Geoderma Regional 39 (2024) e00878

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

Seasonal variation-dependent biochar impacts on coastal acid-sulfate soil in paddy fields and the consequences on rice growth and yield

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ARTICLE INFO

Keywords:
Acid sulfate soil
Biochar
Mitigation
Leaching
Soil amendment
Soil quality

ABSTRACT

Utilizing eco-friendly and cost-effective amendments, like biochar produced from agricultural biomass wastes offers numerous benefits for ameliorating acid-sulfate soils in coastal regions. This study investigates seasonal variation and rice husk and longan biochar's impacts on soil properties, quality, and rice (*Oryza sativa* L.) growth and yield in acid-sulfate paddy fields during dry and rainy seasons. Five treatments (T) were tested: T1 (no biochar), T2 and T3 (10-tone and 20-tone rice-husk biochar ha^{-1}), and T4 and T5 (10-tone and 20-tone longan biochar ha^{-1}). Results showed that biochar improved soil properties with pH increasing by 3.2 % to 9.2 % and exchangeable Al decreasing by 7.7 % to 18.1 %, compared to T1, dependent on treatments and seasons. Soil quality index in biochar treatments increased by 30 %, 54 %, 26 %, and 16 % for T2, T3, T4, and T5, respectively, compared to T1 in the dry season. This season exhibited the highest grain weight (1.06 kg m^{-2}) and total biomass (2.31 kg m^{-2}) in T3, followed by T5, T2, T4, and T1. The rainy season benefits were less pronounced, likely due to leaching, suggesting more frequent applications may be necessary in high-rainfall regions. Liming effects and leaching in the rainy season were identified as primary mechanisms influencing soil quality and rice yield. Rice-husk biochar was more effective than longan biochar in mitigating soil constraints and enhancing rice yield. In short, biochar effectively ameliorates acid-sulfate soil constraints, improving rice yield and growth. However, rapidly diminishing effects during the rainy season necessitate further investigation for optimal application in high-rainfall regions.

1. Introduction

In coastal regions, many areas contain acid-sulfate soils, which leads to low agricultural productivity in the regions. The soils are characterized by a high level of sulfides, strong acidity, and low pH value, leading to the mobilization of metals in soils (Adegaye et al., 2023; Nyman et al., 2023). It is estimated that the world has approximately 17 to 24 million hectares of soil, primarily located in coastal areas within tropical regions (Vehanen et al., 2022). When sulfide minerals encounter oxygen-containing environments, they undergo oxidation processes facilitated by microbial mechanisms, forming sulfuric acid and Fe^{3+}). This leads to a rapid decrease in pH and an escalation of acidity. Frequent activities such as agricultural practices on lands of acid-sulfate soil can bring sulfide minerals to the surface layer, exposing them to atmospheric oxygen for oxidation. Natural drought or human-induced drainage for cropping may lower groundwater tables, bringing sulfide minerals into contact with oxygen (Fitzpatrick et al., 2017; Vehanen et al., 2022). Consequently, metals in soil minerals, such as aluminum (Al), iron (Fe), and manganese (Mn) are more mobile in the soil environment (Lindgren et al., 2022). The soils are also commonly deficient in phosphorous (P) availability due to low pH and high Al and Fe content (Fahmi et al., 2023). These findings indicate that acid-sulfate soil has numerous constraints, which limit crop growth and productivity.

A considerable portion of the coastal region in acid-sulfate soil is used for rice (*Oryza sativa* L.) cultivation and remediation of the soil is essential for better crop production (Janjirawut et al., 2011; Panhwar et al., 2016). On-field activities like plowing and the creation of canals/ditches to drain water out to prepare land for the next rice crop can contribute to the development of acid-sulfate soil-based land through the oxidation process (Sarangi et al., 2022; Vehanen et al., 2022).

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https://doi.org/10.1016/j.geodrs.2024.e00878
Received 28 May 2024; Received in revised form 20 July 2024; Accepted 8 October 2024

Various methods can be employed for the remediation of acid-sulfate soils, including the application of lime (Fitrani et al., 2020) and organic manure (Michael et al., 2015). However, each of these approaches has its own set of advantages and disadvantages. To mitigate the constraints of these lands, leaching is an effective management method often employed (Sarangi et al., 2022). The potential for leaching depends on rainfall amounts and thus varies seasonally throughout the year. During the dry season, the leaching process is expected to be less pronounced due to reduced precipitation. Conversely, leaching efficiency is likely to rise significantly in the rainy season due to higher rainfall volumes. Consequently, we hypothesized that the levels of exchangeable properties, including acidity (H+), aluminum (Al), iron (Fe), manganese (Mn), potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg), would fluctuate seasonally, with potentially lower concentrations during the rainy season and higher levels during the dry season. Moreover, the impact of seasonal variation on rice yield in paddy fields requires further investigation, as the rainy season enhancing leaching can potentially deplete some essential nutrients in the soil, leading to reduced plant productivity (Kuo et al., 2020).

Recently, biochar has emerged as a potential solution for the remediation of acid-sulfate soils (Kinnunen et al., 2021; Sulaiman et al., 2024). Biochar, a carbon-rich material made from plant residues, can be used to ameliorate acid-sulfate soil with varying effectiveness. Its key characteristics including high alkalinity, porosity, nutrient richness, high cation adsorption capacity, and stability in diverse environments, contribute to its efficacy (Amalina et al., 2022; Khan et al., 2024). Consequently, the application of rice husk biochar enhanced pH and soil properties while reducing the concentration of Al and Fe, leading to improved rice growth in acid-sulfate soil (Panhwar et al., 2020). Nevertheless, the effectiveness of biochar remediation largely depends on its properties, determined by the feedstocks used for biochar production (Premalatha et al., 2023). Biochar produced from spruce was reported to have higher adsorption of metals than that produced from birch (Kinnunen et al., 2021). Moreover, as highlighted by Premalatha et al. (2023), most studies evaluating the effects of biochar have been conducted in laboratory settings rather than under field conditions. Biochar applications generally show greater effects on soil properties in laboratory and greenhouse experiments compared to field studies, primarily due to weathering, degradation, and dilution of biochar in field conditions (Singh et al., 2022). This discrepancy underscores the importance of cautious interpretation when comparing or extrapolating results between controlled and field-based studies, as laboratory environments cannot fully replicate the complex dynamics of real-world agricultural settings. These observations highlight the need for extensive field-scale research to evaluate the efficacy of various biochars with diverse properties in remediating acid sulfate soils across different landscape contexts.

Moreover, the effectiveness of biochar also depends on field conditions, such as water regimes determined by seasonal variation. High rainfall during the rainy season may increase the leaching of toxic elements but also reduce the beneficial impacts of biochar due to the leaching of nutrients newly formed by biochar. On one hand, the material with its high porosity may facilitate the leaching process to remove salts (An et al., 2023). On the other hand, due to high retention capacity, applying biochar into soils was reported to decrease nutrient leaching and enhance NH_4^+ adsorption, restricting nutrient loss through the leaching process (Alkharabsheh et al., 2021). Similarly, biochar addition was found to reduce $NO_3^-$and NH_4^+ leaching, resulting in increased rice N uptake from paddy soil (Wang et al., 2017). These findings lead to our second hypothesis that biochar's effectiveness in remediating acid sulfate soils is more profound during the dry season than during the rainy season.

Therefore, the current study was conducted under paddy field conditions in acid-sulfate soil to investigate the effects of biochar derived from rice husk and longan branches during the dry and rainy season on soil properties, quality, and rice growth and yield and identify associated mechanisms. This study offers insight into the efficacy of biochar as a remediation strategy for acid-sulfate soils under varying conditions of rainfall. The results would shed light on whether biochar's effectiveness in acid sulfate soil remediation is consistent across both wet and dry seasons, or if the wet season can reduce its efficacy.

2. Materials and methods

2.1. Experimental materials

The experiment was conducted in a rice field in Tan Thanh Dong commune, Cu Chi district, Ho Chi Minh City, Vietnam (10°55′35.7" N 106°35’24.9" E). This field has a history of over 15 years of continuous rice cultivation, with 2 rice crops per year. Located in a tropical monsoon climate region the area experiences two distinct seasons: the rainy season from May to November and the dry season from December to April of the following year. The total rainfall in the area ranges from 1800 to 2000 mm per year, and the average temperature varies between 27 and 28 °C (Le et al., 2022). The selected rice fields fall under the category of acid-sulfate soil (*thionic fluvisols*) (WRB, 2015). Before the experiment, three soil samples were taken from 5 diagonal points within the selected field at a depth of 15 cm for chemical analyses. These soil samples were transferred to the laboratory, air-dried, ground, and sieved through a 2-mm sieve to remove plant residues and gravel before analysis. The initial properties of the tested soil are shown in Table 1.

The biochar used in this study was produced from agricultural biomass wastes, which were rice husk (*Oryza sativa L.*) and longan branches (*Dimocarpus longan Lour*). Both rice husk biochar (HB) and longan biochar (LB) were sourced from a local market near the experimental field. These biochars were produced using a traditional kiln at a temperature of approximately 400 °C. While the rice husks were used as-is, the longan branches were cut into 10–15 cm lengths before pyrolysis.

Table 1
Initial properties of the tested soil and biochar. The data is presented as averages and the standard deviation of the mean of three replicates. Within a row, data attached with the same letters is not statistically significantly different from each other with $p \leq 0.05$.

Parameter	Unit	Soil	Husk biochar (HB)	Longan biochar (LB)
pH	None	$6.14^c \pm 0.13$	$8.47^a \pm 0.12$	$7.37^b \pm 0.12$
CEC	cmole(*c*) kg^{-1}	$7.66^b \pm 0.44$	$22.5^a \pm 0.53$	$19.43^a \pm 0.74$
NH_4^+	mg kg^{-1}	$356.85^a \pm 26.9$	$2.72^b \pm 0.08$	$1.92^b \pm 0.20$
Mehlich-1 P	mg kg^{-1}	$33.73^c \pm 3.99$	$2260.3^a \pm 72.1$	$546.8^b \pm 16.9$
OC	%	$5.56^c \pm 0.05$	$33.7^b \pm 0.85$	$63.7^a \pm 1.60$
SO_4^{2-}	g kg^{-1}	$4.33^b \pm 0.22$	$7.33^a \pm 0.51$	$0.72^c \pm 0.06$
Exchangeable acidity	cmole(*c*) kg^{-1}	$4.33^b \pm 0.22$	$7.16^a \pm 0.15$	$0.62^c \pm 0.03$
Exchangeable H^+	cmole(*c*) kg^{-1}	$2.91^a \pm 0.33$	$2.56^{ab} \pm 0.08$	$1.92^b \pm 0.20$
Exchangeable K	g kg^{-1}	$1.17^b \pm 0.14$	$10.8^a \pm 0.14$	$1.02^b \pm 0.01$
Exchangeable Na	g kg^{-1}	$1.47^{ab} \pm 0.26$	$2.24^a \pm 0.11$	$1.33^b \pm 0.12$
Exchangeable Ca	g kg^{-1}	$1.87^b \pm 0.21$	$2.71^{ab} \pm 0.16$	$3.18^b \pm 0.16$
Exchangeable Mg	g kg^{-1}	$0.48^a \pm 0.03$	$0.46^a \pm 0.03$	$0.30^b \pm 0.004$
Exchangeable Al	g kg^{-1}	$0.74^a \pm 0.08$	$0.02^b \pm 0.005$	$0.03^b \pm 0.002$
Exchangeable Fe	g kg^{-1}	$0.15^a \pm 0.03$	$0.05^{ab} \pm 0.004$	$0.07^b \pm 0.002$
Exchangeable Mn	g kg^{-1}	$0.05^b \pm 0.003$	$0.07^a \pm 0.001$	$0.05^b \pm 0.002$

Before application to the experimental plots, these two biochars were collected in three sub-samples each for chemical analysis similar to soil samples (Table 1). The rice variety employed in this experiment was Dai Thom 8, characterized by hard and green leaves, elongated grains, a vibrant yellow color, and moderate resistance to certain pests and diseases.

2.2. Experimental setup

The field experiment was set up as a randomized complete block design, consisting of 15 experimental plots, with three replicates and five treatments. Treatment 1 (T1) served as the control without biochar, while treatment 2 (T2) received 10 tons of HB per ha, and treatment 3 (T3) received 20 tons of HB ha^{-1}. Similarly, treatment 4 (T4) received 10 tons of LB ha^{-1}, and treatment 5 (T5) received 20 tons of LB ha^{-1}. Previous studies have reported varying optimal application rates for biochar to enhance rice yield. Liu et al. (2022) suggested rates exceeding 20 tons per hectare, while Oladele (2019) recommended 6–12 tons per ha, and Xu et al. (2022) applied lower rates (2.4 to 12 tons per hectare) over an eleven-year experiment. Given these findings and considering the typical local application rate of organic manure (around 10 tons per hectare), this study employed application rates of 10 and 20 tons of biochar per hectare for comparison. The size of each experimental plot was 12 m^2 (4 × 3 m) (Neupane et al., 2023; Oladele, 2019), separated by small irrigation ditches (about 1 m wide). The experimental plots were planted with rice in the dry and rainy seasons, the first season from the end of November to March (dry season) and the second season from the end of May to August (rainy season). Biochar was applied once at the beginning of the first rice season (dry season). The amendment was evenly spread over the plot surface and incorporated into the top 0–15 cm soil using a hand hoe. Inorganic fertilizers were applied based on local practices ($N = 80$ kg ha^{-1}, $P_2O_5 = 40$ kg ha^{-1}, and $K_2O = 40$ kg ha^{-1} season^{-1}).

2.3. Rice measurements, soil sampling, and chemical analysis

2.3.1. Rice measurements

Grain weight was measured using four 1-m^2 sample frames randomly placed on individual plots and aboveground biomass from these frames was collected. Fresh rice grains from these frames were dried at 55 °C until a constant weight was achieved (Scariot et al., 2020). The dried grains were winnowed and weighed, and grain yield was calculated in kg m^{-2} for each of the 15 plots. Additionally, all rice straw from the four frames in one plot was weighed and around 2 kg of fresh straw was taken, dried, and weighed to compute water content. The dry straw yield was calculated from the fresh straw yield after subtracting water content and presented in kg m^{-2} for individual plots. Root weight was measured using a 40-cm^2 (20 cm × 20 cm) frame, with two frames placed in each of the four-grain frames, making a total of 8 root frames per experimental plot. The top soil layer (0–15 cm) from these root frames was collected and rice roots were collected, washed, and air-dried until constant weight. The dried root was weighed and the root weight was computed in kg m^{-2} for each of the 15 plots.

2.3.2. Soil sampling and chemical analysis

After root collection, soil from 8 root frames was mixed well and spread over a 1-m^2 plastic tarpaulin. Around 3 kg of fresh soil was randomly taken from 8 points on the tarpaulin, air-dried, sieved through a 2-mm sieve, and stored until analyses. All soil samples from both seasons and biochar samples before the experiment were analyzed for various parameters, including pH, organic carbon (OC), cation exchange capacity (CEC), ammonium (NH_4^+), Mehlich-1 phosphorous (P), sulfate (SO_4^{2-}), exchangeable acidity, exchangeable hydrogen (H^+), exchangeable sodium (Na), exchangeable potassium (K), exchangeable magnesium (Mg), exchangeable manganese (Mn), exchangeable aluminum (Al), exchangeable calcium (Ca), and exchangeable iron (Fe). pH was measured using a 1:5 (*w*/w) ratio of soil to water after shaking for 1 h (FAO, 2021). Exchangeable cations in the soil were determined using the barium chloride method (Carter and Gregorich, 2008). In this method, 30.0 mL of 0.1 M $BaCl_2$ was added to a 50-mL centrifuge tube containing 0.5 *g* of air-dried soil, and the mixture was shaken for 2 h. The extracts were then analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES) to determine the concentration of exchangeable cations. SO_4^{2-} levels were quantified using the turbidimetric method (Rice et al., 2017). Mehlich-1 P was determined in the extracts from a mixture of air-dried soil and HCl + H_2SO_4 using an ammonium molybdate method (Bortolon et al., 2010). The levels of OC, NH_4^+, exchangeable acidity, exchangeable H^+, and CEC were quantified using methods outlined in the Soil Chemical Analysis of Soil Sampling and Methods of Analysis book (Carter and Gregorich, 2008).

2.4. Statistical analyses

Experimental data were subjected to a two-way analysis of variance (ANOVA) for a randomized complete block design with three replicates. Five treatments and two seasons were considered as two experimental factors, affecting the observations. Soil quality index (SQI) was calculated based on principal components analysis/factor analysis (PCA/FA) (Mukherjee and Lal, 2014; Nguyen et al., 2021) (Eq. (1)).

$$SQI = \sum_{i=1}^{n} w_i s_i \tag{1}$$

Where n is the number of soil parameters, w_i is the weightage of the ith parameter, and s_i is the score of the ith parameter. The w_i values for the SQI calculation are derived from PCA/FA method, which was applied to the comprehensive dataset encompassing all 15 soil quality parameters measured in our study, following the approach by Abdu et al. (2023). These soil parameters represent a balanced assessment of soil quality, reflecting both acid-sulfate characteristics (SO_4^{2-}, pH, and the exchangeable forms of Fe, Al, Mn, acidity, and H^+) and soil nutritional status (NH_4^+, organic carbon, CEC, Mehlich-1 P, and exchangeable Na, Ca, Mg, and K). This holistic approach ensures that our SQI calculation captures the complex interplay of various soil properties. Latent factors with eigenvalues greater than 1 were retained to estimate the weightage of soil parameters having loading values greater than 0.5. The soil parameter weightage was computed based on the method used in Nguyen et al. (2021). SQI like other soil parameters was also subjected to two-way ANOVA. Additionally, simple linear regression analysis was employed to examine the relationship between rice growth and yield with SQI.

3. Results

3.1. Initial properties of the tested soil and biochar

The properties of the experimental soil and biochar before the experiment are summarized in Table 1. The experimental soil had pH levels varying from 5.91 to 6.37, lower than LB (7.1–7.3), and HB (8.3–8.5). The CEC levels of the two biochars ranged from 19.43 to 22.5 cmol(c) kg^{-1}, significantly higher than the soil (7.66 cmol(c) kg^{-1}). The levels of Mehlich-1 P and OC were substantially greater in HB (2260.3 mg kg^{-1} and 33.7 %, respectively) and LB (546.8 mg kg^{-1} and 63.7 %, respectively) than in the soil (33.73 mg kg^{-1} and 5.56 %, respectively). SO4^{2-} concentration was lowest in LB (0.72 g kg^{-1}), while that in HB and experimental soil had 7.33 g kg^{-1} and 4.33 g kg^{-1}, respectively. Of the three experimental materials, the soil had the highest levels of exchangeable acidity (4.83 cmole(c) kg^{-1}), exchangeable Al (0.74 g kg^{-1}), and exchangeable Fe (0.15 g kg^{-1}), while HB exhibited the greatest values of exchangeable K (10.8 g kg^{-1}), exchangeable Mg (0.46 g kg^{-1}), exchangeable Mn (0.07 g kg^{-1}), and exchangeable Na (2.24 g kg^{-1}). LB had the lowest levels of exchangeable acidity (0.62 cmole(c) kg^{-1}), exchangeable K (1.02 g kg^{-1}), exchangeable Mg (0.3 g kg^{-1}), and exchangeable Na (0.33 g kg^{-1}).

3.2. Soil properties after the experiment

At the end of each experimental season, soil samples were collected from all 15 experimental plots and subsequently analyzed for 15 distinct soil properties, which were presented in Figs. 1, 2, 3, and 4. In the dry season, biochar application significantly (*p*-value <0.05) impacted pH, exchangeable acidity, and exchangeable H$^+$ in the tested soil, while the rainy season exhibited substantial effects on only exchangeable acidity, compared to the control treatment (Fig. 1). The control treatment had significantly lower pH (4.53) and higher levels of exchangeable acidity (6.83 cmol(c) kg^{-1}) and exchangeable H$^+$ (3.12 cmol(c) kg^{-1}) than the biochar-added treatments. In the dry season, treatment 3, applied with 20 tons of HB per ha, had the greatest pH value (4.95), lowest exchangeable acidity (5.1 cmol(c) kg^{-1}), and exchangeable H$^+$ (2.25 cmol(c) kg^{-1}). Increasing the biochar rate to 20 tones ha^{-1} did not significantly change pH, SO$_4^{2-}$, exchangeable acidity, and exchangeable H$^+$ compared the the 10-tone biochar rate. SO$_4^{2-}$ concentration remained consistent across treatments during both seasons, varying from 4.24 to 4.47 g kg^{-1} in the dry season and 3.36 to 3.89 g kg^{-1} in the rainy season. The dry season exhibited higher levels of SO$_4^{2-}$, exchangeable acidity, and exchangeable H$^+$ but lower pH values than the rainy season.

Cation exchange capacity (CEC) is a crucial soil property that reflects its ability to retain essential plant nutrients and the higher CEC values generally indicate better soil fertility and nutrient retention capacity. During the dry season, CEC in T2 and T3 showed significantly (p-value <0.05) higher levels than T1 while T4 and T5 showed similar values to T1 (Fig. 2a). In contrast, the second rice season exhibited similar CEC levels in all five treatments. The application of rice husk biochar (HB) and longan biochar (LB) significantly reduced NH$_4^+$ concentration, varying from 106 to 116 mg kg^{-1}, compared to 132 mg kg^{-1} in T1, in the dry season, while HB addition significantly enhanced the levels of this nutrient to 140 mg kg^{-1} (T2) and 150 mg kg^{-1} (T3), compared to 125.6 mg kg^{-1} in T1 in the rainy season (Fig. 2b). Mehlich-1 P concentration was greatly increased by HB application (7.38 mg kg^{-1} for T2 and 8.68 mg kg^{-1} for T3) but was not affected by LB application, compared to the control treatment (7.17 mg kg^{-1}) in the dry season (Fig. 2c). In the rainy season, this available P was not significantly different among the five treatments. Both biochars enhanced OC content in both seasons, rising from 5.75 % and 5.34 % (T1) to 5.99 % and 5.65 % (T2), 6.17 % and 6.17 % (T3), 5.85 % and 6.12 % (T4), and 6.08 % and 6.38 % (T5) in season 1 and 2, respectively (Fig. 2d).

Biochar addition strongly decreased the levels of both exchangeable Al in both seasons, while exhibiting no significant effects on exchangeable Mn concentration in the soil (Fig. 3), compared to the no-biochar treatment. In both seasons, exchangeable Al concentration was highest in T1 (1.7 in the dry season and 0.63 g kg^{-1} in the rainy season) and lowest in T3 (1.52 in the dry season and 0.52 g kg^{-1} in the rainy season) (Fig. 3a). The levels of exchangeable Fe were substantially lower in the biochar treatments compared to the control treatment during the dry season. Its concentrations varied from 0.35 g kg^{-1} in T1 to 0.23 g kg^{-1} in T3 in the dry season and from 0.05 g kg^{-1} in T1 to 0.02 g kg^{-1} in T5 in

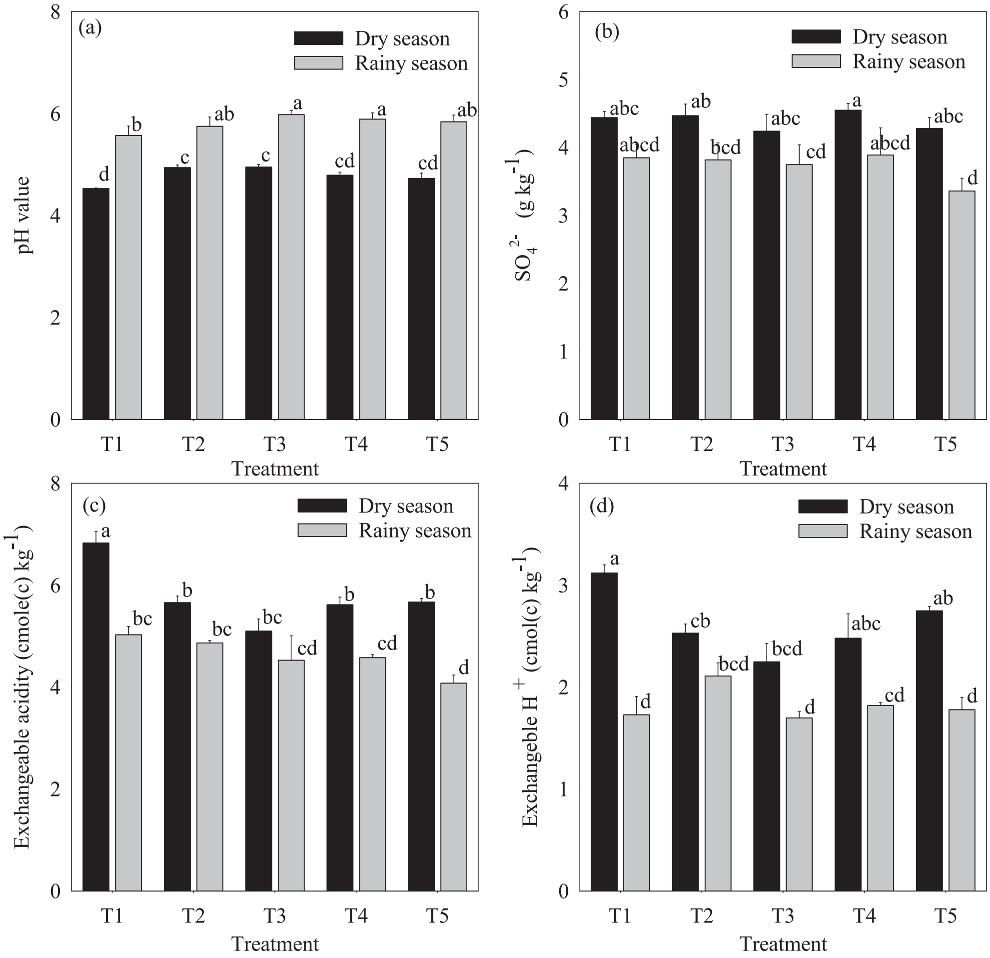

Fig. 1. The levels of pH (a), SO$_4^{2-}$ (b), exchangeable acidity (c), and exchangeable H$^+$ (d) in the soil in two rice seasons. Within a panel, bars labeled with the same letter do not statistically significantly differ from each other with $p \leq 0.05$. T1 = no biochar, T2 = 10 tones HB ha^{-1}, T3 = 20 tons HB ha^{-1}, T4 = 10 tons LB ha^{-1}, and T5 = 20 tons LB ha^{-1}.

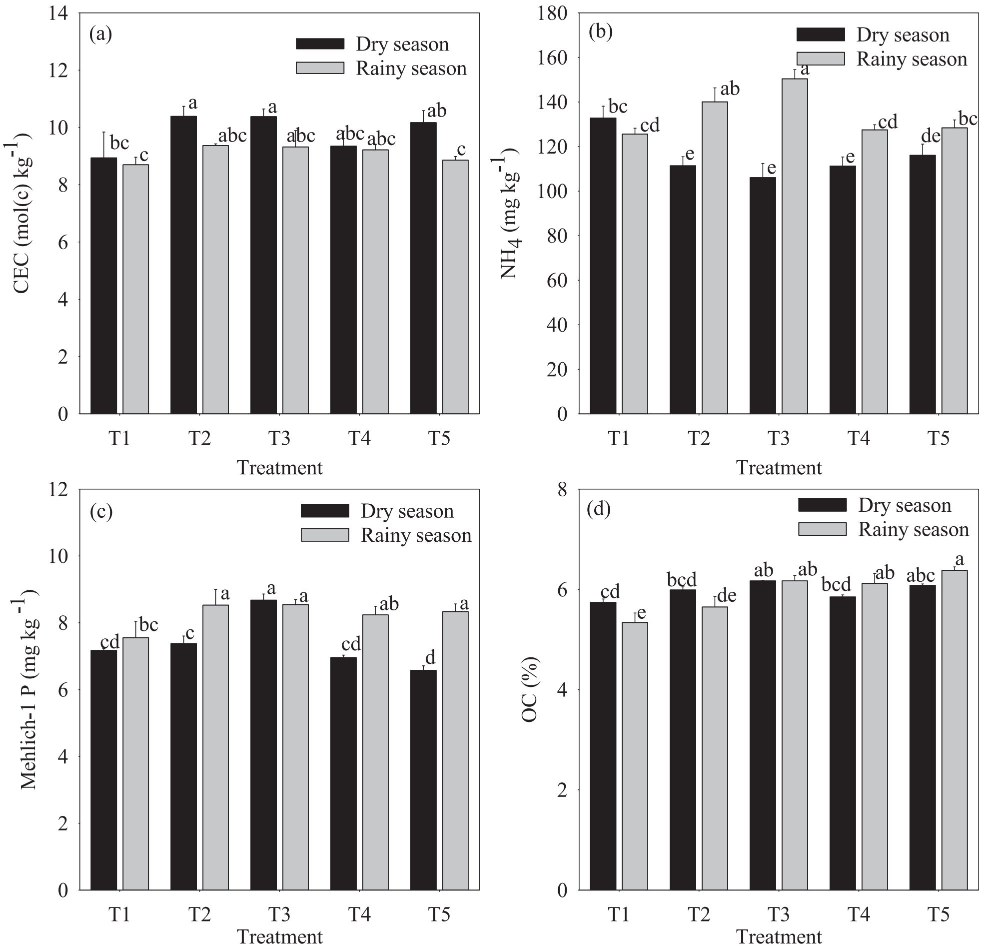

Fig. 2. The levels of CEC (a), NH_4 (b), Mehlich-1 P (c), and organic carbon (OC, d) in the soils in two rice seasons. Within a panel, bars labeled with the same letter do not statistically significantly differ from each other with $p \leq 0.05$. T1 = no biochar, T2 = 10 tones HB ha^{-1}, T3 = 20 tons HB ha^{-1}, T4 = 10 tons LB ha^{-1}, and T5 = 20 tons LB ha^{-1}.

the rainy season (Fig. 3b). The concentration of these three elements in the exchangeable form was lower in the rainy season than in the dry season.

Compared to the control treatment, biochar treatments significantly (*p*-value <0.05) affected exchangeable Na in both seasons, had significant impacts on exchangeable K and Ca in the dry season, but not in the rainy season, and had no influence on exchangeable Mg in both seasons (Fig. 4). Rice husk biochar (HB) greatly increased the exchangeable K levels (2.64 g kg^{-1} in T2 and 2.82 g kg^{-1} in T3), while LB had no considerable impact on the same element (2.34 g kg^{-1} in T4 and 2.31 g kg^{-1} in T5), compared to T1 (2.25 g kg^{-1}), in the dry season (Fig. 4a). The exchangeable Na concentration in soil in the four biochar treatments varied from 1.22 to 1.34 g kg^{-1}, compared to the control treatment (1.47 g kg^{-1}) in the first season (Fig. 4b). The concentrations of exchangeable Ca were much greater in T4 and T5 than in T1 in the first season, while they were statistically similar in all five treatments in the second season (Fig. 4c). The dry season exhibited greater levels of these base cations than the rainy season.

The whole dataset was grouped into two latent factors, based on PCA/FA (Table 2). Factor 1 exhibited strong coefficients with all exchangeable parameters, SO_4^{2-}, pH, and Mehlich-1 P, while factor 2 had high loading values with NH_4^+, OC, and CEC. These two factors together explained 79.9 % of the total variance of the entire dataset. Parameter weightage, calculated from PCA/FA, was used to compute the soil quality index (SQI) shown in Fig. 5. SQI was significantly (*p*-value <0.05) greater in biochar-added soil than no-biochar-added soil in the dry season. In the rainy season, T4 showed a greater SQI than T1 while the other biochar treatments showed statistically similar SQI to T1. Treatment 3 (20 tons of HB ha^{-1}) exhibited the greatest SQI (0.63), followed by T2 (0.53), T4 (0.51), T5 (0.47), and T1 (0.41) during the dry season. The soil in treatment 5 exhibited greater SQI during the rainy season than during the dry season, while the soil in the other biochar-added treatments showed similar SQI in both seasons.

3.3. *Rice growth and yield*

The five experimental treatments exhibited similar effects on root weight in both seasons (Fig. 6a). Biochar application notably increased stem weight in the dry season while showing a statistically similar influence during the rainy season (Fig. 6b). Soil added with biochar had greater grain weight and total biomass of paddy rice in both seasons, compared to soil added without biochar (Fig. 6c and d). In the dry season, T3 had the highest stem weights (1.08 kg m^{-2}), followed by T5, T4, T2, and T1, while all these five treatments had similar stem weights in the rainy season (Fig. 6b). T3 also had the highest grain weight and T1 showed the lowest in both seasons (Fig. 6c). The total biomass of paddy rice was significantly (p-value <0.05) highest in T3 (2.31 and 1.10 kg m^{-2}) and lowest in T1 (1.71 and 0.85 kg m^{-2}) in the dry and rainy seasons, respectively (Fig. 6d). The dry season exhibited a lower root weight but greater stem weight, grain weight, and total biomass than the rainy season.

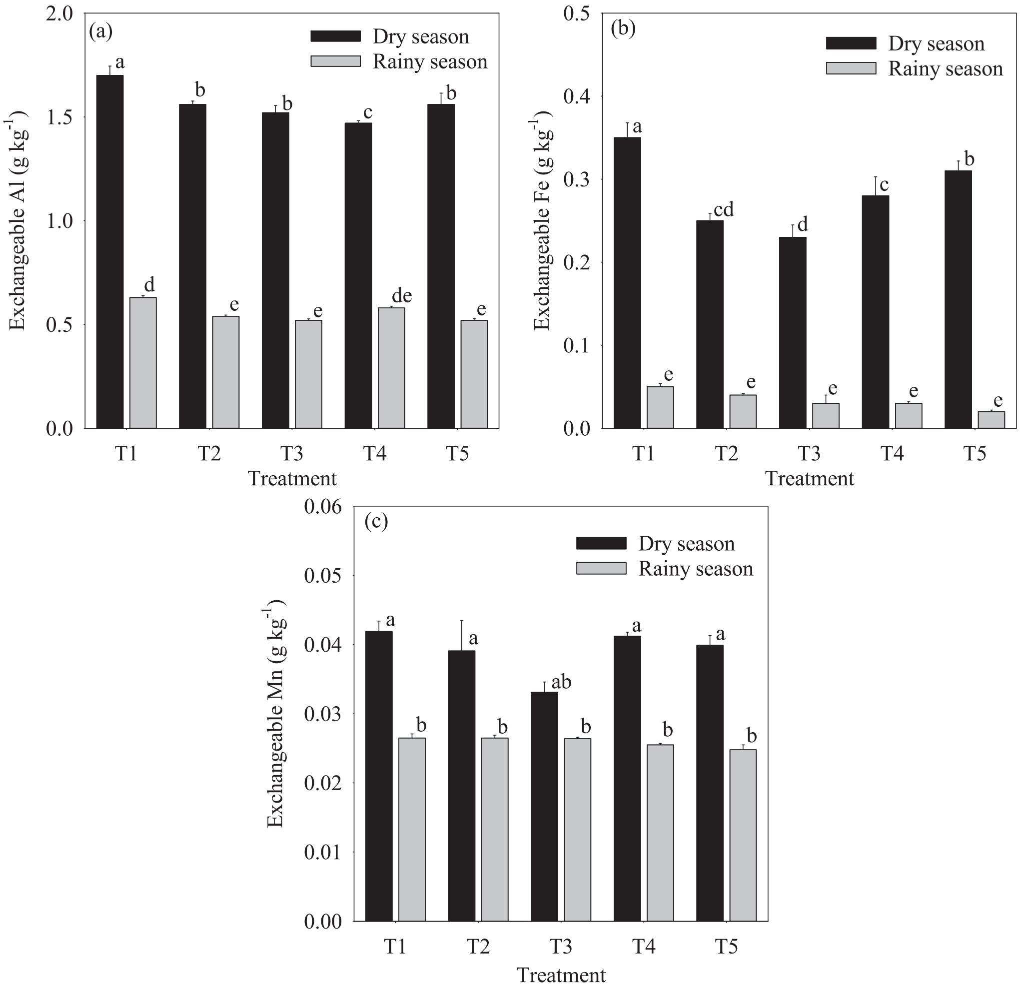

Fig. 3. The levels of exchangeable Al (a), exchangeable Fe (b), and exchangeable Mn (c) in the soil in two rice seasons. Within a panel and in the same rice season, bars labeled with the same letter do not statistically significantly differ from each other with $p \leq 0.05$. T1 = no biochar, T2 = 10 tones HB ha^{-1}, T3 = 20 tons HB ha^{-1}, T4 = 10 tons LB ha^{-1}, and T5 = 20 tons LB ha^{-1}.

3.4. Relationship between soil quality index (SQI) and rice growth and yield

Overall, the dry season demonstrated significant linear relationships between grain weight and total biomass with SQI (Fig. 7). In the dry season, when SQI increased from 0.41 to 0.63, simultaneously, the grain weight fluctuated between 0.74 and 1.08 kg m^{-2} and the total biomass rose from 1.71 to 2.31 kg m^{-2}. The corresponding rates of increase for grain weight and total biomass were 1.27 and 2.14 kg m^{-2}, respectively, for each unit rise in SQI. In the rainy season, the relationships between SQI and grain weight as well as total biomass were not significant.

4. Discussion

4.1. Effects of biochar on soil properties and quality

In this study, we categorized the 15 measured soil parameters into two main groups. The first group termed the “acid-sulfate-related group” includes soil parameters associated with acid-sulfate characteristics, such as SO_4^{2-}, pH, and the exchangeable forms of Fe, Al, Mn, acidity, and H^+. The second group, designated as the “nutrient-related group”, comprises soil parameters reflecting soil nutrition, including NH_4^+, OC, CEC, Mehlich-1 P, exchangeable Na, Ca, Mg, and K. Biochar addition, particularly high-alkalinity biochar such as HB, introduces a considerable quantity of base elements to the soil (Table 1). This addition effectively neutralizes soil acidity, resulting in elevated soil pH and reduced exchangeable H^+ (Fig. 1) during the dry season. These findings align with previous studies (Ahmee and Yakob, 2021; Huang et al., 2023; Jing et al., 2020; Yousaf et al., 2016). Biochar is reported to have high levels of alkaline elements and buffering capacity, making it effective in mitigating soil acidity (Cornelissen et al., 2018; Masud et al., 2020). The increased soil pH and decreased exchangeable acidity led to a reduction in the exchangeable Al and Fe in biochar-added soil (Fig. 3). Additionally, biochar’s ability to adsorb metals, including Al and Fe (Pandey et al., 2022; Qian and Chen, 2014) may contribute to this effect. Furthermore, binding with phosphorus can be an additional mechanism contributing to the reduced exchangeable Al and Fe levels in the tested soil (Nguyen et al., 2022b). The finding is in agreement with other studies, such as (Geng et al., 2022; Wang et al., 2023a). Notably, the impacts on exchangeable Fe and H^+ are observed primarily in the dry season, whereas the influences on pH, exchangeable acidity, and exchangeable Al remain significant across both seasons. This finding suggests that exchangeable Al in the soil can be the primary agent controlling the variation of pH and exchangeable acidity in the soil after the first rice season (Zama et al., 2022). Due to the higher adsorption affinity of cations with greater valence (Doi et al., 2020), Al^{3+} is more strongly adsorbed on soil and biochar particles, compared to H^+ (Chang et al., 2023). Consequently, increasing leaching during the second season with high rainfall, may cause more H^+ loss. These suggest that the effects of biochar on acidity-related parameters could be diminished after the dry season due to leaching while its impacts on multivalent cations such as Al and its associated soil properties persist after the rainy

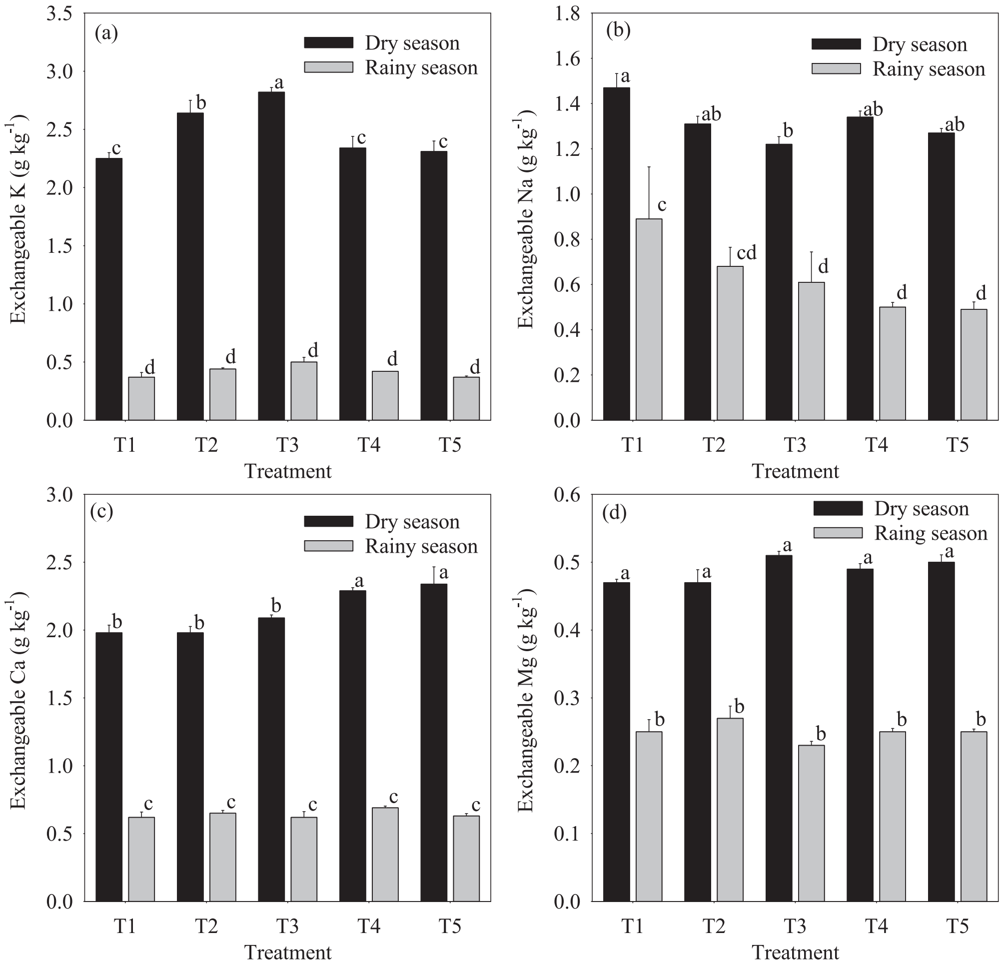

Fig. 4. The levels of exchangeable K (a), exchangeable Na (b), exchangeable Ca (c), and exchangeable Mg (d) in the soil in two rice seasons. Within a panel and in the same rice season, bars labeled with the same letter do not statistically significantly differ from each other with $p \leq 0.05$. T1 = no biochar, T2 = 10 tones HB ha^{-1}, T3 = 20 tons HB ha^{-1}, T4 = 10 tons LB ha^{-1}, and T5 = 20 tons LB ha^{-1}.

Table 2
Factors and parameter weightage of 15 measured soil properties from PCA/FA. The bold numbers are those greater than 0.5.

Parameter	Factor 1	Factor 2	Parameter weightage
Exchangeable Fe	**0.96**	0.20	0.08
Exchangeable Al	**0.94**	0.30	0.08
Exchangeable Mn	**0.93**	0.11	0.08
Exchangeable Na	**0.93**	0.12	0.08
Exchangeable Ca	**0.91**	0.36	0.08
Exchangeable Mg	**0.91**	0.37	0.08
Exchangeable acidity	**0.89**	−0.24	0.08
Exchangeable H^+	**0.88**	0.01	0.08
Exchangeable K	**0.87**	0.43	0.08
SO_4^{2-}	**0.73**	0.07	0.08
NH_4^+	−0.49	**−0.62**	0.01
OC	−0.23	**0.73**	0.01
CEC	0.24	**0.73**	0.01
Mehlich-1 P	**−0.70**	0.30	0.08
pH	**−0.92**	−0.22	0.08
Eigenvalue	10.18	1.80	
Percent (%)	67.88	12.02	
Cumulative Percent (%)	67.88	79.90	
Factor weightage	0.85	0.15	

season.

Biochar addition not only mitigates soil parameters in the acid-sulfate-related group but also introduces nutrient-related elements such as K, Ca, Na, and Mg to the soil, altering their concentration (Fig. 4). The improved levels of exchangeable K observed in the two treatments added with HB (Fig. 4a) can be attributed to the high K content of this biochar type (Table 1). Rice husk biochar is known for its elevated K concentration, which significantly increases soil K levels upon application (Asadi et al., 2021; Mosharrof et al., 2021). The great mobility of K in wet soil (Zeng and Brown, 2000) can be the main reason for no significant difference in its concentration in all five treatments during the rainy season due to leaching. The lower concentration of exchangeable Na in biochar-added soil in both seasons compared to the control treatment (Fig. 4b) could be unclear, but possibly related to the adsorption capacity of the amendments (Nguyen et al., 2022a). The elevated levels of exchangeable Ca in LB-added soil are likely attributed to the higher Ca content in this amendment (Table 1), which aligns with findings from other studies (Berek et al., 2018; Shetty and Prakash, 2020).

The high organic carbon content in biochar leads to improved OC levels in biochar-added soil, compared to the control treatment (Fig. 2d) in both seasons. The interesting findings were observed in the concentrations of NH_4^+ and Mehlich-1 P, which significantly differed among the five treatments (Fig. 2b and c). In the dry season, the lower NH_4^+ concentrations in four biochar treatments relative to the control treatment suggest strong adsorption or retention of NH_4^+ (Hossain et al., 2020; Weldon et al., 2022) and microbial immobilization of NH_4^+ due to the high C:N ratio of the amendment. The increased NH_4^+ concentration in HB-amended soil in the second season could be attributed to improved mineralization of immobilized nitrogen by aged biochar after one season

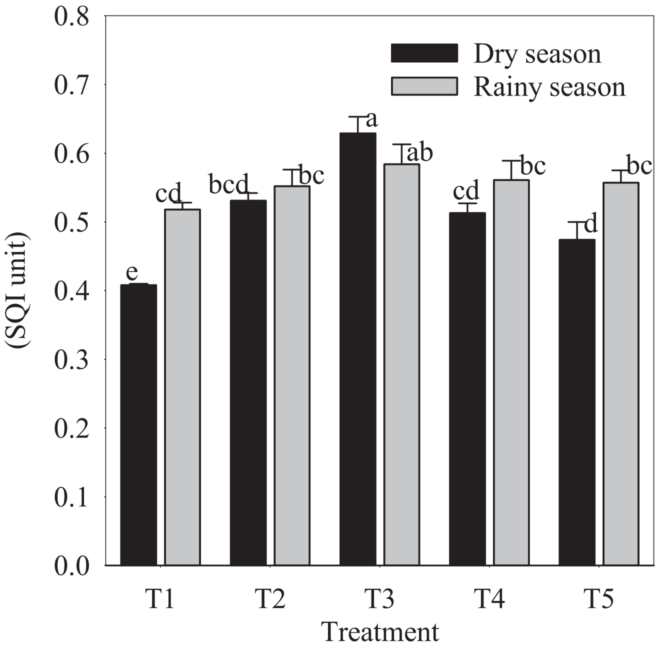

Fig. 5. Soil quality index (SQI) in two rice seasons. In the same rice season, bars labeled with the same letter do not statistically significantly differ from each other with $p \leq 0.05$. T1 = no biochar, T2 = 10 tones HB ha^{-1}, T3 = 20 tons HB ha^{-1}, T4 = 10 tons LB ha^{-1}, and T5 = 20 tons LB ha^{-1}.

(Luo et al., 2016). The fact that only HB-amended soil shows increased NH_4^+ in the second season suggests its stronger impacts on N immobilization or retention than LB. The difference between the two biochar types could be related to their physical and chemical properties. While HB showed better levels of nutrients such as NH_4^+ and Mehlich-1 P than LB (Table 1), HB was reported to have greater surface areas than LB (Nguyen et al., 2022c), accounting for the findings. The available P in soil is affected by various factors, including pH, Al and Fe availability, and organic matter (Hawkins et al., 2022; Kwesi, 2020). The significant increase in Mehlich-1 P in the 20-tone HB-added soil compared to the control treatment suggests a liming effect and co-addition of P of the amendment at a high rate (Hale et al., 2020; Oladele et al., 2024; Vilakazi et al., 2023). The lack of significant effects of biochar on acidity-related properties, such as pH, exchangeable acidity, and exchangeable H^+ in the rainy season (Fig. 1), explains the comparable levels of Mehlich-1 P across all treatments during this period (Fig. 2c). This also emphasizes the primary role of the liming effect of added biochar, especially HB, in elevating soil P availability in the current study.

A consistent pattern emerges among soil parameters in the acid-sulfate-related group (Figs. 1 and 3) and exchangeable forms of K, Na, Ca, and Mg (Fig. 4), showing a significant decrease in magnitude during the rainy season compared to the dry season, with pH being an exception. The rainy season, happening from late May to August 2023, is characterized by high rainfall (around 250 mm per month). Soil parameters such as Al, Fe, and Mn likely originate from pyrites, which undergo oxidation when exposed to the atmosphere during the dry season, releasing these cations into the soil (Manickam et al., 2015; Shamshuddin et al., 2004). Pyrite oxidation also generates sulfuric acid, releasing H^+ into the soil (Nyman et al., 2023). In contrast, the abundant rainfall during the rainy season enhances leaching, removing acid-sulfate-related parameters from the surface layer, responsible for the findings. The leaching process also likely accounts for the reduced levels of base cations in the rainy season, compared to the dry season. The leaching of base cations, coupled with their relative replacement by Al^{3+}, Fe^{2+}, and H^+ ions on soil particles, is the primary process contributing to the formation of acidic soil (Ng et al., 2022). This suggests that base cations can be more susceptible to leaching than Al^{3+}, Fe^{2+}. The leaching of base cations in the current study could be one of several factors contributing to the decreased rice growth and yield in the rainy season compared to the dry season, a topic further explored in the following section.

All changes in soil properties discussed above are overall reflected through SQI, computed from the entire dataset in the current study. All biochar treatments showed an improved SQI compared to the control treatment in the dry season, while only treatment 3 exhibited a considerably higher value of SQI in the rainy season. The findings indicate that the overall effects of biochar on soil quality may diminish in the second rice season. Two main reasons responsible for the findings include strong leaching during the second season of high rainfall (Alves et al., 2023) and diminished effectiveness of biochar after a few seasons (Cornelissen et al., 2018; Nguyen et al., 2021). Nonetheless, essential soil properties, such as NH_4^+, Mehlich-1 P, OC, exchangeable Al, pH, and exchangeable acidity still exhibit improvements in HB-added soil in the second season of high rainfall. These properties may be responsible for the increased grain weight and total biomass of rice in the rainy season, as discussed in the following section.

4.2. Rice growth and yield and related mechanisms

The improvement of soil properties and quality generally leads to enhanced rice growth and yield in biochar treatments compared to the control during the dry season (Fig. 6). This aligns with prior research demonstrating that biochar application at various rates contributes to enhanced plant growth and increased productivity (Chen et al., 2021; Dong et al., 2015; Pratiwi and Shinogi, 2016). Consequently, a significant and linear relationship between SQI with grain weight and total biomass in the dry season was observed, consistent with findings in other studies (Liu et al., 2015; Zhou et al., 2023). The finding indicates that rice yield and growth can be further improved with an increase in soil quality in the dry season. Nevertheless, the rainy season exhibited an insignificant relationship between SQI and rice yield and total biomass (Fig. 7b). This could be attributed to several factors, primarily the leaching of soil exchangeable elements during the rainy season, which mitigates the effects of biochar. Additionally, weather conditions, including rainfall and humidity, may impact rice growth and consequently influence this relationship. Despite this insignificant relationship, grain weight and total biomass were significantly greater in biochar treatments than in the control treatment (Fig. 6d) during the rainy season. In this season, although the overall SQI was not significantly different among the five treatments, some crucial soil parameters including NH_4^+, Mehlich-1 P, OC, exchangeable Al, exchangeable acidity, and pH were still improved by the biochar treatments. These improvements in key soil properties likely explain the observed differences in rice yield and growth among treatments, even in the absence of significant differences in the composite SQI.

Higher levels of exchangeable Al, Fe, and Mn in the dry season compared to the rainy season (Fig. 3) can be attributed to the lower root weight in the dry season (Fig. 6a) in all five treatments. These soil properties induce phytotoxicity in rice, limiting its root growth (Kabir et al., 2016; Ofoe et al., 2023). In response, rice may develop mechanisms to remediate the adverse impacts of these phytotoxic elements (Ofoe et al., 2023; Thalassinos et al., 2023), resulting in root growth being more susceptible to phytotoxicity, while aboveground parts such as stem and grain are less affected. Conversely, aboveground biomass, including stem weight and grain, was substantially higher in the dry season than in the rainy season. This observation can be attributed to various factors, primarily differences in weather conditions between the two seasons. The dry season experienced low rainfall (11 to 140 mm per month) compared to the rainy season (204 to 279 mm per month) (Hang et al., 2022). Intensive rainfall during the rainy season can cause various damages to rice, including lodging, unfilled grains, and preharvest sprouting, leading to yield loss (Su and Kuo, 2023). Increasing rainfall

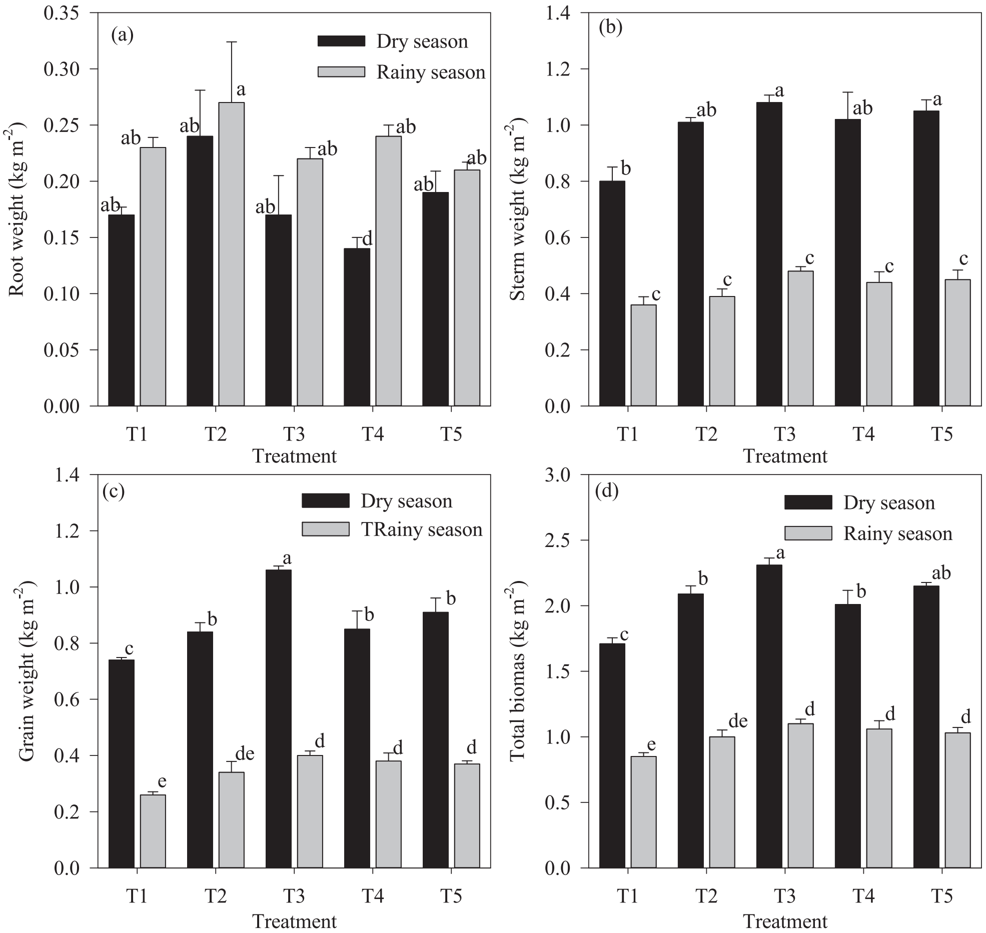

Fig. 6. Root weight (a), stem weight (b), grain weight (c), and total biomass (d) of rice in two rice seasons. Within a panel and in the same rice season, bars labeled with the same letter do not statistically significantly differ from each other with $p \leq 0.05$. T1 = no biochar, T2 = 10 tones HB ha^{-1}, T3 = 20 tons HB ha^{-1}, T4 = 10 tons LB ha^{-1}, and T5 = 20 tons LB ha^{-1}.

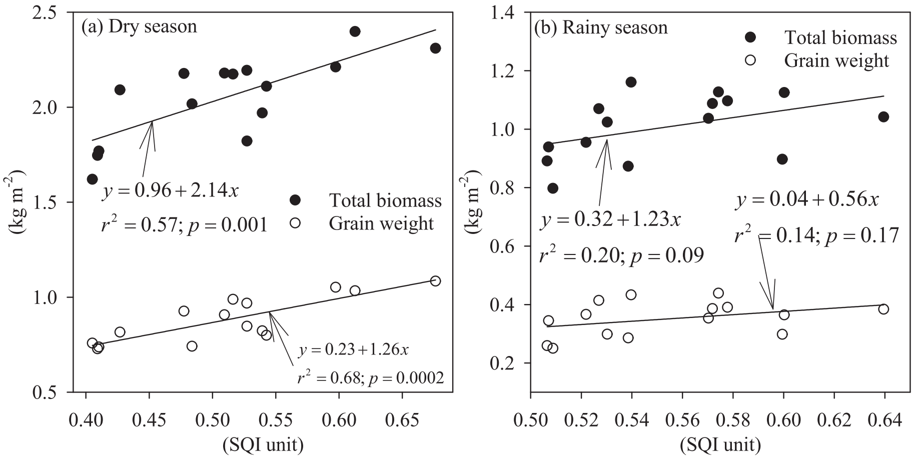

Fig. 7. Correlation between soil quality index (SQI) and rice growth and yield in two rice seasons.

may also elevate air humidity, making rice more susceptible to pests and diseases (Mousumi et al., 2023). Furthermore, leaching during the rainy season may cause the loss of base elements through downward movement, reducing their availability and subsequently affecting rice yield. These findings strongly indicate that rice yield in the current study is influenced by a complex interplay of factors, with nutrient leaching and seasonal weather conditions playing crucial roles.

4.3. *Implication for management and limitations of the current study*

The current study affirms biochar application as an effective strategy for managing acid-sulfate soils. Derived from the pyrolysis of organic matter, biochar, especially rice husk biochar, rich in alkaline elements, greatly improves soil properties related to acidity and nutrition. This amendment helps neutralize the intrinsic properties of acidity features, reducing levels of some phytotoxic elements such as Al, Fe, and Mn, consequently enhancing rice yield and growth in paddy fields. Converting abundant crop residues available in most countries all over the world to biochar offers multiple benefits, including soil constraint mitigation and improved rice productivity. Furthermore, in light of ongoing global climate change (Lindsey and Dahlman, 2024) and substantial greenhouse gas emissions from rice production (Wang et al., 2023b), biochar addition to rice fields is highly encouraged because it plays a crucial role in mitigating these global issues by limiting methane emissions and increasing carbon sequestration in rice-cultivated soils (Bagheri Novair et al., 2023).

The study reveals a complex relationship between biochar application and seasonal weather patterns in acid-sulfate soil regions. While the initial improvements were observed in the dry season, the beneficial impacts of biochar on soil properties diminished during the second season of high rainfall. This led to minimal overall improvement in the soil quality index, suggesting that the applied biochar rate in the current study may be insufficient to fully address soil constraints, or that the soil has a great buffering capacity against biochar-induced changes. Additionally, the high rainfall during the rainy season likely diminished the effectiveness of biochar through leaching, suggesting that biochar application may yield more enduring effects in low-rainfall regions. These findings suggest the need for periodic re-application of biochar in high-rainfall areas with acid-sulfate soils. The study also emphasizes that biochar's effectiveness can vary based on various factors such as biochar type, application rate, and land conditions, highlighting the need for further research in diverse acid-sulfate soil environments to inform sustainable rice production practices.

This study presents important findings that contribute to our understanding of the quality and the characteristics of acid-sulfate soils, as well as providing a potential solution for ameliorating these problematic soils. However, the study has some limitations that need to be addressed in future research. Firstly, the experimental design involved two consecutive seasons (dry and wet), with results showing a decrease in biochar effectiveness after the second rainy season. This decrease is likely due to nutrient leaching caused by rain, which mitigates the effectiveness of biochar. Alternatively, it could be due to the natural decline of biochar's efficacy over time in the soil (Oladele, 2019). To verify this, another study with the order reversed (rainy season followed by dry season) is needed, which would strengthen conclusions about the impact of seasonal variation on biochar effectiveness. Secondly, attention should be paid to the leaching mechanism that mitigates the effectiveness of biochar in acid-sulfate soils. While leaching is typically a technical measure to improve these soils (Imanudin et al., 2021), it also reduces the content of mobile nutrients like K^+ and NH_4^+ in the soil. It is uncertain whether the simultaneous reduction of nutrients and phytotoxic elements like Al, Fe, and H^+ increases plant productivity. Finally, a limitation of the study is that it only monitored soil quality parameters reflecting the chemical properties. Some physical and microbiological soil properties should also be observed to provide a more comprehensive assessment of biochar's effects on acid-sulfate soils.

5. Conclusions

This study analyzed the properties of biochar produced from rice husks and longan branches and evaluated its impacts on soil properties, quality, and rice yield in paddy fields of acid-sulfate soil. The results demonstrated that biochar addition improved soil acidity and reduced the levels of exchangeable Al, and Fe in the soil, which are related to the liming effects of the amendment. The availability of some specific soil properties related to plant nutrition is also improved, likely due to co-addition with the amendment and positive change in soil chemistry. Consequently, the soil quality index was enhanced by biochar addition, typically rice-husk-derived biochar, in the dry season but not in the rainy season. Rice husk biochar demonstrates greater effectiveness than longan biochar in mitigating soil constraints and improving rice growth and yield. While biochar highly increases rice growth and yield in the dry season, its impacts are comparatively lower in the subsequent rainy season. The high rainfall season diminished the beneficial impacts of biochar, possibly due to leaching, suggesting that more frequent applications of the amendment may be necessary in high rainfall regions. Those findings raise the need to implement more studies to examine the impacts of biochar derived from various feedstocks on acid–sulfate soil across diverse regions and conditions over a longer period.

Declaration of competing interest

The authors have no conflict of interest to declare.

Data availability

The authors do not have permission to share data.

Acknowledgments

This research was supported by Industrial University of Ho Chi Minh City (IUH) under grant number 22/1MT04. Special thanks go to the Institute of Environmental Science, Engineering, and Management (IESEM) of IUH. The assistance of the staff and students at IESEM in conducting field trips and laboratory activities is greatly appreciated.

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