pods biochar on the chemical properties of an acid soil from West Cameroon. *Archives of Agronomy and Soil Science*, *69*, 744–758.
- Qi, S., Yang, S., Lin, X., Hu, J., Jiang, Z., & Xu, Y. (2023). The long-term effectiveness of biochar in increasing phosphorus availability and reducing its release risk to the environment in water-saving irrigated paddy fields. *Agricultural Water Management*, *282*, 108295. <https://doi.org/10.1016/j.agwat.2023.108295>
- Rice, E. W., Baird, R. B., & Eaton, A. D. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association, American Water Works Association, Water Environment Federation.
- Rosilawati, A., Shamshuddin, J., & Ishak, C. (2014). Effects of incubating an acid sulfate soil treated with various liming materials under submerged and moist conditions on pH, Al and Fe. *African Journal of Agricultural Research*, *9*, 94–112. <https://doi.org/10.5897/AJAR12.289>
- Sarangi, S. K., Mainuddin, M., & Maji, B. (2022). Problems, management, and prospects of acid sulphate soils in the Ganges Delta. *Soil Systems*, *6*, 95.
- Shangguan, Y. X., Qin, Y., Yu, H., Chen, K., Wei, Y., Zeng, X., Zhou, Z., Guo, S., & He, S. (2019). Lime application affects soil cadmium availability and microbial community composition in different soils. *CLEAN—Soil, Air, Water*, *47*, 1800416.
- Shaygan, M., & Baumgartl, T. (2022). Reclamation of salt-affected land: A review. *Soil Systems*, *6*, 61.
- Shetty, R., Vidya, C. S.-N., Prakash, N. B., Lux, A., & Vaculik, M. (2021). Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: A review. *Science of the Total Environment*, *765*, 142744. <https://doi.org/10.1016/j.scitotenv.2020.142744>
- Singh, H., Northup, B. K., Rice, C. W., & Prasad, P. V. V. (2022). Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: A meta-analysis. *Biochar*, *4*, 8. <https://doi.org/10.1007/s42773-022-00138-1>
- Srivatsav, P., Bhargav, B. S., Shanmugasundaram, V., Arun, J., Gopinath, K. P., & Bhatnagar, A. (2020). Biochar as an eco-friendly and economical adsorbent for the removal of colorants (dyes) from aqueous environment: A review. *Water*, *12*, 3561.
- Sun, J., Lu, X., Wang, S., Tian, C., Chen, G., Luo, N., Zhang, Q., & Li, X. (2023). Biochar blended with nitrogen fertilizer promotes maize yield by altering soil enzyme activities and organic carbon content in black soil. *International Journal of Environmental Research and Public Health*, *20*, 1–14. <https://doi.org/10.3390/ijerph20064939>
- van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food*, *2*, 494–501. <https://doi.org/10.1038/s43016-021-00322-9>
- Wang, B., Gao, Y., Lai, X., Luo, L., Zhang, X., Hu, D., Shen, Z., Hu, S., & Zhang, L. (2023). The effects of biochar derived from feedstock with different Si and Al concentration on soil N₂O and CO₂ emissions. *Environmental Pollution*, *317*, 120731. <https://doi.org/10.1016/j.envpol.2022.120731>
- WRB. (2015). *World reference base for soil resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps*. World Soil Resources Reports No. 106. FAO.
- Xiao, L., & Meng, F. (2020). Evaluating the effect of biochar on salt leaching and nutrient retention of Yellow River Delta soil. *Soil Use and Management*, *36*, 740–750. <https://doi.org/10.1111/sum.12638>
- Yang, W., Feng, G., Miles, D., Gao, L., Jia, Y., Li, C., & Qu, Z. (2020). Impact of biochar on greenhouse gas emissions and soil carbon sequestration in corn grown under drip irrigation with mulching. *Science of the Total Environment*, *729*, 138752. <https://doi.org/10.1016/j.scitotenv.2020.138752>
- Yue, Y., Guo, W. N., Lin, Q. M., Li, G. T., & Zhao, X. R. (2016). Improving salt leaching in a simulated saline soil column by three biochars derived from rice straw (*Oryza sativa* L.), sunflower straw (*Helianthus annuus*), and cow manure. *Journal of Soil and Water Conservation*, *71*, 467–475.

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