Biochar Enhanced Rice (Oryza sativa L.) Growth by Balancing Crop Growth-Related Characteristics of Two Paddy Soils of Contrasting Textures

Article *in* Journal of Soil Science and Plant Nutrition · March 2022

DOI: 10.1007/s42729-022-00790-3

10 authors, including:

Binh Nguyen
Industrial University of Ho Chi Minh
31 PUBLICATIONS **1,378** CITATIONS

Tong Nguyen
Industrial University of Ho Chi Minh
27 PUBLICATIONS **151** CITATIONS

Hao Phu Dong
Industrial University of Ho Chi Minh
5 PUBLICATIONS **46** CITATIONS

Trung Phan
Ho Chi Minh City University of Technology (HCMUT)
10 PUBLICATIONS **42** CITATIONS

Journal of Soil Science and Plant Nutrition
https://doi.org/10.1007/s42729-022-00790-3

ORIGINAL PAPER

Biochar Enhanced Rice (*Oryza sativa* L.) Growth by Balancing Crop Growth-Related Characteristics of Two Paddy Soils of Contrasting Textures

Binh Thanh Nguyen[1] · Vinh Ngoc Nguyen[2] · Tong Xuan Nguyen[1] · My Hoang Nguyen[1] · Hao Phu Dong[1] · Gai Dai Dinh[1] · Binh Trung Phan[1] · Tan-Viet Pham[3] · Nam Van Thai[4] · Huong Thu Thi Tran[5]

Received: 4 October 2021 / Accepted: 26 January 2022

Abstract

Rice (*Oryza sativa* L.) growth can be influenced by base cation, plant-available nutrients, and potentially phytotoxic elements in soils. These soil-property groups can be altered by biochar addition, depending on soil textures. The current study aimed to examine the impacts of biochar on rice growth and identify associated mechanisms related to characteristics of soils of contrasting textures. A pot experiment was conducted using clayey and sandy soils added with five biochar rates (0, 0.5, 1, 2, and 5%, w/w) and planted with rice. Rice biomass was measured, and soil samples were taken to be analyzed for ten parameters when the experiment was ended. The base index (BI, average concentrations of exchangeable calcium, magnesium, sodium, and potassium), the nutrient index (NI, average concentrations of NH_4^+ and Mehlich-1 P), and the potentially phytotoxic index (PI, average concentrations of exchangeable aluminum, iron, and manganese) were computed for assessment. Biochar improved total rice biomass in the sandy soil (by 55%) more than in the clayey soil (42%). Biochar enhanced properties, the BI, and the NI while reducing the PI in the two tested soils. Total rice biomass was positively correlated with the base ratio (BI/PI) and the nutrient ratio (NI/PI). The findings suggest that mechanisms accounting for improved rice growth could be involved in the enhanced ratios caused by biochar addition. Biochar addition increased rice growth in the sandy soil more than in the clayey soil by raising the base and nutrient ratios of the two soils.

Keywords Biochar · Sandy Soil · Clayey Soil · Soil Fertility · Rice Growth

1 Introduction

Biochar has been reported to improve rice (*Oryza sativa L.*) growth and soil fertility (Awad et al. 2018; Jiang et al. 2021; Lu et al. 2020; Zhang et al. 2020a). Biochar also elevated the soil concentration of some nutrients, such as potassium (K), calcium (Ca), and available phosphorous (P) (Butphu et al. 2020), while reducing the concentration of potentially phytotoxic elements such as aluminum (Al), manganese (Mn), and iron (Fe) (Shetty et al. 2021; Yulnafatmawita et al. 2020). These findings suggest that the impacts of biochar on rice growth could depend on how the material balances the concentrations of nutritional elements and potentially phytotoxic elements in paddy soils, which were insufficient to discuss in the literature. Furthermore, soils with a greater clay content may be more resistant to the changes caused by biochar addition due to a higher buffering capacity than soils with lower clay content. This implies that the effects of biochar could additionally depend on soil texture, which was limitedly addressed.

✉ Nam Van Thai
tv.nam@hutech.edu.vn

1 Institute of Environmental Science, Engineering, and Management, Industrial University of Ho Chi Minh City, 12 Nguyen Van Bao, Go Vap District, Ho Chi Minh City, Vietnam

2 Department of Environmental Engineering, International University - Vietnam National University, Ho Chi Minh City, Quarter 6, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam

3 Institute of Biotechnology and Food Technology, Industrial University of Ho Chi Minh City, 12 Nguyen Van Bao Street, Go Vap District, Ho Chi Minh City, Vietnam

4 HUTECH Institute of Applied Sciences, HUTECH University, 475A, Dien Bien Phu, Ward 25, Binh Thanh District, Ho Chi Minh City, Vietnam

5 Faculty of Environment, Ha Noi University of Mining and Geology, 18 Pho Vien, Duc Thang, Bac Tu Liem, Hanoi, Vietnam

Published online: 16 March 2022

Paddy rice may require a variety of nutrients to grow properly, including N, P, and K (macronutrients); Mg and Ca (secondary macronutrients); and Fe and Mn (micronutrients) (Jiban et al. 2020). Fe and Mn can be phytotoxic to crops when present in high concentrations (Aung and Masuda 2020; Wang et al. 2015). In addition, Al in soils can be harmful to rice, causing the crop's root system to grow abnormally (Awasthi et al. 2017; Wang et al. 2015). Sodium (Na), an important soil element, is not essential but can be a beneficial nutrient to rice (Nieves-Cordones et al. 2016). These elements can be classified into three primary soil-property groups, which are the base group (Ca, Mg, Na, and K), nutrient group (NH_4^+ and available P), and potentially phytotoxic group (Al, Mn, and Fe). An enhancement of the base and nutrient groups, together with the reduction of the potentially phytotoxic group, could lead to improved rice growth, which could be influenced by biochar addition.

Biochar is a carbon-rich and porous material with some functional groups (-OH, -COOH), that can adsorb cations (Du et al. 2020; Yang et al. 2018a; Zhang et al. 2020b). Generally, various biochars produced from different feedstocks at different pyrolysis temperatures were well documented to improve soil quality (Tomczyk et al. 2020) and crop productivity (Biederman and Harpole 2013; Pandit et al. 2018; Zheng et al. 2013). Biochar addition was reported to increase the concentration of some elements in the base groups (K, Ca, and Mg) and the nutrient group (mineral N and available P) (Butphu et al. 2020; Mensah and Frimpong 2018; Vijay et al. 2021) while decreasing the concentration of elements in the potentially phytotoxic group (Al, Mn, and Fe) (Shetty et al. 2021; Yulnafatmawita et al. 2020). These findings suggest that biochar can be used as a potential paddy-soil amendment to improve rice growth and productivity.

In fact, many studies have shown that biochar can improve the yield and growth of rice and the properties of paddy soils. For example, biochar addition can increase rice yield and improve soil properties, such as pH, organic carbon, and bulk density (Pratiwi and Shinogi 2016; Yang et al. 2018b). Muhammad et al. (2017) demonstrated that wheat straw-derived biochar significantly increased rice growth and yield, compared to the no-biochar treatment. The authors also showed that biochar increased the concentrations of total organic carbon, nitrogen, Ca, and P, but decreased the extractable concentrations of other nutrients (K and Mn) of their tested soils. An increase in some nutrients and depletion in others may lead to nutritional imbalance, restricting crop productivity. Other studies found that biochar addition could have positive, negative, or neutral effects on the extractable fractions of various soil nutrients (Gaskin et al. 2010; Miranda et al. 2017; Muhammad et al. 2017). These inconsistent findings suggest that biochar may have varying impacts on the properties of paddy soils. Furthermore, limited studies have been carried out to investigate the connection between the three soil-property groups and rice growth, which could be considered as a primary and comprehensive mechanism of biochar in improving rice growth.

Moreover, the effects of biochar on rice growth could depend on soil characteristics, such as soil texture (Chen et al. 2021; Dai et al. 2020). Soil with a greater clay content (clayey soil) was found to have a higher concentration of many elements than soil with a higher sand content (sandy soil) (Abubakar 2017; Dou et al. 2016; Tahir and Marschner 2016). Some elements in soils such as Al, Mn, and Fe may be largely originated from the clay mineral, and therefore their concentrations in the clayey soils can be greater than in the sandy soils (Dixon 1991; Gill et al. 2000). Additionally, clayey soils with greater buffering capacity could be more resistant to the change caused by biochar addition than sandy soils. In contrast, with a high content of some phytotoxic elements, the clayey soils could benefit more from biochar addition because the material can reduce the exchangeable form of these elements. These arguments are insufficiently discussed in the literature and hence are in need to be tested.

Therefore, the current study was carried out to examine the impacts of biochar on rice growth and identify associated mechanisms related to characteristics of two paddy soils of contrasting textures. It was hypothesized that biochar would have stronger effects on soil properties and rice growth in clayey soil than in sandy soil and that the improved rice growth caused by biochar addition would be determined by the combination of the three soil-property groups.

2 Materials and Methods

2.1 Experimental Materials

The current study was conducted in a greenhouse, using two soils of contrasting textures, obtained from two paddy fields in Vietnam. The clayey and sandy soils were chosen because they may react differently to the impacts of biochar (Dai et al. 2020). The clayey soil with a high clay concentration and therefore buffering capacity may restrict the effects of biochar, whereas the sandy soil with a low clay content may be influenced strongly by the material. The clayey soil was taken from a dystric fluvisol (FAO/UNESCO) in Long Hoa commune, Can Duoc District, Long An province (106° 35′ E and 10° 34′N), and the sandy soil was from a haplic acrisol in Xuan Thoi Son commune, Hoc Mon District, Ho Chi Minh City (106° 35′E and 10° 52′N) for the current experiment. The two fields were located in a tropical climatic zone with two distinct seasons, the rainy season from May to October and the dry season from December to April. Ho Chi Minh City has an annual rainfall of around 1868 mm and an average temperature of around 27.4 °C. Ten soil samples (0–10 cm) (Muhammad et al. 2017) were taken from different sites randomly selected over each of two paddy fields, and mixed thoroughly to form two composite samples, which were air-dried, ground, and sieved to pass through a 2-mm sieve to remove plant residues and gravel. Three sub-samples of each composite soil were taken for chemical and physical analysis, and the remainder was used for the current experiment.

The biochar used in the current study was produced from rice straw and husk several months before the experiment, using a kiln developed by Nguyen et al. (2018b) with some modification. The kiln reactor was built from a steel sheet rolled into a 0.8 × 1.5m cylinder (width × height). The rice straw and rice husk were collected, washed out, air-dried, and chopped into 3–5-cm segments (for the rice straw) before being pyrolyzed at temperatures estimated to be around 350 to 400 °C. The rice straw-derived biochar and rice husk-derived biochar were mixed at a 1:1 ratio (hereinafter referred to as biochar) before using for the experiment. Other materials such as inorganic fertilizers and the rice variety (OM 2517) were purchased from stores near the sampling fields (within 2 km). The properties of the three experimental materials are shown in Table 1.

2.2 Experimental Setup

A greenhouse pot experiment was set up using a completely randomized design with three replicates and two experimental factors (two soils × five biochar rates). Each of the two sieved soils was mixed with biochar at five different rates (0, 0.5, 1, 2, and 5%, w/w), resulting in a total of 10 experimental treatments (T1, T2, T3, T4, and T5 were the treatments of clayey soil added with 0, 0.5, 1, 2, and 5% biochar, respectively, and T6, T7, T8, T9, and T10 were the treatment of sandy soil added with 0, 0.5, 1, 2, and 5% biochar, respectively). To achieve a uniform soil volume in all 30 pots, 3.6–4.6 kg of the biochar-soil mixture (hereinafter referred to as experimental soil), depending on biochar rates and soils, was repacked into a pot (17.5 cm × 20 cm, diameter × height) with some gentle tamps. The experimental soil in each pot was 14-cm tall, with a few centimeters from the top of the pots used for standing water. The 30 experimental pots were randomly placed in a separate area (3-m wide and 4-m long), within an experimental greenhouse (8-m wide × 20-m long), with temperatures varying from 25 °C (night) to 36 °C (day), no direct rain or wind, and 70–80% humidity. The experimental pots were filled with tap water to a depth of 3 cm — water for 10 days before transferring rice seedlings (some agronomic practices used in rice cultivation are shown in Supplementary Text 1). The surface water depth was regulated between 1 and 3 cm during the 3.5-month life cycle of the rice crop.

2.3 Measurements of Rice Growth and Soil Properties

Rice biomass (the weight of root, stem, and grain) was harvested from 30 individual pots using the procedure applied by Nguyen et al. (2018a). The stem biomass including stem, leaves, tillers, and panicles (but not the grain) was determined by cutting the aboveground plants at the ground level into a plastic bag. Grain biomass was collected from all panicles of each pot into a plastic bag. Water from experimental pots was then decanted, and soil samples were collected from the 0–10-cm surface layer using a soil sampler for chemical analysis. The remaining soil from individual pots was spread out on a plastic sheet and rinsed with tap water to collect root biomass. The collected biomass was oven-dried at 70 °C to a constant weight (Chaimala et al. 2020; Zhang et al. 2019). The dried biomass from individual pots was weighed for assessment.

Soil and Biochar Samples Before the experiment, the sieved soil and biochar were sampled in three replicates for chemical analysis. After the experiment, about 1 kg of experimental soil (0–10 cm) from each pot was collected, air-dried, and ground to pass a 2-mm sieve before analysis.

Table 1 Initial properties of experimental materials. *SE*, standard error. The clay, silt, and sand content of the clayey soil were 60.9, 33.1, and 6%, respectively, and those of the sandy soil were 5.5, 3.4, and 91.1%, respectively. *OC*, organic carbon

Material	Statistics	pH	Ca	Mg	Na	K	Al	Mn	Fe	NH_4^+	Mehlich-1 P	OC	N
			mg kg^{-1}									%	
Biochar	Mean	8.7	1032	146	1271	8495	2.0	18.7	6.8	12.3	104.7	38.73	0.69
	SE	0.0	11	1.5	12	46	0.2	0.1	0.2	2.0	4.3	0.23	0.031
Clayey soil	Mean	6.8	2284	1220	290	889	12.6	19.3	4.0	32.9	2.7	1.84	0.18
	SE	0.2	16	9	24	34	0.3	0.7	0.3	3.7	0.0	0.03	0.003
Sandy soil	Mean	7.0	1007	31	29	77	2.1	1.1	1.2	24.2	4.6	0.80	0.06
	SE	0.1	6	0.8	11	6	0.9	0.1	0.2	1.4	0.1	0.13	0.006

Chemical Analyses All soil and biochar samples were analyzed for pH, plant-available nutrients (Mehlich-1 P and NH_4^+), and exchangeable concentration (Na, K, Mg, Ca, Al, Fe, and Mn). The materials were added with distilled water in a 1:2 (w/w) ratio, and the extract was measured for pH using a Thermo Scientific™ Orion™ 3-Star Benchtop pH meter. The concentration of NH_4^+ was measured with 2M KCl, and the concentration of Mehlich-1 P was determined using the Mehlich-1 method (Carter and Gregorich 2008). The concentrations of exchangeable Na, K, Mg, Ca, Al, Fe, and Mn were measured using the $BaCl_2$ method, and the extract was analyzed using an inductively coupled plasma-optical emission spectrometry (ICP-OES) (Carter and Gregorich 2008). Total organic carbon and nitrogen were determined using the dry combustion method with an elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) (Knoblauch et al. 2021). In addition, the sieved soil was analyzed for particle size distribution (Carter and Gregorich 2008). The before-experiment biochar was examined for chemical functional groups using a Fourier-transform infrared spectroscopy (Jasco FT/IR-4700 type A spectrophotometer) (Li et al. 2020) and for porosity using a scanning electron microscope (SEM, model LE01430VP, Germany) (Nguyen et al. 2010).

2.4 Statistical Analyses

To evaluate biochar effects, the change in soil concentration was calculated by subtracting the measured concentration of biochar-containing treatments (T2, T3, T4, and T5) from the associated concentration of the no-biochar treatment (T1) (the measured values of all 10 soil parameters are shown in Supplementary Tables 1 and 2). Three soil indexes were computed; the base index (BI) was calculated by averaging the total concentrations of exchangeable Ca, Mg, Na, and K; the nutrient index (NI) was average concentrations of NH_4^+ and Mehlich-1 P, and the phytotoxic index (PI) was average concentrations of exchangeable Al, Fe, and Mn. The base ratio and nutrient ratio were computed by dividing BI by PI, and NI by PI, respectively. All data, indexes, and ratios were statistically analyzed, following the procedure of the analysis of variance (ANOVA) of a two-factor completely randomized design, using JMP 10 (SAS Institute Inc., NC, USA). When the ANOVA result indicated a significant effect at $P \leq 0.05$, the Tukey's honestly significant difference test was used to classify treatment means. Linear and non-linear regression fits were performed to examine dependent patterns of soil properties on biochar rates. The linear and non-linear models were determined based on the shape of the scatter plot, r^2 value (coefficient of determination), and a 95% confidence level ($P \leq 0.05$).

3 Results

3.1 Rice Growth as Affected by Biochar Rates

The sandy soil exhibited significantly higher root weight than the clayey soil (Figure 1a) for each biochar rate. The increase in biochar rate improved root weight in both examined soils with different dynamic patterns of exponential growth and a linear trend. On average, root weight rose from 20 to 37 (g DWT pot^{-1}) in the sandy soil and from 4 to 10 (g DWT pot^{-1}) in the clayey soil when the biochar rate was increased from 0 to 5%. Although the influence of biochar rates on stem weight was unclear, the clayey soil had a greater stem weight (24.2 g DWT pot^{-1}) than the sandy soil (19.2 g DWT pot^{-1}) (Figure 1b). The clayey soil had a higher grain weight (15.4) than the sandy soil (12.1 g DWT pot^{-1}) (Figure 1c). When the biochar rate was increased from 0 to 5%, the average grain weight was increased from 13 to 17 (g DWT pot^{-1}) in the clayey soil and 10 to 14 (g DWT pot^{-1}) in the sandy soil.

Consequently, total rice biomass, a sum of root, stem, and grain weight, was not significantly affected by the interaction of biochar rate and soil but was strongly affected by biochar rate and soil independently (Figure 1d). With an increase in the biochar rate (from 0 to 5%), the average total rice biomass was increased from 39 to 56 (g DWT pot^{-1}) (increased by 42%) in the clayey soil and from 48 to 74 (g DWT pot^{-1}) (increased by 55%) in the sandy soil. The rising patterns in the total rice biomass differed between the two tested soils, with an exponential rise in the clayey soil and a linear trend in the sandy soil. The sandy soil had significantly greater total biomass (59.6 g DWT pot^{-1}) than the clayey soil (45.8 g DWT pot^{-1}).

3.2 Plant Growth-Related Properties of Paddy Soils as Affected by Biochar Addition

3.2.1 Base and Nutrient Groups

The change in the concentrations of exchangeable Ca, Mg, Na, and K of the paddy soils is shown in Figure 2 (the observed concentrations are shown in Supplementary Table 1). The interaction effect of biochar and soil on the change in exchangeable Ca and K concentrations was significant, but not on exchangeable Mg and Na concentrations (Figure 2a, 2b, 2c, and 2d). Biochar addition significantly raised the exchangeable Ca concentration of the clayey soil, following a linear model, but increased that of the sandy soil, according to an exponential-rise model (Figure 2a and 2c). The change in exchangeable K concentrations of the two soils was best described by a

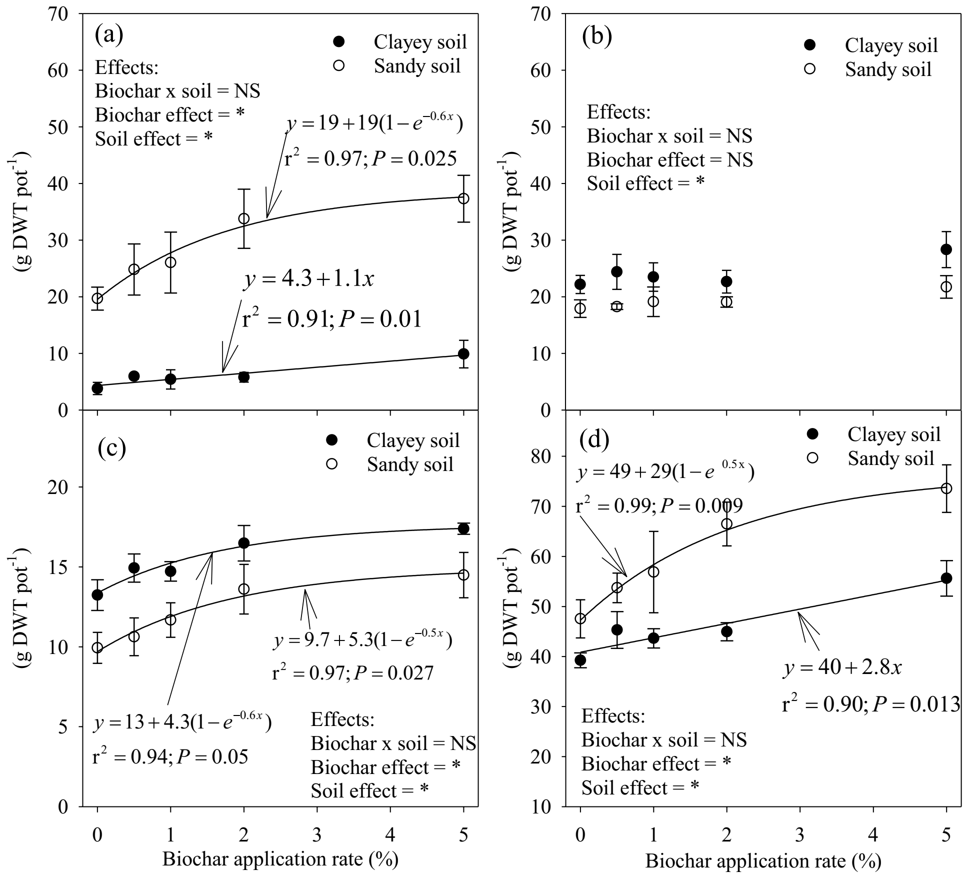

Fig. 1 Root weight (**a**), stem weight (**b**), grain weight (**c**), and total biomass (**d**) in two paddy soils as affected by biochar addition. Error bars represent the standard error of the mean. NS and * indicate the effects are not significant and significant, respectively. DWT, dried weight

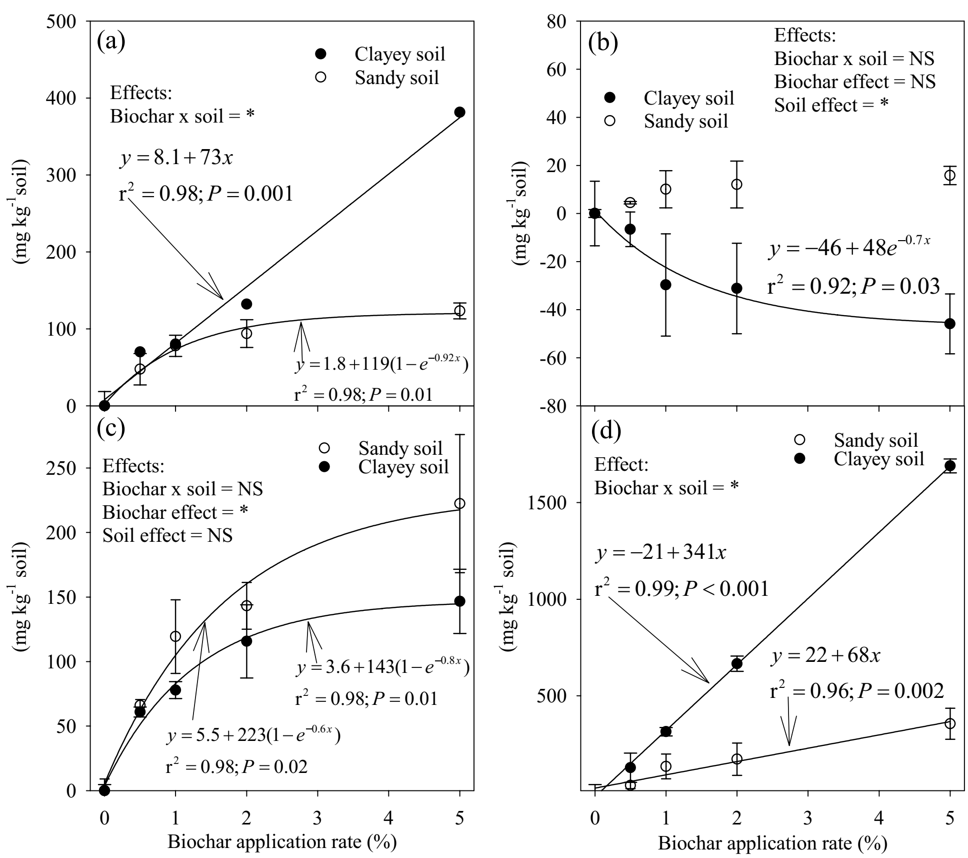

Fig. 2 Changes in the concentrations of exchangeable Ca (**a**), Mg (**b**), Na (**c**), and K (**d**) of the two paddy soils caused by biochar addition. Error bars represent the standard error of the mean. NS and * indicate the effects are not significant and significant, respectively

linear function, with an increased K rate of 341 and 68 (mg kg^{-1}) for every increasing biochar percent in clayey and sandy soil, respectively. The change in concentrations of exchangeable Ca and K was greater in the clayey soil than in the sandy soil. The changing pattern of exchangeable Na concentrations in both tested soils was similarly best fit by the exponential rise model. The exchangeable Na concentration in the clayey soil was increased by 61 (T2) to 147 (mg kg^{-1}, T5), and that in the sandy soil was from 66 (T7) to 222 (mg kg^{-1}, T10). The effect of biochar rate on the exchangeable Mg concentration in the sandy soil was minimal, but significant in the clayey soil. An increase in biochar rate led to a reduction in the exchangeable Mg concentration by −6.6 (T2) to −45.9 (mg kg^{-1}, T5) when compared to the no-biochar treatment (T1).

The changes in the concentration of both NH_4^+ and Mehlich-1 P were not significantly affected by the interaction between biochar and soil but were affected by individual factors (Figure 3a, 3b). With an increase in the biochar rate, the concentration of NH_4^+ and Mehlich-1 P of the two tested soils was increased significantly. The rising trend of these two nutrients of the two soils followed an exponential rise paradigm. The concentration of NH_4^+ rose by 3.2 (T2) to 10.3 (mg kg^{-1}, T5) in the clayey soil and by 2.3 (T7) to 9.6 (mg kg^{-1}, T10) in the sandy soil when compared to the no-biochar treatments of the corresponding soil. Similarly, the concentration of Melich-1 P was raised by 0.2 (T2) to 2.6 (mg kg^{-1}, T5) in the clayey soil and by 1.4 to 4.4 (mg kg^{-1}, T10) in the sandy soil, relative to the no-biochar treatment.

The base index (the average concentration of exchangeable Ca, Mg, Na, and K) of the two tested soils was significantly affected by the interaction between biochar and soil (Figure 3c). An increase in biochar rate resulted in a linear rise in the base index of the clayey soil with an increasing rate of 107 (mg kg^{-1}). The base index in the sandy soil was elevated from 257 (T6) to 437 (mg kg^{-1}, T10) over the range of biochar rate, following an exponential growth model. The nutrient index (average concentration of NH_4^+ and Mehlich-1 P) was not significantly affected by the interaction between biochar and soil (Figure 3d). Biochar addition significantly increased the index, following an exponential rise function. The nutrient index was increased from 15 (T1) to 21.5 (mg kg^{-1}, T5) in the clayey soil and 7.5 (T6) to 14.5 (mg kg^{-1}, T10) in the sandy soil. The clayey soil had significantly greater base and nutrient indexes than the sandy soil.

3.2.2 The Potentially Phytotoxic Group

The change in the concentration of exchangeable Al and Mn was significantly affected by the interaction between biochar and soil, but not that of Fe (Figure 4a and 4b) (the measured concentration of these elements in this group is

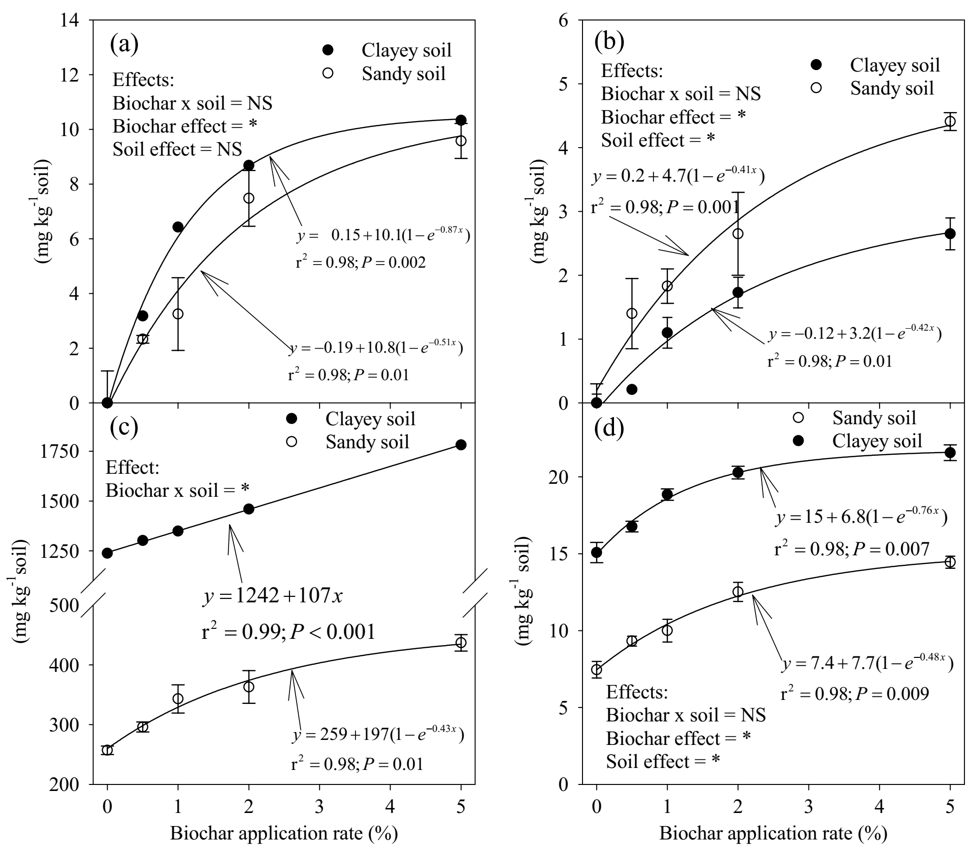

Fig. 3 Changes in the concentrations of NH_4^+ (**a**), Mehlich-1 P (**b**), base index (**c**), and nutrient index (**d**) in the two tested soils. Error bars represent the standard error of the mean. NS and * indicate the effects are not significant and significant, respectively

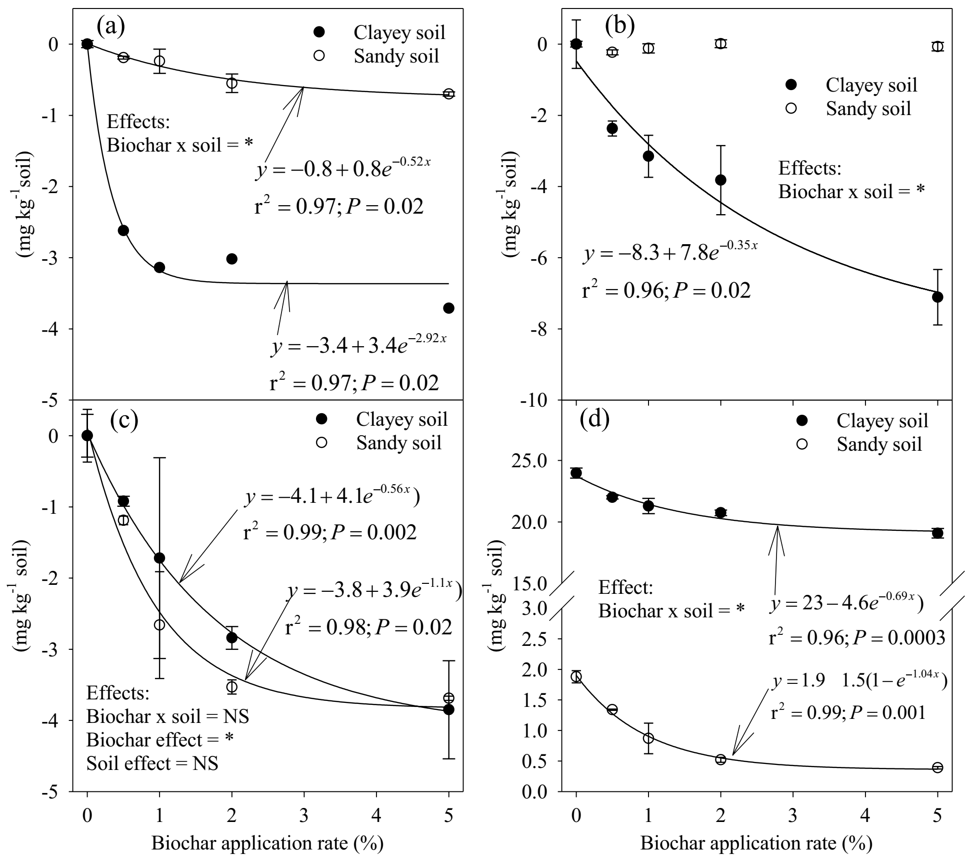

Fig. 4 Changes in the concentrations of exchangeable Al (**a**), Mn (**b**), and Fe (**c**), and the potentially phytotoxic index (**d**) of the two paddy soils affected by biochar addition. Error bars represent the standard error of the mean. NS and * indicate the effects are not significant and significant, respectively

shown in Supplementary Table 2). In the clayey soil, the exchangeable Al concentration was rapidly decreased by 2.6 (T2) to 3.7 (mg kg^{-1}, T5) when the biochar rate was raised from 0.5 to 5%, respectively, compared to the T1 of no-biochar addition. In the sandy soil, the exchangeable Al concentration was slowly decreased by 0.2 (T7) to 0.7 (mg kg^{-1}, T10). The concentration of exchangeable Mn in the clayey soil was reduced significantly by 2.4 (T2) to 7.1 (mg kg^{-1}, T5), but not in the sandy soil when the biochar rate was increased from 0.5 to 5%. The exchangeable Fe concentration of both tested soils was similarly decreased as the biochar rate was increased (Figure 4c). When the biochar rate was increased from 0.5 to 5%, the exchangeable Fe concentration in the clayey soil was declined by 0.9 (T2) to 3.8 (mg kg^{-1}, T5), and the sandy soil was decreased by 1.2 (T7) to 3.7 (mg kg^{-1}, T10). The phytotoxic index (average concentration of exchangeable Al, Mn, and Fe) was significantly reduced with the biochar rate, following an exponential decay model. The index of the clayey soil was decreased from 24 to 19 (mg kg^{-1}), when the biochar rate was enhanced from zero to 5%, respectively. The index of the clayey soil was much greater than that of the sandy soil, which was declined from 1.9 to 0.4 (mg kg^{-1}) with a rise in the biochar rate from zero to 5%, respectively.

3.2.3 The Base and Nutrient Ratios and pH

The base ratio (the ratio of the base index to the potentially phytotoxic index) and the nutrient ratio (the ratio of the nutrient index to the potentially phytotoxic index) were calculated and shown in Figure 5a and 5b. These two ratios were significantly influenced by the interaction of biochar and soil. The base ratio in the clayey soil was proportionally increased at a rate of 8 units per 1% of biochar added. The base ratio in the sandy soil rose exponentially across the range of the biochar rate, increasing from 138 (T6) to 1130 (T5). Similarly, the nutrient ratio in the clayey soil was linearly increased with biochar rates, with an increasing rate of 0.09 units per 1% biochar added. This ratio was increased from 4.0 (T6) to 37.3 (T10) when biochar was raised from 0 to 5% in the sandy soil. The increase in these two ratios was much faster in the sandy soil than in the clayey soil. Soil pH was not significantly affected by the interaction of biochar and soil (Figure 5c). The pH values of the sandy soil were greater than those of the clayey soil.

3.3 The Relationship Between Rice Growth and Soil-Property Groups

For the two tested soils, the total rice biomass rose exponentially over the range of the base ratio (50 to 1305) and

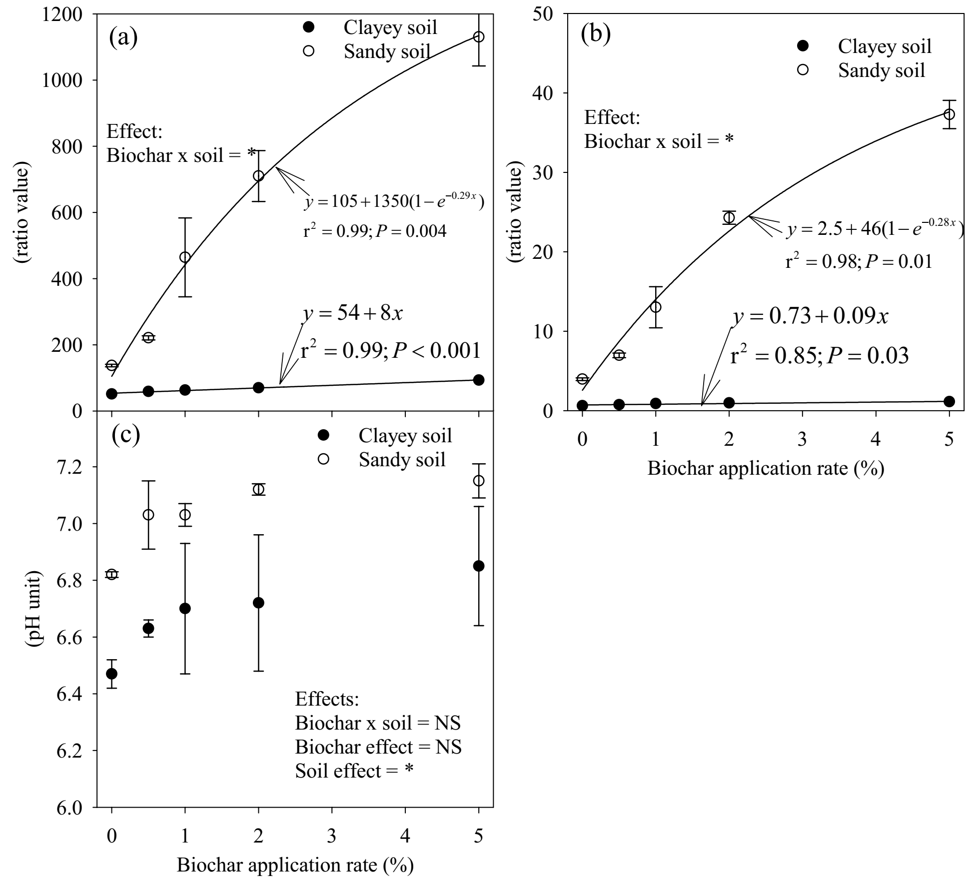

Fig. 5 The base ratio (**a**), the nutrient ratio (**b**), and pH (**c**) of the two paddy soils affected by biochar addition. Error bars represent the standard error of the mean. NS and * indicate the effects are not significant and significant, respectively

nutrient ratio (0.6 to 40.2) (Figure 6a and 6b). Total biomass was increased rapidly when the base ratio was below 600 units and the nutrient ratio was less than 25 units. The total rice biomass in the clayey soil was the highest (56 g DWT pot^{-1}) when the base ratio was about 93.5 and the nutrient ratio was about 1.13 units (Figure 6c). Compared to the clayey soil, the sandy soil had significantly higher total rice biomass, which reached its highest value (73.6 g DWT pot^{-1}), when the base ratio was about 1130 and the nutrient ratio was about 37.29 units (Figure 6d).

4 Discussion

Biochar addition significantly improving rice growth components (root weight, grain weight, and total biomass) in two soils with different textures (Figure 1) was consistent with previous studies (Dong et al. 2015; Kartika et al. 2018; Muhammad et al. 2017). The sandy soil had a substantially higher root weight but a lower grain weight than the clayey soil (Figure 1a and 1c). Some possible explanations for the higher root weight of sandy soil than the clayey soil may include (1) the sandy soil had a higher sand content, which resulted in a better portion of the large-size pore, facilitating rice root development, (2) the sandy soil with a lower nutrient content (Table 1) may stimulate rice roots to develop faster than the clayey soil to acquire more nutrients, and (3) the clayey soil exhibited a greater concentration of exchangeable Al, Mn, and Fe (Table 1), which may cause toxicity to the rice's root system (Gill et al. 2000; Shetty et al. 2021). In contrast, the clayey soil had a significantly better grain weight than the sandy soil that was in line with a previous study (Dou et al. 2016). The better rice grain might be attributed to the higher nutrient content of the clayey soil than the sandy soil (Figures 2 and 3). Consequently, the total rice biomass was improved and significantly higher in the sandy soil than in the clayey soil, which may be explained by the changes in soil properties caused by biochar addition. Biochar enhanced rice growth more strongly in the sandy soil than in the clayey soil, which was consistent with earlier studies (Ye et al. 2019). The improved rice growth by biochar in the current study could be the consequence of balancing soil properties in the three soil-property groups, which would be discussed later.

The measured NH_4^+ reflects the balance of input (mainly N fertilizer and biochar addition) and output (nitrification, gas emission, and plant uptake) in the current study. Nevertheless, the increased concentration of NH_4^+ over the biochar rates (Figure 3a) could be mostly attributable to the added biochar, whereas plant uptake in the high biochar-rate

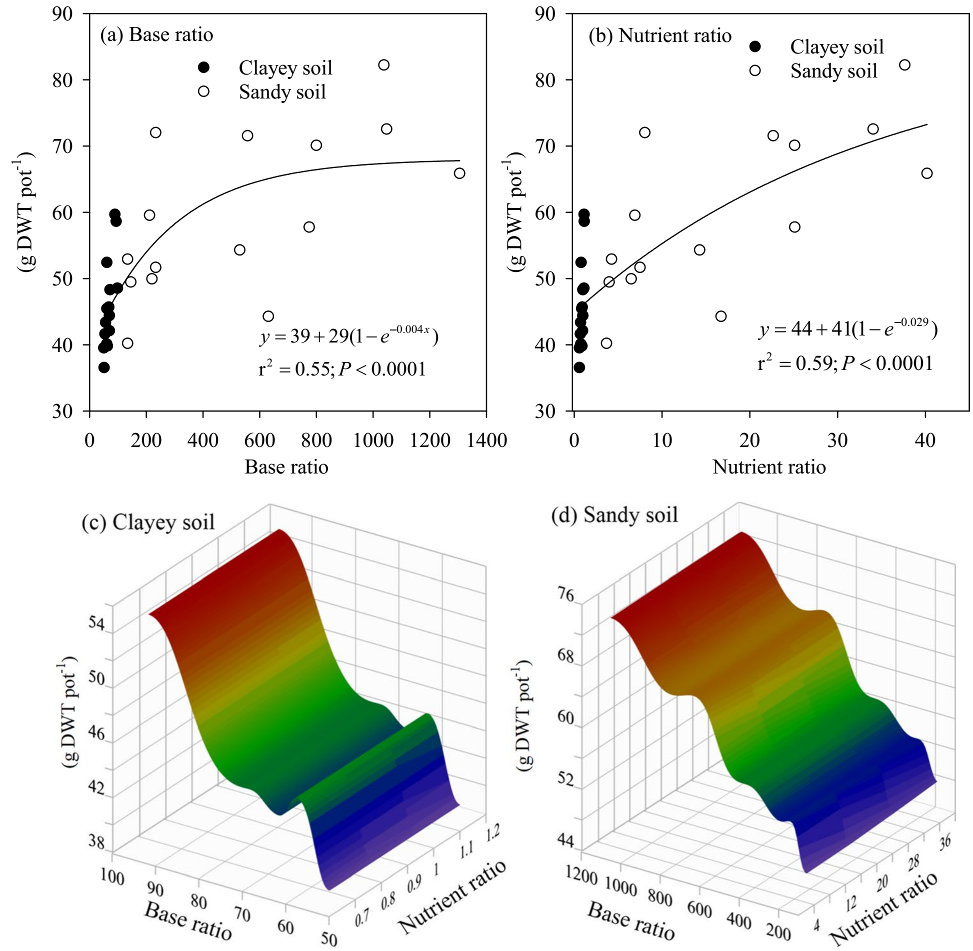

Fig. 6 a–d Relationship between total rice biomass and the base ratio and nutrient ratio of the two paddy soils. DWT, dried weight

treatments may decrease soil NH_4^+ concentration due to improved rice growth (Figure 1). Although the real reasons could be unclear, given that the NH_4^+ concentration of biochar (12.3 mg kg^{-1}) was much lower than that of the clayey (32.9 mg kg^{-1}) and sandy soil (24.2 mg kg^{-1}), one possibility accounting for the increased NH_4^+ concentration might be linked to the priming effect. Biochar addition has been shown to accelerate the mineralization of native soil organic matter (positive priming) (Luo et al. 2011; Mensah and Frimpong 2018). Organic N, as a part of soil organic matter (Normand et al. 2017), could be decomposed to enhance the available N concentration in soils upon the mineralization of soil organic matter.

The current study also found that biochar addition increased the concentration of Mehlich-1 P (Figure 3b), which is similar to a previous study (Schmidt et al. 2021). The co-addition of this nutrient with the added biochar could be the direct source of the increased Mehlich-1 P in the two studied soil. This is because the Mehlich-1 P concentration of biochar (104.7 mg kg^{-1}) was 39 and 23 times greater than that of the clayey soil (2.7) and the sandy soil (4.6 mg kg^{-1}), respectively. A considerable quantity of P released into solution during biochar decomposition (Yao et al. 2010) may also suggest that the increased concentration of Mehlich-1 P of the two tested soils could partly be derived from the added biochar. Moreover, the increased Mehlich-1 P following biochar addition could be explained by a few additional possibilities. One explanation could be related to organic matter decomposition due to the priming effect. This is because a portion of soil P may be linked to organic matter (Schlesinger and Bernhardt 2013), and the decomposition of the associated organic matter may release P into the soil solution. The other possibility for increasing soil Mehlich-1 P could be related to the exchangeable Al and Fe concentrations, which were considerably reduced with biochar addition rates (Figure 4a and 4c).

The addition of biochar lowered the concentration of exchangeable Al, Mn, and Fe (Figure 4a, 4b, and 4c) in the two tested soils. Mechanisms related to the effect could be liming effect and adsorption of these elements on biochar particles (Qian et al. 2013). While the former was involved in the increased soil pH, which was more frequently reported (Hale et al. 2020; Jeffery et al. 2011), the latter was reported less. Aluminum adsorption on biochar was reported to reduce the exchangeable Al concentration of the biochar-added soils (Qian and Chen 2014). Biochar could also adsorb Fe from water (Dang et al. 2018), thereby lowering its exchangeable concentration in soils. Precipitation and formation of organometallic complexes with the organic ligand from biochar might also contribute to a decrease in the exchangeable Fe concentration in the two soils (Dume et al. 2017).

Because the biochar contained much more exchangeable Na and K than the two paddy soils (Table 1), its addition enhanced the concentrations of these two exchangeable elements in the two soils (Figure 2c and 2d). Other studies have shown comparable results (Apori et al. 2021; Phuong et al. 2020). Statistically, the interaction impact of biochar and soil on the exchangeable Na concentration was not significant, and neither was the soil effect. These findings indicate that the increase in the exchangeable Na concentration in both soils was similar and was mostly attributable to biochar addition. Nevertheless, the significant interaction impact of biochar and soil on the exchangeable K concentration (Figure 2d) implies that in addition to the K contained in the added biochar, the increased exchangeable K in the tested soils after biochar addition could be derived from the original soils.

An interesting finding from the current study was the interaction effects of biochar and the tested soil on the concentration of exchangeable Ca (Figure 2a), K (Figure 2d), Al (Figure 4a), Mn (Figure 4b), the base index (Figure 3c), and the potentially phytotoxic index (Figure 4d). Biochar addition increased the concentration of exchangeable Ca, K, and the base index, while reducing the concentration of exchangeable Al, Mn, and the potentially phytotoxic index more profoundly in the clayey soil than in the sandy soil. This finding could not be explained only by the mechanistic co-addition of Ca, K, and Al contained in the added biochar. Given that the clayey soil had a considerably greater concentration of exchangeable Ca and K than the sandy soil, the added biochar in the clayey soil may help to solubilize the immobilized fraction of these elements and make them more exchangeable than the sandy soil. Similarly, the clayey soil exhibited a greater concentration of exchangeable Al and Mn than the sandy soil (Table 1). Due to the increased pH caused by biochar addition, the clayey soil had a greater magnitude of exchangeable Al and Mn that could be transformed into the fixed fraction than the sandy soil. The biochar used in the current study was porous and contained negative functional groups (Supplementary Figs. 1, 2, and 3). These enable biochar to exchangeably adsorb the relatively fixed forms of the base elements from the tested soils, thereby increasing their exchangeable concentrations. The high negative-charge density of biochar was identified as the main cause for the increased CEC of the biochar-added soil (Abrishamkesh et al. 2015; Gamage et al. 2016; Liang et al. 2006). Nonetheless, more studies are needed to define the real reasons, which are still unclear in the current study.

The base and nutrient ratios of the sandy soil were significantly higher than those of the clayey soil (Figure 5). The sandy soil exhibited a much lower concentration of exchangeable Al, Mn, and Fe, and consequently the potentially phytotoxic index than the clayey soil (Table 1, Supplementary Table 2), which might explain the finding. When the base ratio was greater than 600 and/or the nutrient ratio was higher than 20, total rice biomass may reach its greatest values over 65 (g DWT pot^{-1}) (Figure 6a and 6b). This result corresponded to the sandy soil (Figure 6d), implying that the sandy soil having much higher total biomass than the clayey soil could be attributable to the greater base and nutrient ratios of the sandy soil than the clayey soil (Figure 5a and 5b). Pandit et al. (2018) found that biochar addition raised the Ca/Al ratio, and Cornelissen et al. (2018) found that biochar addition improved maize yield and the improvement could be related to the Ca/Al ratio. In the current study, Ca and Al were the two exchangeable cations belonging to the base group and potentially phytotoxic group, respectively. Cation exchange capacity (CEC), which was equivalent to the base index in the current study, was important and can be used to forecast crop yield (Crane-Droesch et al. 2013). Nevertheless, the CEC alone may not adequately reflect the effects of biochar on soil properties and rice growth as shown in the current study. A combination of the three soil-property groups may be more relevant in accounting for the improved rice growth caused by biochar addition in the two paddy soils of contrasting texture.

A positive rise in total rice biomass with the base ratio and nutrient ratio (Figure 6a, 6b, 6c, and 6d) may confirm that rice growth could be strongly determined by the combination of soil properties in three groups of nutrients, base, and potentially phytotoxic elements. We additionally performed a multiple regression analysis, and results revealed that the two ratios together explained 68% of the total variance in total rice biomass (the base ratio explaining 25% and the nutrient explaining 43%). Another multiple regression analysis showed that the three indexes together explained 77% of the total variance in rice biomass (base index explaining 9%, nutrient index explaining 53%, and the potentially phytotoxic index explaining 15%). In a long-term experiment, biochar was found to increase rice production by improving soil carbon content and nutrient pools (N and P) (Zhang et al. 2020a). Nitrogen and phosphorous were constituents used to compute the nutrient index in the current study. These findings may confirm that of the three soil-property groups primarily influencing rice growth, the nutrient group may be the most important factor in determining total rice biomass.

The current study was a pot experiment carried out in a greenhouse under well-controlled environmental conditions. This indicates that the effects of biochar on soil properties and rice growth through changing base and nutrient ratios may be weaker under field conditions, where environmental conditions vary greatly. For example, leaching, erosion, and irrigation may weaken the impacts of biochar in the field. Additionally, biochar rates of 2 and 5% are equal to 22 and 55 ton ha^{-1}, respectively (assuming bulk density is 1.1 (g cm^{-3}) and for 0.1-m surface layer). When applied to the field, these rates can be quite high, possibly making the rates impractical. Split application over a few rice seasons could be an option for using the high biochar rates. Moreover, the fact that biochar greatly reduced the PI (Figure 4d) indicates that the material could be a suitable amendment for acidic soils, which have high concentrations of phytotoxic Al and Fe. Therefore, more studies on biochar applied to acidic soils in the field are necessary for better sustainable agricultural production.

5 Conclusions

Biochar addition improved rice growth and soil concentrations of NH_4^+, Mehlich-1 P, exchangeable calcium, potassium, and sodium while lowering others such as exchangeable aluminum and iron of two paddy soils of contrasting texture. The rice-growth impacts of biochar are involved in an increase in the base index (BI, average concentrations of exchangeable calcium, magnesium, sodium, and potassium) and the nutrient index (NI, average concentration of NH_4^+, Mehlich-1 P), and a decrease in the potentially phytotoxic index (PI, average concentrations of exchangeable aluminum, iron, and manganese) of the two tested soils. The improved base ratio (BI/PI) and nutrient ratio (NI/PI) by biochar could be the primary cause of enhanced rice growth in the two clayey and sandy soils. The impacts of biochar on rice growth were stronger in the sandy soil than in the clayey soil, indicating that rice growth in the sandy soil was more responsive to biochar addition than in the clayey soil. The findings suggest that the biochar application rate to improve rice productivity should be based on soil properties, especially soil texture. For a comparable increase in rice growth, more biochar should be applied to clayey soils whereas a lower rate could be considered for sandy soils.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42729-022-00790-3.

Acknowledgements The authors would like to thank the Institute of Environmental Science, Engineering, and Management (IESEM), Industrial University of Ho Chi Minh City (IUH) for supporting the current study as well as students and colleagues who assisted with a field trip and lab analyses.

Funding This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 105.08-2019.341.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Abrishamkesh S, Gorji M, Asadi H, Bagheri-Marandi GH, Pourbabaee AA (2015) Effects of rice husk biochar application on the properties of alkaline soil and lentil growth. Plant Soil Environ. 61:475-482. doi: https://doi.org/10.17221/117/2015-PSE

Abubakar A (2017) Effects of soil texture on vegetative and root growth of senna obtusifolia seedlings indigenous to bichi, Sudan savannah of Northern Nigeria, in green house conditions. IOSR Journal of Agriculture and Veterinary Science 10:70–74. https://doi.org/10.9790/2380-1004027074

Apori SO, Byalebeka J, Muli GK (2021) Residual effects of corncob biochar on tropical degraded soil in central Uganda. Environ. Syst. Res. 10:35. https://doi.org/10.1186/s40068-021-00235-3

Aung MS, Masuda H (2020) How does rice defend against excess iron?: physiological and molecular mechanisms. Front. Plant Sci. 11. https://doi.org/10.3389/fpls.2020.01102

Awad YM, Wang J, Igalavithana AD, Tsang DCW, Kim K-H, Lee SS, Ok YS (2018) Chapter one - Biochar effects on rice paddy: meta-analysis. In: Sparks, D. L. (ed.): Advances in agronomy (Academic Press), pp. 1-32. doi: https://doi.org/10.1016/bs.agron.2017.11.005

Awasthi JP, Saha B, Regon P, Sahoo S, Chowra U, Pradhan A, Roy A, Panda SK (2017) Morpho-physiological analysis of tolerance to aluminum toxicity in rice varieties of North East India. PLoS One 12:e0176357. https://doi.org/10.1371/journal.pone.0176357

Biederman LA, Harpole WS (2013) Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. GCB Bioenergy 5:202–214. https://doi.org/10.1111/gcbb.12037

Butphu S, Rasche F, Cadisch G, Kaewpradit W (2020) Eucalyptus biochar application enhances Ca uptake of upland rice, soil available P, exchangeable K, yield, and N use efficiency of sugarcane in a crop rotation system. J. Plant. Nutr. Soil Sci. 183:58–68. https://doi.org/10.1002/jpln.201900171

Carter MR, Gregorich EG (2008) Soil sampling and methods of analysis, 2nd edition, Boca Raton: CRC Press, Taylor & Francis Group.

Chaimala A, Jogloy S, Vorasoot N, Toomsan B, Jongrungklang N, Kesmala T, Holbrook CC, Kvien CK (2020) Responses of total biomass, shoot dry weight, yield and yield components of Jerusalem artichoke (*Helianthus tuberosus* L.) varieties under different terminal drought duration. Agriculture 10:198. doi: https://doi.org/10.3390/agriculture10060198

Chen X, Yang S, Ding J, Jiang Z, Sun X (2021) Effects of biochar addition on rice growth and yield under water-saving irrigation. Water 13:209. https://doi.org/10.3390/w13020209

Cornelissen G, Jubaedah NNL, Hale SE, Martinsen V, Silvani L, Mulder J (2018) Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. Sci Total Environ. 634:561–568. https://doi.org/10.1016/j.scitotenv.2018.03.380

Crane-Droesch A, Abiven S, Jeffery S, Torn MS (2013) Heterogeneous global crop yield response to biochar: a meta-regression analysis. Environ. Res. Lett. 8:044049. https://doi.org/10.1088/1748-9326/8/4/044049

Dai Y, Zhixiang J, Xing B (2020) Combined effects of biochar properties and soil conditions on plant growth: a meta-analysis. Sci Total Environ. 713:136635. https://doi.org/10.1016/j.scitotenv.2020.136635

Dang T, Marschner P, Fitzpatrick R, Mosley L (2018) Assessment of the binding of protons. Al and Fe to biochar at different pH values and soluble metal concentrations. Water 10. https://doi.org/10.3390/w10010055

Dixon JB (1991) Roles of clays in soils. Appl. Clay Sci. 5:489–503. https://doi.org/10.1016/0169-1317(91)90019-6

Dong D, Feng Q, McGrouther K, Yang M, Wang H, Wu W (2015) Effects of biochar amendment on rice growth and nitrogen retention in a waterlogged paddy field. J. Soils Sediments 15:153–162. https://doi.org/10.1007/s11368-014-0984-3

Dou FG, Soriano J, Tabien R, Chen K (2016) Soil texture and cultivar effects on rice (*Oryza sativa,* L.) grain yield, yield components and water productivity in three water regimes. PLoS One 11:e0150549. https://doi.org/10.1371/journal.pone.0150549

Du Q, Zhang S, Song J, Zhao Y, Yang F (2020) Activation of porous magnetized biochar by artificial humic acid for effective removal of lead ions. J. Hazard. Mater. 389:122115. https://doi.org/10.1016/j.jhazmat.2020.122115

Dume B, Tessema D, Regassa A, Yadessa G (2017) Effects of biochar on phosphorus sorption and desorption in acidic and calcareous soils. Civ. Eng. Res. 9:2224–5790

Gamage DNV, Mapa RB, Dharmakeerthi RS, Biswas A (2016) Effect of rice-husk biochar on selected soil properties in tropical Alfisols. Soil Res. 54:302–310. https://doi.org/10.1071/SR15102

Gaskin J, Adam Speir R, Harris K, Das KC, Lee R, Morris L, Fisher D (2010) Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status, and yield. Agron J. 102. https://doi.org/10.2134/agronj2009.0083

Gill JS, Sivasithamparam K, Smettem KRJ (2000) Soil types with different texture affects development of Rhizoctonia root rot of wheat seedlings. Plant Soil 221:113–120. https://doi.org/10.1023/A:1004606016745

Hale SE, Nurida NL, Jubaedah MJ, Sørmo E, Silvani L, Abiven S, Joseph S, Taherymoosavi S, Cornelissen G (2020) The effect of biochar, lime and ash on maize yield in a long-term field trial in a Ultisol in the humid tropics. Sci Total Environ. 719:137455. https://doi.org/10.1016/j.scitotenv.2020.137455

Jeffery S, Verheijen FGA, van der Velde M, Bastos AC (2011) A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric Ecosyst Environ 144:175–187. https://doi.org/10.1016/j.agee.2011.08.015

Jiang Z, Yang S, Pang Q, Xu Y, Chen X, Sun X, Qi S, Yu W (2021) Biochar improved soil health and mitigated greenhouse gas emission from controlled irrigation paddy field: Insights into microbial diversity. J. Clean. Prod. 318:128595. https://doi.org/10.1016/j.jclepro.2021.128595

Jiban S, Manoj K, Subash S, Kabita KS (2020) Role of nutrients in rice (*Oryza sativa* l.): a review. Agrica 9:53-62. 10.5958/2394-448X.2020.00008.5

Kartika K, Lakitan B, Wijaya A, Kadir S, Widuri L, Siaga E, Meihana M (2018) Effects of particle size and application rate of rice-husk biochar on chemical properties of tropical wetland soil, rice growth and yield. Aust. J. Crop Sci. 12. https://doi.org/10.21475/ajcs.18.12.05.PNE1043

Knoblauch C, Priyadarshani SHR, Haefele SM, Schröder N, Pfeiffer E-M (2021) Impact of biochar on nutrient supply, crop yield and microbial respiration on sandy soils of northern Germany. Eur. J. Soil Sci. 72:1885–1901. https://doi.org/10.1111/ejss.13088

Li B, Liu D, Lin D, Xie X, Wang S, Xu H, Wang J, Huang Y, Zhang S, Hu X (2020) Changes in biochar functional groups and its reactivity after volatile−char interactions during biomass pyrolysis. Energy Fuels 34:14291–14299. https://doi.org/10.1021/acs.energyfuels.0c03243

Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, Skjemstad JO, Thies J, Luizao FJ, Petersen J, Neves EG (2006) Black carbon increases cation exchange capacity in soils. Soil Sci Soc Am J 70:1719–1730. https://doi.org/10.2136/sssaj2005.0383

Lu H, Bian R, Xia X, Cheng K, Liu X, Liu Y, Wang P, Li Z, Zheng J, Zhang X, Li L, Joseph S, Drosos M, Pan G (2020) Legacy of soil health improvement with carbon increase following one time amendment of biochar in a paddy soil – a rice farm trial. Geoderma 376:114567. https://doi.org/10.1016/j.geoderma.2020.114567

Luo Y, Durenkamp M, De Nobili M, Lin Q, Brookes PC (2011) Short term soil priming effects and the mineralisation of biochar following its incorporation to soils of different pH. Soil Biol. Biochem. 43:2304–2314. https://doi.org/10.1016/j.soilbio.2011.07.020

Mensah AK, Frimpong KA (2018) Biochar and/or compost applications improve soil properties, growth, and yield of maize grown in acidic rainforest and coastal savannah soils in Ghana. Int. J. Agron. 2018:8. https://doi.org/10.1155/2018/6837404

Miranda NDO, Pimenta AS, Silva GGCD, Oliveira EMM, Carvalho MABD (2017) Biochar as soil conditioner in the succession of upland rice and cowpea fertilized with nitrogen. Rev. Caatinga 30:313-323. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1983-21252017000200313&nrm=iso

Muhammad N, Aziz R, Brookes P, Xu J (2017) Impact of wheat straw biochar on yield of rice and some properties of Psammaquent and Plinthudult. J. Soil Sci. Plant Nutr. 17:808–823. https://doi.org/10.4067/S0718-95162017000300019

Nguyen BT, Lehmann J, Hockaday WC, Joseph S, Masiello CA (2010) Temperature sensitivity of black carbon decomposition and oxidation. Environ. Sci. Technol. 44:3324–3331. https://doi.org/10.1021/es903016y

Nguyen BT, Trinh NN, Le CMT, Nguyen TT, Tran TV, Thai BV, Le TV (2018a) The interactive effects of biochar and cow manure on rice growth and selected properties of salt-affected soil. Arch. Agron. Soil Sci. 64:1744–1758. https://doi.org/10.1080/03650340.2018.1455186

Nguyen TQH, Le KT, Nguyen MK, Le TNH (2018b) Potential of biochar production from agriculture residues at household scale: a case study in Go Cong Tay District, Tien Giang Province, Vietnam. Environ. Nat. Resour. J. 16. 10.14456/ennrj.2018.15

Nieves-Cordones M, Martínez V, Benito B, Rubio F (2016) Comparison between arabidopsis and rice for main pathways of K^+ and Na^+ uptake by roots. Front. Plant Sci. 7. https://doi.org/10.3389/fpls.2016.00992

Normand AE, Smith AN, Clark MW, Long JR, Reddy KR (2017) Chemical composition of soil organic matter in a subarctic peatland: influence of shifting vegetation communities. Soil Sci Soc Am J 81:41–49. https://doi.org/10.2136/sssaj2016.05.0148

Pandit NR, Mulder J, Hale SE, Martinsen V, Schmidt HP, Cornelissen G (2018) Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low-input Nepalese soil. Sci Total Environ. 625:1380–1389. https://doi.org/10.1016/j.scitotenv.2018.01.022

Phuong NTK, Khoi CM, Ritz K, Linh TB, Minh DD, Duc TA, Sinh NV, Linh TT, Toyota K (2020) Influence of rice husk biochar and compost amendments on salt contents and hydraulic properties of soil and rice yield in salt-affected fields. Agronomy 10:1101. https://doi.org/10.3390/agronomy10081101

Pratiwi EPA, Shinogi Y (2016) Rice husk biochar application to paddy soil and its effects on soil physical properties, plant growth, and methane emission. Paddy Water Environ.:1-12. https://doi.org/10.1007/s10333-015-0521-z

Qian L, Chen B (2014) Interactions of aluminum with biochars and oxidized biochars: implications for the biochar aging process. J. Agric. Food Chem. 62:373–380. https://doi.org/10.1021/jf404624h

Qian L, Chen B, Hu D (2013) Effective alleviation of aluminum phytotoxicity by manure-derived biochar. Environ. Sci. Technol. 47:2737–2745. https://doi.org/10.1021/es3047872

Schlesinger WH, Bernhardt ES (2013) Chapter 6 - The biosphere: biogeochemical cycling on land. In: Schlesinger, W. H., Bernhardt, E. S. (eds.) Biogeochemistry (Third Edition) (Academic Press, Boston), pp. 173-231. doi: https://doi.org/10.1016/B978-0-12-385874-0.00006-6

Schmidt H-P, Kammann C, Hagemann N, Leifeld J, Bucheli TD, Sánchez Monedero MA, Cayuela ML (2021) Biochar in agriculture – a systematic review of 26 global meta-analyses. GCB Bioenergy 13:1708–1730. https://doi.org/10.1111/gcbb.12889

Shetty R, Vidya CS-N, Prakash NB, Lux A, Vaculík M (2021) Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: a review. Sci Total Environ. 765:142744. https://doi.org/10.1016/j.scitotenv.2020.142744

Tahir S, Marschner P (2016) Clay addition to sandy soil: effect of clay concentration and ped size on microbial biomass and nutrient dynamics after addition of low C/N ratio residue. J. Soil Sci. Plant Nutr. 16. https://doi.org/10.4067/S0718-95162016005000061

Tomczyk A, Sokołowska Z, Boguta P (2020) Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Rev. Environ. Sci. Biotechnol. 19:191–215. https://doi.org/10.1007/s11157-020-09523-3

Vijay V, Shreedhar S, Adlak K, Payyanad S, Sreedharan V, Gopi G, VDV S, Tessa MP, Yi S, Gebert J, Aravind P (2021) Review of large-scale biochar field-trials for soil amendment and the observed influences on crop yield variations. Front. Energy Res:9. https://doi.org/10.3389/fenrg.2021.710766

Wang W, Zhao XQ, Hu ZM, Shao JF, Che J, Chen RF, Dong XY, Shen RF (2015) Aluminium alleviates manganese toxicity to rice by decreasing root symplastic Mn uptake and reducing availability to shoots of Mn stored in roots. Ann. Bot. 116:237–246. https://doi.org/10.1093/aob/mcv090

Yang F, Zhang S, Li H, Li S, Cheng K, Li J-S, Tsang DCW (2018a) Corn straw-derived biochar impregnated with α-FeOOH nanorods for highly effective copper removal. Chem. Eng. Sci. 348:191–201. https://doi.org/10.1016/j.cej.2018.04.161

Yang S, Jiang Z, Sun X, Ding J, Xu J (2018b) Effects of biochar amendment on CO_2 emissions from paddy fields under water-saving irrigation. Int. J. Environ. Res. Public Health 15:2580. https://doi.org/10.3390/ijerph15112580

Yao FX, Arbestain MC, Virgel S, Blanco F, Arostegui J, Maciá-Agulló JA, Macías F (2010) Simulated geochemical weathering of a mineral ash-rich biochar in a modified Soxhlet reactor. Chemosphere 80:724–732. https://doi.org/10.1016/j.chemosphere.2010.05.026

Ye L, Camps Arbestain M, Shen Q, Lehmann J, Singh B, Sabir M (2019) Biochar effects on crop yields with and without fertilizer: a meta-analysis of field studies using separate controls. Soil Use Manag. 36. https://doi.org/10.1111/sum.12546

Yulnafatmawita Y, Yasin S, Maira L (2020) Effectiveness of rice husk biochar in controlling heavy metals at polluted paddy soil. IOP Conf. Ser. Earth Environ. Sci. 583:012008. https://doi.org/10.1088/1755-1315/583/1/012008

Zhang H, Liu H, Hou D, Zhou Y, Liu M, Wang Z, Liu L, Gu J, Yang J (2019) The effect of integrative crop management on root growth and methane emission of paddy rice. Crop J. 7:444–457. https://doi.org/10.1016/j.cj.2018.12.011

Zhang Q, Song Y, Wu Z, Yan X, Gunina A, Kuzyakov Y, Xiong Z (2020a) Effects of six-year biochar amendment on soil aggregation, crop growth, and nitrogen and phosphorus use efficiencies in a rice-wheat rotation. Sci Total Environ. 242:118435. https://doi.org/10.1016/j.jclepro.2019.118435

Zhang S, Du Q, Sun Y, Song J, Yang F, Tsang DCW (2020b) Fabrication of L-cysteine stabilized α-FeOOH nanocomposite on porous hydrophilic biochar as an effective adsorbent for Pb^{2+} removal. Sci Total Environ. 720:137415. https://doi.org/10.1016/j.scitotenv.2020.137415

Zheng H, Wang Z, Deng X, Herbert S, Xing B (2013) Impacts of adding biochar on nitrogen retention and bioavailability in agricultural soil. Geoderma 206:32–39. https://doi.org/10.1016/j.geoderma.2013.04.018