



# Biochar Addition Balanced Methane Emissions and Rice Growth by Enhancing the Quality of Paddy Soil

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## Abstract

Paddy rice production may contribute to both the global issues of methane emissions and food security. Biochar derived from organic wastes may offer a potential solution to address these two challenges. The current study aimed to examine the dynamics of methane emissions, rice growth, and soil quality as affected by biochar and to assess the biochar role in balancing methane emissions and rice growth in paddy soil. Paddy soil was mixed with rice-husk-derived biochar at five levels (0, 1.5, 3, 6, and 12% w/w) and planted with rice (*Oryza sativa* L.) in two consecutive seasons in a greenhouse. Methane emissions from experimental pots were measured weekly. After each of the two seasons, the crop's root, stem, and grain mass were determined, and soil samples were collected and analyzed for 10 physicochemical properties, which were used to compute the soil quality index (SQI). Compared to the no-biochar treatment, biochar increased total rice biomass from 8 to 48% while suppressing methane emissions from 7 to 42%, dependent on biochar rates and seasons. Biochar with different rates also enhanced SQI by 10 to 45% and 38 to 101% after the first and second seasons, respectively. A strong relationship was observed between methane emissions and total rice biomass with SQI suggesting that soil quality may play a major role in suppressing CH<sub>4</sub> emissions and enhancing rice growth. Adding biochar to paddy soil can reduce methane emissions while improving rice growth, which is strongly linked to the enhanced quality of the biochar-added soil.

**Keywords** Biomass · Circular economy · Greenhouse gas emissions · Paddy rice · Soil quality index

## 1 Introduction

Global warming and food security are currently among the most concerning issues influencing sustainable development worldwide. The former is largely caused by excessive greenhouse gas emissions, while the latter could be involved in the production of various food crops. Paddy rice (*Oryza sativa* L.) is an important cereal crop, which provides spilled rice grain for many people all over the world but also emits a considerable quantity of methane (CH<sub>4</sub>), a greenhouse gas, annually (Yang et al. 2019; Yun et al. 2022). Paddy rice production can account for up to 30% of total global

CH<sub>4</sub> emissions yearly (Gupta et al. 2021) while supplying staple food for about half of the world's population (Sivapalan 2015). To produce better growth and yields, paddy rice should be planted under flood conditions (Sivapalan 2015). Nonetheless, more CH<sub>4</sub> emissions can be generated and emitted into the atmosphere because the activities of CH<sub>4</sub>-producing microorganisms are stimulated under submerged conditions. These findings indicate that paddy fields may produce high rice growth and yields while also emitting a great amount of CH<sub>4</sub>, which must be balanced for long-term development.

These two contrastive aspects of paddy rice production could be balanced by using biochar as a soil amendment. The material can be made from organic wastes, including agricultural by-products using a slow pyrolysis process under high-temperature and oxygen-limited conditions. Many studies have shown that biochar can promote rice growth and yield by improving soil quality (Chen et al. 2021; Huang et al. 2018; Shetty and Prakash 2020). Other studies were conducted to examine the effects of biochar on CH<sub>4</sub> emissions from paddy soils, and the reasons for the reduced gas

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emissions may be linked to the changes in soil properties and the activities of methanogenic and methanotrophic communities (Nan et al. 2021; Rahman and Yamamoto 2020; Yun et al. 2022). These findings suggest that biochar as a soil amendment could be a dual-benefit solution in mitigating CH<sub>4</sub> emissions while improving rice growth and yield in paddy soils. Nevertheless, our recent review of the literature revealed a scarcity of studies discussing the effects of biochar on both of these issues concurrently. This leads to our first research hypothesis that biochar addition may have dual benefits of suppressing methane emissions while enhancing rice growth in paddy soils.

The direct effects of biochar on reduced CH<sub>4</sub> emissions and improved rice growth could be linked to the alteration of soil properties caused by the amendment. Some soil properties such as plant-available nutrients (NH<sub>4</sub><sup>+</sup>-N and available P), soil acidity, and the concentration of exchangeable base cations such as K, Ca, and Mg were improved by biochar addition (Joseph et al. 2021; Nguyen et al. 2021; Nguyen et al. 2022). The concentration of some soluble potential phytotoxic elements such as Al, Mn, and Fe could be decreased as a result of biochar addition (Hailegnaw et al. 2020; Nguyen et al. 2022; Shetty and Prakash 2020). These findings imply that soil quality could be improved first, resulting in enhanced rice growth and yield. Furthermore, biochar can elevate the soil pH and porosity of biochar-added soils (Joseph et al. 2021). Although natural CH<sub>4</sub> emissions can be determined by the activities of two microbial communities, methanogen, and methanotroph (Kumar et al. 2021), the gas emissions can be sensitive to changes in the pH and oxygen availability of the environment (Oertel et al. 2016; Rahman and Yamamoto 2020; Ramachandran and Ramachandran 2001). Consequently, biochar addition was found to suppress CH<sub>4</sub> emissions by changing soil conditions and the consequent activities of the two microbial communities (Nan et al. 2021). The findings strongly indicate that mitigated CH<sub>4</sub> emissions and enhanced rice growth in paddy soils could be the result of improved soil quality caused by biochar addition, which was limitedly discussed in the literature. Consequently, our second research hypothesis was initiated that biochar could improve soil quality, which balances the reduced methane emissions and improved rice growth in paddy soils.

Moreover, the effects of biochar on CH<sub>4</sub> emissions and rice growth could be dependent on the applied rate of the amendment. Nevertheless, many studies were conducted based on a single or a few biochar rates, which lead to an increase in rice yield (Danso et al. 2021). Chen et al. (2021) applied three biochar rates to a paddy field and found that rice yield increased over the biochar rates from zero to 20 and 40 tones per ha. Recently, Yang et al. (2022) investigated four biochar rates of 0, 10, 20, and 40 tonnes ha<sup>-1</sup> and concluded that the rate of 10 tonnes ha<sup>-1</sup> was optimal for

lowering CH<sub>4</sub> emissions while retaining rice yield. Despite this, the higher biochar rate (40 tonnes ha<sup>-1</sup>) resulted in a lower rice yield than the lower rate (10 tonnes ha<sup>-1</sup>) (Yang et al. 2022), which needs further investigation. These findings also suggest that using lower biochar rates may have the greatest impact on lowering CH<sub>4</sub> emissions and improving rice growth while minimizing biochar costs. This results in our last research hypothesis that a lower range of biochar rates may have a greater and more effective impact on methane emissions and rice growth than a higher range. Therefore, the current study was conducted on paddy soil, using five biochar rates and planting paddy rice for two seasons with the three research hypotheses stated above. The aims of the current study were to examine the dynamics of methane emissions, rice growth, and soil quality as affected by biochar addition, as well as to assess the role of biochar in balancing methane emissions and rice growth in paddy soil.

## 2 Materials and Methods

### 2.1 Experimental Materials

Biochar and paddy soil were the two primary materials used in the current study. Biochar was produced from rice husk, a by-product of rice production, which is widely available in Vietnam and other tropical countries. The method used to make biochar was similar to that used by Nguyen et al. (2018b). Soil material was taken from a paddy field (around 1000 m<sup>2</sup>) in Cu Chi District, Ho Chi Minh City, Vietnam, (11° 01' N and 106° 26' E) and classified as a *Haplic Acrisols* (WRB 2015). The field has a long history of rice cultivation with two main seasons a year. The soil sample was taken from ten sites distributed over the selected field in the surface layer of 0–15 cm depth. The collected soil material from these sites was mixed thoroughly to make one composite sample, which was transferred to a laboratory, air-dried, and sieved through a 2-mm sieve to remove plant residues and gravel before the experiment.

### 2.2 Experimental Setup

The current study was set up as a completely randomized design with three replicates. The air-dried and sieved soil was mixed with biochar at five different rates of 0, 1.5, 3, 6, and 12% (w/w), equivalent to 0, 22.5, 45, 90, and 180 tonnes per ha based on bulk density of 1.0 g/cm<sup>3</sup> and soil depth of 15 cm, making five experimental treatments, hereafter called T1, T2, T3, T4, and T5, respectively. The soil-biochar mixture (hereafter referred to as experimental soil) was repacked into 15 pots (five treatments x three replicates) with a size of 20 cm × 20 cm (diameter × height). Around 3.6–4.6 kg of experimental soil was repacked into each

pot depending on biochar rates with some gentle tamps to establish a uniform height (around 15 cm) of the soil column in all pots. The 15 experimental pots were randomly placed in a greenhouse with temperatures varying from 25 °C (night) to 36 °C (day), with no direct rain or wind. The pots were filled with tap water to a depth of 3–5 cm for around 8 days and then left for 2 days to dry out the standing water before direct seeding of germinated Jasmine 85 rice seeds. Initially, 12 germinated seeds were applied to each pot, and after 8–10 days, five abnormal (smallest or biggest) seedlings were removed and seven relatively similar seedlings in individual pots were maintained until the end of the experiment. Seven seedlings were kept in each pot to form a plant density of around 292 seedlings per m<sup>2</sup> as in the real cultivation condition. Additionally, before seeding, inorganic fertilizers (N, P, and K) with application rates similar to Luu and Nguyen (2006) were top-dressed and mixed into the surface of the experimental soil in individual pots. Inorganic fertilizers were applied in the amounts of 0.2 g urea-N, 0.075 g superphosphate-P, and 0.075 g potassium-K per pot, equivalent to 80 kg N, 30 kg P, and 30 kg K per ha (Luu and Nguyen 2006). All P fertilizer was applied at the same time as the biochar and soil were mixed; N and K fertilizers were applied in three splits (applied after 7–10 days, 20–25 days, and 45–50 days) and two splits (after 7–10 days and 45–50 days), respectively (Luu and Nguyen 2006).

When biochar is incorporated into soils, it may go through three reaction stages, including dissolution, reactive surface development, and aging, which may last beyond 6 months (Joseph et al. 2021). Consequently, the current study was carried out over two consecutive rice seasons, lasting 9 months (November 2020 to March 2021 and from April 2021 to August 2021). Following the first season, all rice biomass was collected and around 500 g of experimental soil was taken for chemical analysis. The remaining soil in each pot was allowed to dry naturally and re-watered with thorough mixing 10 days before the next season began. Some inorganic fertilizers with rates similar to the first season were re-applied, while biochar was not applied in the second rice season and the rice variety was the same as the first season. Throughout the two rice seasons, the level of standing water of around 3–4 cm high in each experimental pot was checked daily and replenished with tap water if necessary.

## 2.3 Measurements

### 2.3.1 Methane Emissions

Methane emissions were measured using the closed chamber method by Minamikawa et al. (2015), which was described in detail by (Nguyen et al. 2020). In brief, a closed chamber, made of a plastic sheet was applied over individual experimental pots for air accumulation. A 50-mL syringe was used

to sample air within the closed chamber at 0, 10, 20, and 40 min after superimposing the chambers. Pre-vacuumed glass vials were used to store the collected air from the chambers and transferred to the analytical laboratory of the Cuu Long Delta Rice Research Institute on the same day to analyze for CH<sub>4</sub> concentration using a Gas Chromatography-Flame Ionization Detector (Qi et al. 2018). Gas samplings were carried out weekly during the two rice seasons, and a total of 10 samplings were implemented in each rice season (gas samples in the last 2 weeks before the end of each season were not collected to prepare for harvest). The total CH<sub>4</sub> emissions over the whole season in g CH<sub>4</sub>-C m<sup>-1</sup> season<sup>-1</sup> were computed and reported for assessment.

### 2.3.2 Rice Growth

Rice biomass of different parts (root, stem, and grain) from 15 pots was determined after each season using the procedure applied by Nguyen et al. (2018a). After collecting rice biomass, soil samples from 15 pots were taken from the 0–15 cm surface layer using a soil sampler for chemical analysis. The collected biomass (grain, stem, and root) was weighed for assessment after being oven-dried at 70 °C to a constant weight (Chaimala et al. 2020; Zhang et al. 2019).

### 2.3.3 Chemical Analysis

Before the experiment, the air-dried and sieved soil and biochar were taken in 4 replicates for chemical analysis (Table 1). After each season, 15 soil samples were collected from 15 experimental pots from the 0–15 cm surface layer, air-dried, and sieved through a 2-mm sieve for chemical analysis. All soil and biochar samples were analyzed for total organic carbon (TOC), pH, cation exchange capacity (CEC), NH<sub>4</sub><sup>+</sup>-N, Mehlich-1 P, and exchangeable K, Ca, Mg, Al, Fe, and Mn. The TOC concentration was measured using the dry combustion method with an elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) (Knoblauch et al. 2021). Inorganic carbon in the soil used for the current study could be negligible because the used soil had a pH value below 6.5 (Knoblauch et al. 2021), leading to total organic carbon (TOC) measured through this method. The pH was measured using a Thermo Scientific™ Orion™ 3-Star Benchtop pH meter after the samples were added to distilled water in a 1:5 (w/w) ratio for 1 h. CEC was quantified using the ammonium acetate method (Nguyen and Lehmann 2009). The concentration of NH<sub>4</sub><sup>+</sup>-N was determined using 2M KCl, and the concentration of Mehlich-1 P was measured using the Mehlich-1 method (Carter and Gregorich 2008). The concentration of exchangeable K, Ca, Mg, Al, Fe, and Mn was determined using the BaCl<sub>2</sub> method, and the extract was analyzed using an inductively coupled plasma-optical emission spectrometry (ICP-OES) (Carter

and Gregorich 2008). In addition, the pre-experimental sieved soils were analyzed for particle size distribution (Carter and Gregorich 2008). The ash content of biochar was quantified using the combustion method at 650 °C overnight.

## 2.4 Statistical Analysis

The soil quality index (SQI) was computed using the principal component analysis/factor analysis (PCA/FA), as described by Nguyen et al. (2021). The dynamics of CH<sub>4</sub> emissions, rice growth components, and soil properties over the range of biochar rates were examined using the scatter plot, and the relationship between these parameters was quantified using linear and non-linear models. The  $r^2$  value (coefficient of determination) was computed, and analysis of variance (ANOVA) was applied to determine the statistical significance of the individual relationship with a 95% confidence level ( $P \leq 0.05$ ). Some data were statistically analyzed, following the ANOVA procedure for a completely randomized design, using JMP 16 (SAS Institute Inc, NC, USA). When the ANOVA result showed a significant effect at  $P \leq 0.05$ , the Tukey's honestly significant difference test was used to classify treatment means. All figures were established using Sigmaplot 14.0 (Systat Software Inc., San Jose, California).

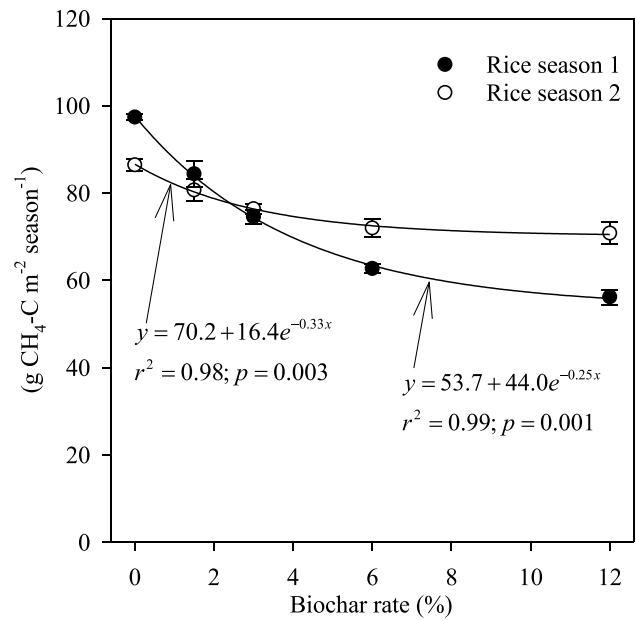
## 3 Results

### 3.1 Methane Emissions

An increase in biochar rate led to a reduction of CH<sub>4</sub> emissions, following an exponential decay model (Fig. 1). Treatment 1 had CH<sub>4</sub> emissions of 97.4 and T5 had 56.2 (g CH<sub>4</sub>-C m<sup>-2</sup> season<sup>-1</sup>), resulting in a 42% reduction in emissions during the first rice season. During the second season, CH<sub>4</sub> emissions varied from 86.4 to 70.4 (g CH<sub>4</sub>-C m<sup>-2</sup> season<sup>-1</sup>) in T1 and T5, respectively. The reduction of CH<sub>4</sub> emissions by around 18% due to biochar addition during the second season was much lower than that during the first season, indicating that the effect of biochar on CH<sub>4</sub> emissions may weaken after one season.

### 3.2 Rice Growth

Root weight was not significantly affected by biochar addition (Fig. 2a), while stem weight and grain weight were significantly increased over the biochar rates (Fig. 2b and c) after each of the two rice seasons. After the first season, T1 had the lowest stem weight (17.8 g pot<sup>-1</sup>) and grain weight (12.7 g pot<sup>-1</sup>), while T5 had the highest stem (24.0 g pot<sup>-1</sup>) and grain weight (23.9 g pot<sup>-1</sup>). After the second season, of the five treatments, T5 still had the highest stem weight and grain weight. In the first season, the stem weight and grain weight increased rapidly for the biochar rates from zero to



**Fig. 1** Dynamics of total CH<sub>4</sub> emissions during two rice seasons as affected by biochar. Error bars indicate the standard deviation of the mean.  $r^2$  is the coefficient of determination and  $p < 0.05$  indicates the relationship is significant following the non-linear regression analysis

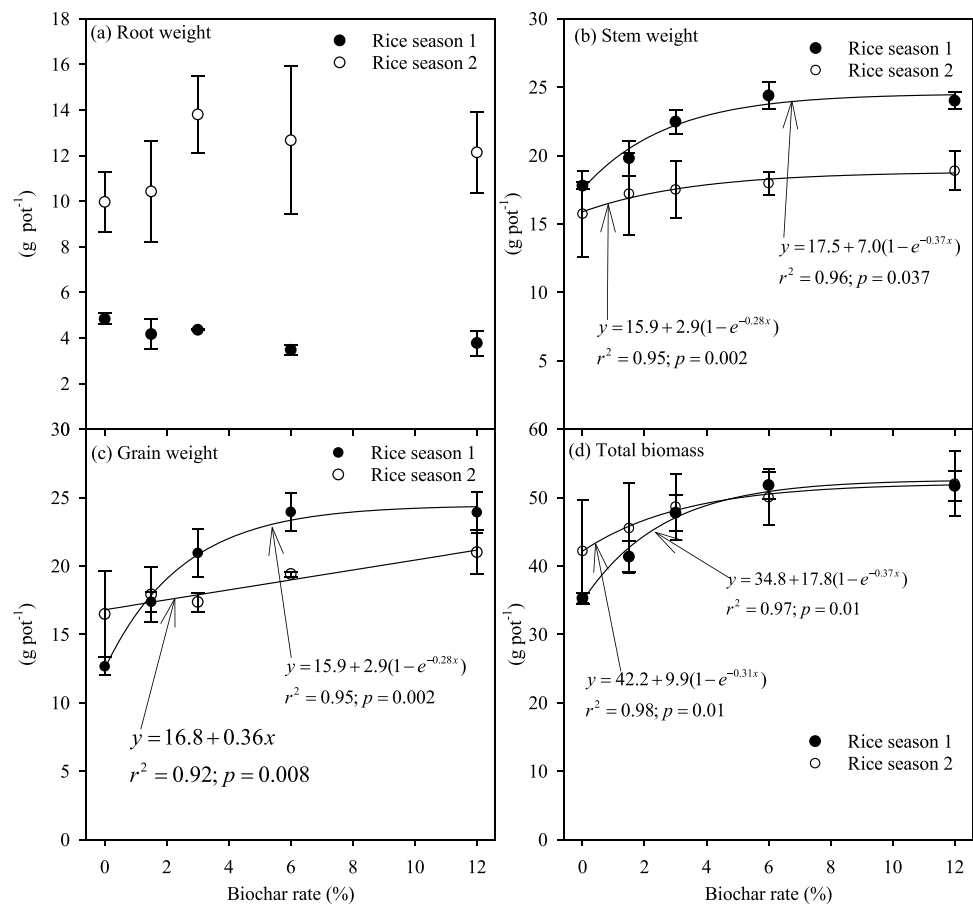
3%, then leveled off. The second season had a lower stem weight and grain weight than the first season. In both seasons, the total biomass (sum of root weight, stem weight, and grain weight) increased with an increase in biochar rates, following an exponential-rise-to-maximum model (Fig. 2d). The total biomass increased from 35.3 in T1 to 51.7 (g pot<sup>-1</sup>) in T5 after the first season, while it increased from 42.2 in T1 to 52.0 (g pot<sup>-1</sup>) in T5 after the second season. When biochar rates were less than 3%, the increasing rate of total biomass was more rapid in both rice seasons.

### 3.3 Soil Quality

An increase in biochar rates resulted in a reduction in the concentration of NH<sub>4</sub><sup>+</sup>-N (Fig. 3a) and exchangeable Ca (Fig. 3e) in the soil after the first season, but an increase of these elements after the second season. After both seasons, biochar significantly raised the concentration of Mehlich-1 P (Fig. 3b), exchangeable K (Fig. 3d), and CEC (Fig. 3c). The concentration of exchangeable Mg elevated significantly when the biochar rate increased after the second season, but it was similar among the five experimental treatments after the first season (Fig. 3f). The concentration of Mehlich-1 P, exchangeable K, Ca, and Mg after the second season was much higher than that after the first season.

Biochar also greatly enhanced the pH of the tested soil, varying from 6.0 in T1 to 6.6 in T5 after the first season (Fig. 4a). After the

**Fig. 2** The dynamics of rice growth components of rice in two seasons as affected by biochar. Error bars indicate the standard deviation of the mean. Note root weight was not significantly affected by biochar.  $r^2$  is the coefficient of determination and  $p < 0.05$  indicates the relationship is significant following the non-linear regression analysis



second season, soil pH was not significantly influenced by biochar addition. Biochar addition significantly reduced the concentration of exchangeable Al in both seasons (Fig. 4b) and the concentration of exchangeable Fe in the first season (Fig. 4c). The exchangeable Mn concentration was not affected by biochar addition (Fig. 4d).

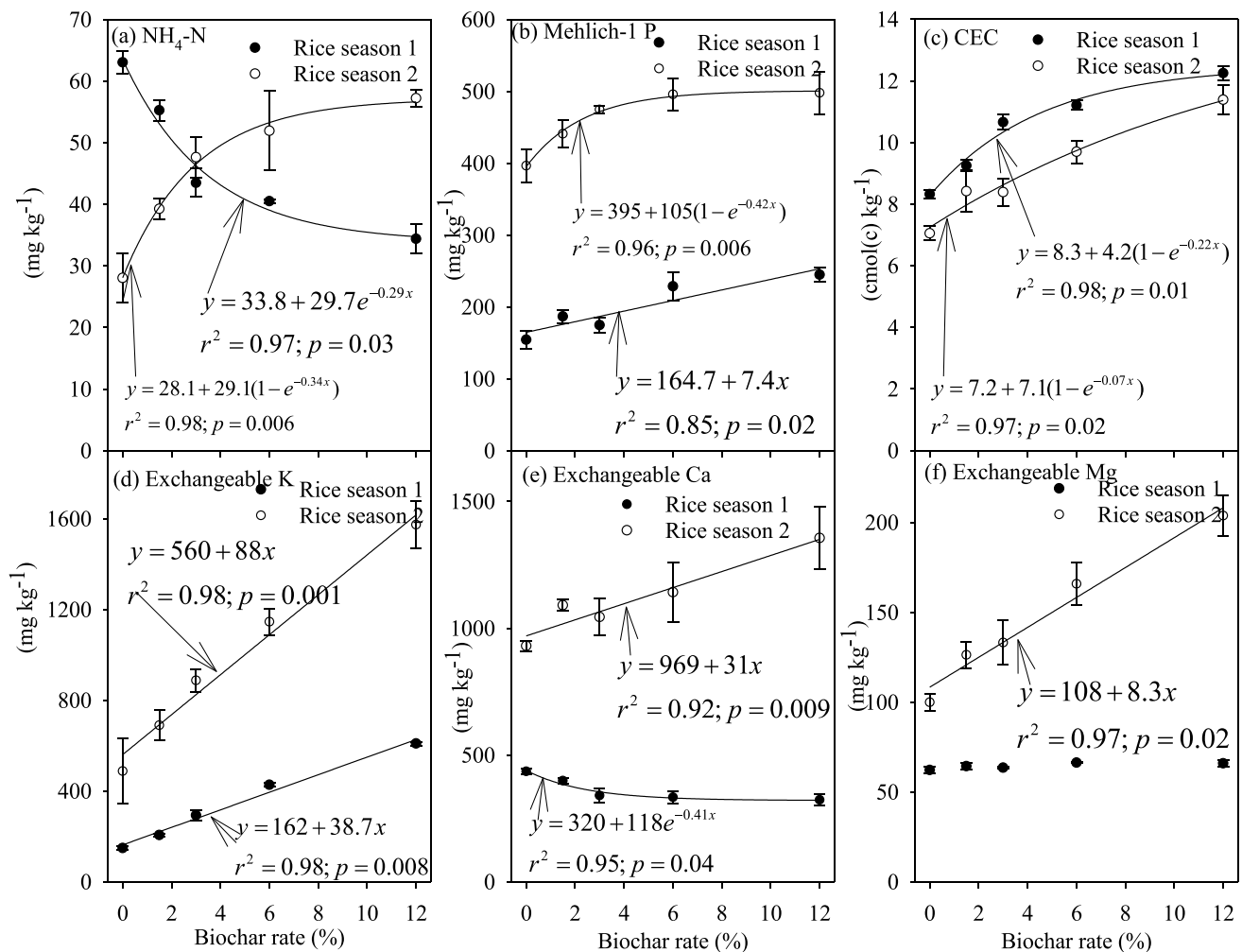
The ten soil parameters (properties) measured in the current study were statistically analyzed using the PCA/FA, and the results were shown in Table 2. The ten soil parameters were grouped into three factors, with factor 1 explaining 47.4% of the total variance in the entire dataset, factor 2 explaining 27.1%, and factor 3 explaining 15.5%. Factor 1 included exchangeable Mg, Ca, K, Mn, and Mehlich-1 P; factor 2 included exchangeable Al, CEC, and pH; and factor 3 included exchangeable Fe and  $\text{NH}_4^+\text{-N}$ . The parameter weightage shown in Table 2 was used to estimate the soil quality index (SQI), which is shown in Fig. 5. Biochar greatly increased SQI from 0.32 in T1 to 0.46 in T5 (increased by 44.4%) after the first season. SQI was enhanced from 0.35 in T1 to 0.74 in T5 (increased by 110.5%) after the second season. Biochar enhanced SQI in the second season more than in the first season. SQI increased more rapidly when the biochar rate rose from zero to around 3% and then relatively leveled off.

### 3.4 Relationships

The SQI and total rice biomass were significantly correlated with each other, following an exponential model (Fig. 6). When the SQI increased from 0.32 to 0.74, total rice biomass increased from 35.3 to 52.0 (g pot<sup>-1</sup>) over the two rice seasons. Total rice biomass increased much more quickly when the SQI was less than 0.4 and remained relatively stable when the SQI was greater than 0.4. A strong and negative relationship between the SQI and total  $\text{CH}_4$  emissions was also found (Fig. 6). Total methane emissions declined from 97.4 to 56.2 (g  $\text{CH}_4\text{-C m}^{-2}$  season<sup>-1</sup>) when the SQI rose from 0.32 to 0.74 over the two rice seasons. Total methane emissions reduced more rapidly when the SQI was below 0.4 and leveled off over greater values of the SQI.

## 4 Discussion

Results from the current study confirmed our first hypothesis that biochar addition suppressed  $\text{CH}_4$  emissions while enhancing rice growth after two consecutive seasons. The limited  $\text{CH}_4$  emissions from paddy soil planted with rice by biochar are consistent with other studies (Nan et al. 2021;



**Fig. 3** The concentration dynamics of nutrition-related parameters of soil after each of two rice seasons as affected by biochar. Error bars indicate the standard deviation of the mean.  $r^2$  is the coefficient of

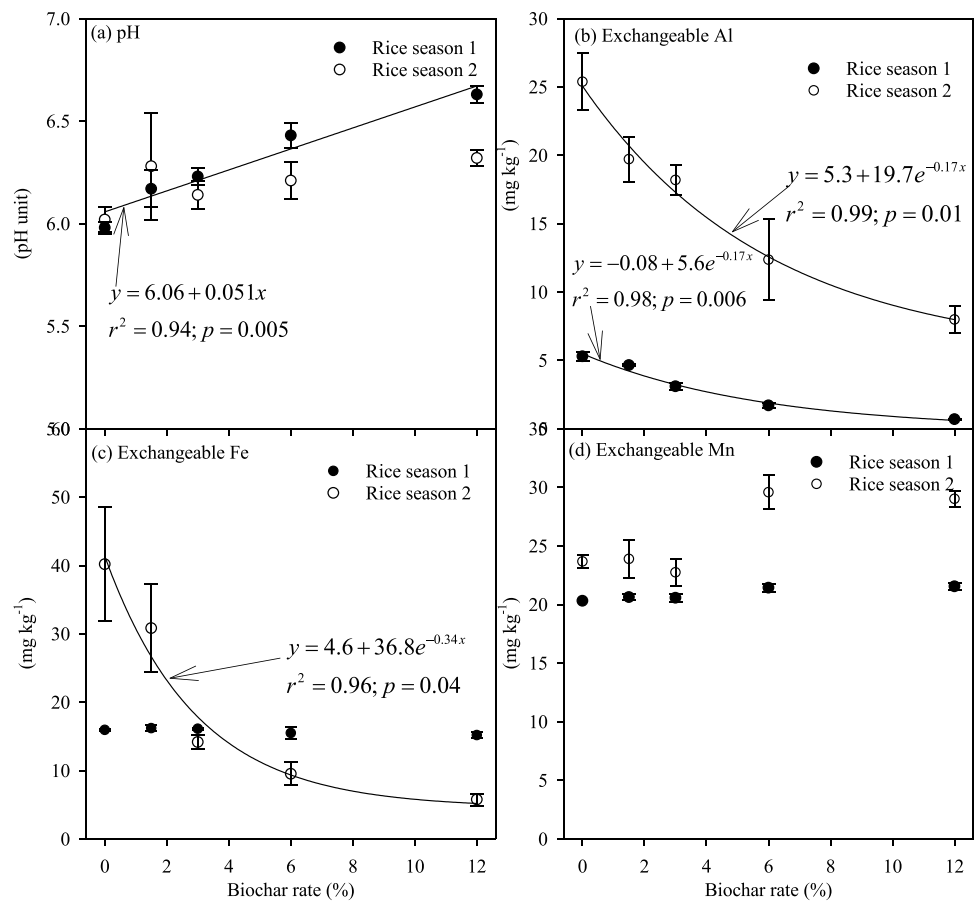
determination and  $p < 0.05$  indicates the relationship is significant following the linear or non-linear regression analysis

Yanan et al. 2018; Yang et al. 2017). Generally, natural  $\text{CH}_4$  emissions can occur as a result of both biotic and abiotic processes. While the former may be connected to the activities of two bacterial communities of methane-generating methanogens and methane-consuming methanotrophs under anaerobic conditions (Nan et al. 2021; Nguyen et al. 2020; Sriphrom et al. 2021; Wang et al. 2018), the latter could happen under high-pressure and/or temperature environment (Althoff et al. 2014). The reduced  $\text{CH}_4$  emissions found in the current study could be likely involved in the biotic process, which could be dependent on the activities of the two bacterial communities. Biochar may create unfavorable conditions that restrict the activities of these two bacteria, thereby suppressing  $\text{CH}_4$  emissions from the biochar-added soil. Because  $\text{CH}_4$  emissions are sensitive to elevated pH (Oertel et al. 2016; Rahman and Yamamoto 2020) and oxygen availability (Ramachandran and Ramachandran 2001), increased soil pH and enhanced rice growth, which could

transport oxygen from the atmosphere to the rice plant's root system via the aerenchyma channel (Colmer 2003), by biochar addition may restrict the activities of methane-generating bacteria (Nguyen et al. 2020). Likely, biochar addition could reduce  $\text{CH}_4$  emissions by 40% when compared to no-biochar treatment (Liu et al. 2014), and the reason for this was demonstrated to be involved in the increase in soil pH caused by the amendment (Qin et al. 2016; Yang et al. 2017). However, the effects of biochar on  $\text{CH}_4$  emissions were diminished after the first rice season (Fig. 1). Similarly, stem weight and soil pH values of the biochar-added soil were lower in the second season than in the first season. These findings strongly indicate that the reduced  $\text{CH}_4$  emissions could be attributed to the change in soil properties induced by biochar addition, which has a weakened effect on  $\text{CH}_4$  emissions after the first rice season.

Figure 6 shows that changes in  $\text{CH}_4$  emissions and rice growth are strongly linked to the SQI, which confirmed our

**Fig. 4** The dynamics of the pH and concentration of exchangeable Al, Fe, and Mn after each of two rice seasons as affected by biochar. Error bars indicate the standard deviation of the mean.  $r^2$  is the coefficient of determination and  $p < 0.05$  indicates the relationship is significant following the linear or non-linear regression analysis



**Table 1** Selected properties of the tested soil and biochar. Ash, total nitrogen, and hydrogen content of biochar were 49.1%, 0.55%, and 1.83%, respectively; TOC, total organic carbon; CEC, cation exchange capacity;  $n=4$ ; SE, the standard deviation of the mean

Materials	Statistics	Clay (%)	Silt (%)	Sand (%)	pH	CEC (cmol <sub>c</sub> kg <sup>-1</sup> )	NH <sub>4</sub> <sup>+</sup> -N (mg kg <sup>-1</sup> )	Mehlich-1 P (mg kg <sup>-1</sup> )
Soil	Mean	21.10	19.25	59.65	5.75	11.93	53.60	118.15
	SE	0.11	0.26	0.35	0.13	0.58	2.05	4.24
Biochar	Mean				9.02	23.56	9.51	3363.7
	SE				0.19	2.15	1.03	81.13
Materials	Statistics	TOC (%)	Exchangeable concentration (mg kg <sup>-1</sup> )					
Soil	Mean	3.04	K	Ca	Mg	Al	Fe	Mn
	SE	0.03	147.7	426.5	69.61	20.89	27.37	21.88
Biochar	Mean	34.36	7.9	31.5	1.63	2.33	1.75	0.37
	SE	0.77	1911.3	164.1	84.69	1.10	16.37	20.68
			553.1	7.0	3.43	0.13	1.73	0.46

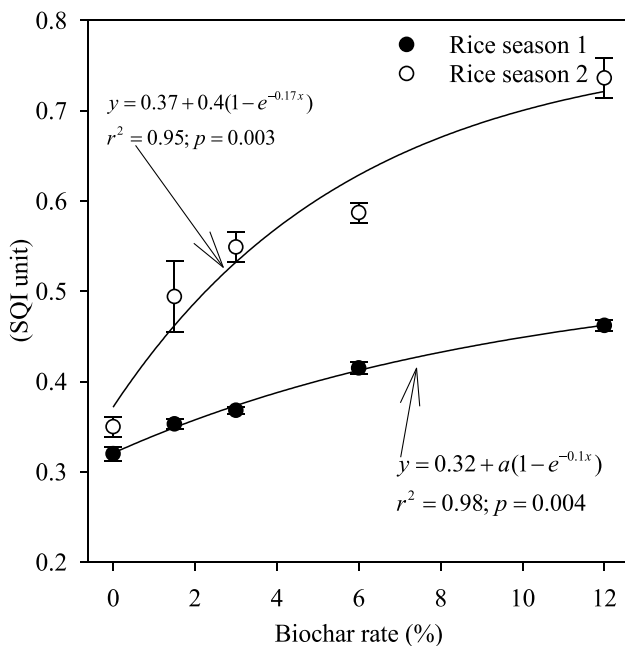
second hypothesis. The improved total biomass in the current study could be the consequence of enhanced soil quality caused by biochar addition. Likewise, many studies found that biochar addition could improve rice yield and growth in paddy soil due to enhanced soil properties (Haque et al. 2022; Huang et al. 2018; Wu et al. 2021). Liu et al. (2016) found that biochar enhanced pH, organic carbon, and the concentration of plant-available P and K in the biochar-added soil, leading to increased rice yield over two seasons.

The influences of biochar on soil properties and plant growth can be explained through liming capacity, porosity, sorption capacity, water holding capacity, and nutrient transformation (Hagemann et al. 2017; Mosharraf et al. 2021).

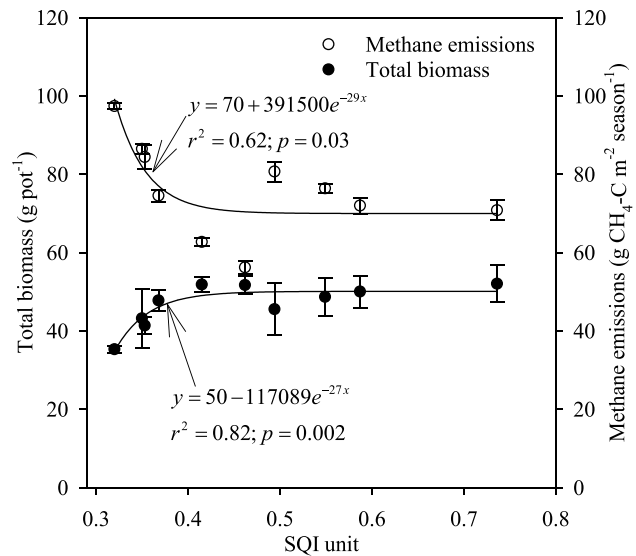
Although the exchangeable concentration of some potentially phytotoxic elements such as Al and Fe was declined by biochar addition, their concentration was higher in the second rice season than in the first season. This may inhibit the aboveground growth (Nguyen et al.

**Table 2** Loading values and weightage of 10 soil parameters from principal component analysis/factor analysis. Bold numbers are those greater than 0.5

Parameters	Factor 1	Factor 2	Factor 3	Parameter weightage
Exchangeable Mg	<b>0.97</b>	-0.01	0.13	0.136
Exchangeable Ca	<b>0.95</b>	-0.26	-0.06	0.136
Mehlich-1 P	<b>0.94</b>	-0.17	-0.14	0.136
Exchangeable K	<b>0.93</b>	0.23	0.13	0.136
Exchangeable Mn	<b>0.91</b>	0.04	0.13	0.136
Exchangeable Al	0.48	<b>-0.68</b>	-0.49	0.078
Exchangeable Fe	-0.14	-0.37	<b>-0.82</b>	0.044
CEC	0.00	<b>0.93</b>	0.23	0.078
pH	0.04	<b>0.87</b>	-0.24	0.078
NH <sub>4</sub> <sup>+</sup> -N	0.05	-0.20	<b>0.90</b>	0.044
Eigenvalue	4.74	2.71	1.55	
Percent	47.43	27.11	15.48	
Cumulative percent	47.43	74.54	90.02	
Factor weight	0.53	0.30	0.17	

**Fig. 5** The dynamics of soil quality index after each of two rice seasons as affected by biochar. Error bars indicate the standard deviation of the mean.  $r^2$  is the coefficient of determination and  $p < 0.05$  indicates the relationship is significant following the non-linear regression analysis

2022), which could account for the higher stem weight and grain weight in the first season than in the second season. Al may act to restrict the growth of plant roots (Panda et al. 2009) in general. Biochar addition affected the root weight of rice insignificantly while reducing the exchangeable Al concentration in the tested soil significantly in

**Fig. 6** Relationship between SQI and total rice biomass and methane emissions over the two seasons. Error bars indicate the standard deviation of the mean.  $r^2$  is the coefficient of determination and  $p < 0.05$  indicates the relationship is significant following the non-linear regression analysis

both seasons. This suggests that changes in the soil concentration of exchangeable Al may not be related to the development of rice roots. In addition, root weight in the second season was greatly higher than that in the first season, while exchangeable Al concentration in the second season was greater than that in the first season. This finding also confirms that either the growth of rice roots in the current study was not linked to Al status or the magnitude of exchangeable Al concentration in soil was insufficient to induce a significant effect on root growth. These may suggest that greater root biomass in the second season than in the first season could be related to better soil quality in the second season than in the first season.

The 10 soil parameters measured in the current study changed differently due to biochar addition. The current study found that pH and the concentration of some soil nutrients such as Mehlich-1 P, exchangeable K, Ca, and Mg, as well as CEC, were improved over biochar rates after the first rice season. The pH value of the tested biochar was 9.02, which was much greater than that of the tested soil, leading to the enhanced pH of the biochar-added soil. Dai et al. (2014) found that soil pH increased with biochar rates, and the pH enhancement became weaker with experimental duration. The current study also found that the effect of different biochar rates on soil pH was not significant after the second rice season, suggesting that its influence could fade after the first season. This is in line with CH<sub>4</sub> emissions, which showed that the magnitude of the reduced gas emissions by biochar rates was smaller

in the second season than in the first season. Because the tested biochar contained a considerable quantity of some main alkaline elements such as K, Ca, and Mg, its addition raised the concentration of exchangeable K, exchangeable Ca after the second season, and exchangeable Mg after the second season of the biochar-added soil. The improved concentration of these exchangeable elements could be the cause of increased CEC by biochar addition, which is consistent with previous studies (Hailegnaw et al. 2019; Nguyen et al. 2021; Wang et al. 2014). The CEC of the biochar was also much higher than that of the tested soil (Table 1), which could additionally account for the increase in the CEC of the biochar-added soil.

The enhanced concentration of Mehlich-1 P by biochar rates after the two rice seasons, which is similar to the other studies (Glaser and Lehr 2019; Yang et al. 2021), could be related to other mechanisms such as liming and priming effects. The former could result from the elevated pH of soil added with various biochar rates due to the alkaline nature of the material (Fidel et al. 2017). The enhanced pH of the biochar-added soil could be the primary reason for the decrease in the concentration of exchangeable Al and Fe, converting the Al and Fe-fixed P pool into an extractable P pool (Ch'ng et al. 2014; Johan et al. 2021), increasing the concentration of Mehlich-1 P as shown in Fig. 3b. The latter may be involved in the biochar-accelerated decomposition of native soil organic carbon (Dodor et al. 2018) that could inorganize and solubilize a considerable quantity of organic P. Stimulation of soil microbial communities to release particular enzymes to decompose native soil organic C is also attributed to the priming effects of biochar (Dey and Mavi 2022). Biochar also declined the concentration of  $\text{NH}_4^+\text{-N}$  after the first season while enhancing its concentration after the second season. Biochar exhibited a great capacity to adsorb  $\text{NH}_4^+\text{-N}$  on its surface area (Yang et al. 2018), possibly leading to a reduction in the  $\text{NH}_4^+\text{-N}$  concentration after the first rice season. Similarly, soil added with 5% biochar had a lower concentration of  $\text{NH}_4^+\text{-N}$  than soil added without biochar (Zheng et al. 2013). Nevertheless, after the second rice season, soil added with different biochar rates exhibited a greater concentration of  $\text{NH}_4^+\text{-N}$  than non-biochar-added soil, and the real reason for the finding is still unknown that requires further investigation. One possibility could be again linked to the adsorption capacity of the biochar and the  $\text{NH}_4^+\text{-N}$  status in the soil. The amount of  $\text{NH}_4^+\text{-N}$  adsorbed/contained in the added biochar may be desorbed into the soil matrix, improving the  $\text{NH}_4^+\text{-N}$  concentration over the range of biochar rates after the second season. Another related mechanism could be the priming effect (Dey and Mavi 2022; Dodor et al. 2018), which is induced by biochar to stimulate the decomposition of native soil organic C, converting the organic N to  $\text{NH}_4^+\text{-N}$  in the biochar-added soil.

The higher concentration of  $\text{NH}_4^+\text{-N}$ , Mehlich-1 P, exchangeable K, Ca, and Mg observed after the second season compared to the first season could explain the improvement in SQI after the second season. This may be linked to the adsorption and desorption of these elements on biochar particles (Joseph et al. 2021). Biochar has been found to have a great capacity for adsorbing nutrients and cations (Ambaye et al. 2020). Additionally, it was shown to retain  $\text{NH}_4^+$ ,  $\text{NO}_3^-$ , metals (Wang et al. 2022c), and phosphorous (Wang et al. 2022a) from the environment. The biochar-retained elements in the first season may be released into surrounding soil during the second season as a result of the fading effects of biochar over time. This is consistent with the observation that the effects of biochar on  $\text{CH}_4$  emissions weakened after the first rice season. Based on its ability to adsorb and release elements, biochar was studied and used as a slow-release fertilizer amendment for better crop production and environmental benefits (Dong et al. 2020; Wang et al. 2022a).

Results from the current study showed that changes in the responsive variables happened more rapidly at biochar rates lower than 3% and were relatively leveled off at higher biochar rates. The findings strongly support our third hypothesis that the relatively changing magnitude of reduced  $\text{CH}_4$  and enhanced rice biomass is greater in the lower range of biochar rates than in the higher range. The finding indicates that the changing pattern of  $\text{CH}_4$  emissions and rice biomass over the range of applied biochar rates followed an exponential model. Some soil properties such as  $\text{NH}_4^+\text{-N}$ , Mehlich-1 P, CEC, exchangeable Ca, Al, and Mn, and consequent SQI also changed, following a similar model. Based on the model, it would be best to apply the lower range of biochar rates to suppress  $\text{CH}_4$  emission and increase rice growth while minimizing biochar costs. Figure 6 shows that an SQI value of around 0.4 may be the optimal level for balancing reduced  $\text{CH}_4$  emission and improved rice growth. The 0.4-SQI could be obtained at biochar rates ranging from 2 to 3%. These rates are equivalent to biochar amounts ranging from 30 to 45 tones per ha, assuming a bulk density of  $1.0 \text{ g cm}^{-3}$  and a 15 cm soil layer from the surface. These quantities could be too much to apply in a single application for a rice season. Because biochar is stable in various environments (Wang et al. 2022b), a few applications of biochar at a rate of 5–10 tones per ha per season could be used to achieve the desired rates (33 to 49.5 tones per ha) after a few rice seasons. Nonetheless, the current study was conducted in a greenhouse where most environmental conditions were well controlled. More studies on fields at various scales should be implemented with a focus on agronomic effects, environmental effects, and economic effects to determine the optimal rate for sustainable management of paddy production with low greenhouse gas emissions and high rice yield.

## 5 Conclusion

With an increase in biochar rate, methane (CH<sub>4</sub>) emissions decreased, while total rice biomass increased exponentially. The effects of biochar addition on reduced CH<sub>4</sub> emissions were stronger during the first season and weakened during the second season, while its effects on improved rice growth were similar in both seasons. Some soil properties such as pH, cation exchange capacity (CEC), the concentration of Mehlich-1 P (phosphorous measured using the Mehlich-1 method), exchangeable K (potassium), Ca (calcium), and Mg (magnesium) were improved, while some potential phytotoxic elements such as Al (aluminum) and Fe (iron) were reduced with an increase in biochar rates, leading to an increase in soil quality of the biochar-added soil. A strong relationship between CH<sub>4</sub> emissions and total rice biomass with soil quality index suggests that changes in soil quality may be the primary cause of suppressed CH<sub>4</sub> emissions and enhanced rice growth by biochar addition. Changes in CH<sub>4</sub> emissions and rice growth were more rapid at lower biochar rates than at higher rates. Consequently, the optimal biochar rates may fall within the range of 2 to 3%, which needs more studies on fields to be specifically determined. The findings from the current study confirmed that biochar concurrently suppressed CH<sub>4</sub> emissions while improving rice growth and that these changes were strongly linked to the quality of the biochar-added soil.

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**Author Contribution** Binh Thanh Nguyen initiated the study, wrote, polished, and submitted the manuscript; Nghia Van Nguyen conducted the study and data analysis, wrote the draft, and co-revised the paper. All authors reviewed the manuscript.

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**Data Availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethical Approval** Not applicable.

**Consent to Participate** Not applicable.

**Consent for Publication** Not applicable.

**Competing Interests** The authors declare no competing interests.

## References

- Althoff F, Benzing K, Comba P, McRoberts C, Boyd DR, Greiner S, Keppler F (2014) Abiotic methanogenesis from organosulphur compounds under ambient conditions. *Nat Commun*. 5:4205. <https://doi.org/10.1038/ncomms5205>
- Ambaye TG, Vaccari M, van Hullebusch ED, Amrane A, Rtimi S (2020) Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater. *Int J Environ Sci Technol (Tehran)*. <https://doi.org/10.1007/s13762-020-03060-w>
- Carter MR, Gregorich EG (2008) Soil sampling and methods of analysis, 2nd edn. CRC Press, Taylor & Francis Group, Boca Raton
- Chaimala A, Jogloy S, Vorasoot N, Toomsan B, Jongrungrklang 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. <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>
- Ch'ng HY, Ahmed OH, Majid NMA (2014) Improving phosphorus availability in an acid soil using organic amendments produced from agroindustrial wastes. *Sci World J* 2014:6; Article ID 506356 <https://doi.org/10.1155/2014/506356>
- Colmer TD (2003) Long-distance transport of gases in plants: a perspective on internal aeration and radial oxygen loss from roots. *Plant Cell Environ* 26:17–36. <https://doi.org/10.1046/j.1365-3040.2003.00846.x>
- Dai Z, Wang Y, Muhammad N, Xiongsheng Y, Xiao K, Meng J, Liu X, Xu J, Brookes P (2014) The effects and mechanisms of soil acidity changes, following incorporation of biochars in three soils differing in initial pH. *Soil Sci Soc Am J* 78:1606. <https://doi.org/10.2136/sssaj2013.08.0340>
- Danso F, Agyare WA, Bart-Plange A (2021) Modelling rice yield from biochar-inorganic fertilizer amended fields. *J Sci Food Agric* 4:100123. <https://doi.org/10.1016/j.jafr.2021.100123>
- Dey D, Mavi MS (2022) Co-application of biochar with non-pyrolyzed organic material accelerates carbon accrual and nutrient availability in soil. *Environ Technol Innov* 25:102128. <https://doi.org/10.1016/j.eti.2021.102128>
- Dodor D, Amanor Y, Attor F, Adjadeh T, Neina D, Miyittah M (2018) Co-application of biochar and cattle manure counteract positive priming of carbon mineralization in a sandy soil. *Environ Syst Res* 7:5. <https://doi.org/10.1186/s40068-018-0108-y>
- Dong D, Wang C, Van Zwieten L, Wang H, Jiang P, Zhou M, Wu W (2020) An effective biochar-based slow-release fertilizer for reducing nitrogen loss in paddy fields. *J Soils Sediments* 20:3027–3040. <https://doi.org/10.1007/s11368-019-02401-8>
- Fidel RB, Laird DA, Thompson ML, Lawrinenko M (2017) Characterization and quantification of biochar alkalinity. *Chemosphere* 167:367–373. <https://doi.org/10.1016/j.chemosphere.2016.09.151>
- Glaser B, Lehr V-I (2019) Biochar effects on phosphorus availability in agricultural soils: a meta-analysis. *Sci Rep* 9. <https://doi.org/10.1038/s41598-019-45693-z>
- Gupta K, Kumar R, Baruah KK, Hazarika S, Karmakar S, Bordoloi N (2021) Greenhouse gas emission from rice fields: a review from Indian context. *Environ Sci Pollut Res* 28:30551–30572. <https://doi.org/10.1007/s11356-021-13935-1>
- Hagemann N, Joseph S, Schmidt H-P, Kammann CI, Harter J, Borch T, Young RB, Varga K, Taherymoosavi S, Elliott KW, McKenna A, Albu M, Mayrhofer C, Obst M, Conte P, Dieguez-Alonso A, Orsetti S, Subdiaga E, Behrens S, Kappler A (2017) Organic coating on biochar explains its nutrient retention and stimulation

- of soil fertility. *Nat Commun* 8:1089. <https://doi.org/10.1038/s41467-017-01123-0>
- Hailegnaw N, Mercl F, Pračke K, Száková J, Tlustoš P (2019) Mutual relationships of biochar and soil pH, CEC, and exchangeable base cations in a model laboratory experiment. *J Soils Sediments*. <https://doi.org/10.1007/s11368-019-02264-z>
- Hailegnaw N, Mercl F, Pračke K, Praus L, Száková J, Tlustoš P (2020) The role of biochar and soil properties in determining the available content of Al, Cu, Zn, Mn, and Cd in soil. *Agronomy* 10 <https://doi.org/10.3390/agronomy10060885>
- Haque ANA, Uddin MK, Sulaiman MF, Amin AM, Hossain M, Solaiman ZM, Aziz AA, Mosharraf M (2022) Combined use of biochar with 15nitrogen labelled urea increases rice yield, N use efficiency and fertilizer N recovery under water-saving irrigation. *Sustainability* 14:7622. <https://doi.org/10.3390/su14137622>
- Huang M, Fan L, Chen J, Jiang L, Zou Y (2018) Continuous applications of biochar to rice: Effects on nitrogen uptake and utilization. *Sci Rep* 8:11461. <https://doi.org/10.1038/s41598-018-29877-7>
- Johan PD, Ahmed OH, Omar L, Hasbullah NA (2021) Phosphorus transformation in soils following co-application of charcoal and wood ash. *Agronomy* 11:2010. <https://doi.org/10.3390/agronomy11102010>
- Joseph S, Cowie AL, Van Zwieten L, Bolan N, Budai A, Buss W, Cayuela ML, Graber ER, Ippolito JA, Kuzyakov Y, Luo Y, Ok YS, Palansooriya KN, Shepherd J, Stephens S, Weng Z, Lehmann J (2021) How biochar works, and when it doesn't: a review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy* n/a. <https://doi.org/10.1111/gcbb.12885>
- 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>
- Kumar M, Yadav AN, Saxena R, Rai PK, Paul D, Tomar RS (2021) Novel methanotrophic and methanogenic bacterial communities from diverse ecosystems and their impact on environment. *Bio-catal Agric Biotechnol* 33:102005. <https://doi.org/10.1016/j.cbab.2021.102005>
- Liu J, Shen J, Li Y, Su Y, Ge T, Jones DL, Wu J (2014) Effects of biochar amendment on the net greenhouse gas emission and greenhouse gas intensity in a Chinese double rice cropping system. *Eur J Soil Biol* 65:30–39. <https://doi.org/10.1016/j.ejsobi.2014.09.001>
- Liu Y, Lu H, Yang S, Wang Y (2016) Impacts of biochar addition on rice yield and soil properties in a cold waterlogged paddy for two crop seasons. *Field Crops Res* 191:161–167. <https://doi.org/10.1016/j.fcr.2016.03.003>
- Luu HM, Nguyen NH (2006) Effect of decomposed rice straw at different times on rice yield. *Omonrice* 14(14):58–63
- Minamikawa K, Tokida T, Sudo S, Padre A, Yagi K (2015) Guidelines for measuring CH<sub>4</sub> and N<sub>2</sub>O emissions from rice paddies by a manually operated closed chamber method. National Institute for Agro-Environmental Sciences, Tsukuba, Japan
- Mosharraf M, Uddin MK, Sulaiman MF, Mia S, Shamsuzzaman SM, Haque ANA (2021) Combined application of biochar and lime increases maize yield and accelerates carbon loss from an acidic soil. *Agronomy* 11:1313. <https://doi.org/10.3390/agronomy11071313>
- Nan Q, Xin L, Qin Y, Waqas M, Wu W (2021) Exploring long-term effects of biochar on mitigating methane emissions from paddy soil: a review. *Biochar* 3:125–134. <https://doi.org/10.1007/s42773-021-00096-0>
- Nguyen BT, Lehmann J (2009) Black carbon decomposition under varying water regimes. *Org Geochem* 40:846–853. <https://doi.org/10.1016/j.orggeochem.2009.05.004>
- Nguyen BT, Trinh NN, Le CMT, Nguyen TT, Tran TV, Thai BV, Le TV (2018) 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 BT, Trinh NN, Bach Q-V (2020) Methane emissions and associated microbial activities from paddy salt-affected soil as influenced by biochar and cow manure addition. *Appl Soil Ecol* 152:103531. <https://doi.org/10.1016/j.apsoil.2020.103531>
- Nguyen BT, Le LB, Pham LP, Nguyen HT, Tran TD, Van Thai N (2021) The effects of biochar on the biomass yield of elephant grass (*Pennisetum Purpureum Schumach*) and properties of acidic soils. *Ind Crops Prod* 161:113224. <https://doi.org/10.1016/j.indcrop.2020.113224>
- Nguyen BT, Nguyen VN, Nguyen TX, Nguyen MH, Dong HP, Dinh GD, Phan BT, Pham T-V, Van Thai N, Tran HTT (2022) Biochar enhanced rice (*Oryza sativa L.*) growth by balancing crop growth-related characteristics of two paddy soils of contrasting textures. *Soil Sci Plant Nutr* 22:2013–2025. <https://doi.org/10.1007/s42729-022-00790-3>
- 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. <https://doi.org/10.14456/enrj.2018.15>
- Oertel C, Matschullat J, Zurba K, Zimmermann F, Erasmí S (2016) Greenhouse gas emissions from soils—a review. *Geoch* 76:327–352. <https://doi.org/10.1016/j.chemer.2016.04.002>
- Panda SK, Baluska F, Matsumoto H (2009) Aluminum stress signaling in plants. *Plant Signal Behav* 4:592–597. <https://doi.org/10.4161/psb.4.7.8903>
- Qi L, Niu H-D, Zhou P, Jia R-J, Gao M (2018) Effects of biochar on the net greenhouse gas emissions under continuous flooding and water-saving irrigation conditions in paddy soils. *Sustainability* 10:1403. <https://doi.org/10.3390/su10051403>
- Qin X, Ye Li, Wang H, Liu C, Li J, Wan Y, Gao Q, Fan F, Liao Y (2016) Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: a four-year case study in south China. *Sci Total Environ* 569–570:1390–1401. <https://doi.org/10.1016/j.scitotenv.2016.06.222>
- Rahman M, Yamamoto A (2020) Methane cycling in paddy field: a global warming Issue. *Agrometeorology, Ram Swaroop Meena, IntechOpen*, <https://doi.org/10.5772/intechopen.94200>. Available from: <https://www.intechopen.com/chapters/74264>. In: 1-21 <https://doi.org/10.5772/intechopen.94200>
- Ramachandran P, Ramachandran R (2001) Natural and anthropogenic methane emission from coastal wetlands of south India. *Environ Manage* 27:547–557. <https://doi.org/10.1007/s002670010169>
- Shetty R, Prakash NB (2020) Effect of different biochars on acid soil and growth parameters of rice plants under aluminium toxicity. *Sci Rep* 10:12249. <https://doi.org/10.1038/s41598-020-69262-x>
- Sivapalan S (2015) Water balance of flooded rice in the tropics. In: Muhammad SJ (ed) *Irrigation and Drainage*. IntechOpen, Rijeka, p 5. <https://doi.org/10.5772/59043>
- Sriphrom P, Chidthaisong A, Yagi K, Tripetchkul S, Boonapatcharoen N, Towprayoon S (2021) Effects of biochar on methane emission, grain yield, and soil in rice cultivation in Thailand. *Carbon Manag* 12:109–121. <https://doi.org/10.1080/17583004.2021.1885257>
- Wang Y-Q, Bai R, Di HJ, Mo L-Y, Han B, Zhang L-M, He J-Z (2018) Differentiated mechanisms of biochar mitigating straw-induced greenhouse gas emissions in two contrasting paddy soils. *Front Microbiol* 9:2566–2566. <https://doi.org/10.3389/fmicb.2018.02566>
- Wang C, Luo D, Zhang X, Huang R, Cao Y, Liu G, Zhang Y, Wang H (2022) Biochar-based slow-release of fertilizers for sustainable agriculture: a mini review. *Environ Sci Technol Ecotechnol* 10:100167. <https://doi.org/10.1016/j.ese.2022.100167>
- Wang H, Nan Q, Waqas M, Wu W (2022b) Stability of biochar in mineral soils: assessment methods, influencing factors and potential problems. *Sci Total Environ* 806:150789. <https://doi.org/10.1016/j.scitotenv.2021.150789>

- Wang L, Ok YS, Tsang DCW, Alessi DS, Rinklebe J, Mašek O, Bolan NS, Hou D (2022c) Biochar composites: emerging trends, field successes and sustainability implications. *Soil Use Manag* 38:14–38. <https://doi.org/10.1111/sum.12731>
- Wang Y, Yin R, Liu R (2014) Characterization of biochar from fast pyrolysis and its effect on chemical properties of the tea garden soil. *J Anal Appl Pyrolysis* 110. <https://doi.org/10.1016/j.jaap.2014.10.006>
- WRB (2015) World reference base for soil resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome
- Wu L, Zhang S, Chen M, Liu J, Ding X (2021) A sustainable option: biochar addition can improve soil phosphorus retention and rice yield in a saline–alkaline soil. *Environ Technol Innov* 24:102070. <https://doi.org/10.1016/j.eti.2021.102070>
- Yanan X, Yang S-H, Xu J, Ding J, Sun X, Jiang Z (2018) Effect of biochar amendment on methane emissions from paddy field under water-saving irrigation. *Sustainability* 10:1371. <https://doi.org/10.3390/su10051371>
- Yang X, Lan Y, Meng J, Chen W, Huang Y, Cheng X, He T, Cao T, Liu Z, Jiang L, Gao J (2017) Effects of maize stover and its derived biochar on greenhouse gases emissions and C-budget of brown earth in Northeast China. *Environ Sci Pollut Res* 24:8200–8209. <https://doi.org/10.1007/s11356-017-8500-0>
- Yang HI, Lou K, Rajapaksha AU, Ok YS, Anyia AO, Chang SX (2018) Adsorption of ammonium in aqueous solutions by pine sawdust and wheat straw biochars. *Environ Sci Pollut Res* 25:25638–25647. <https://doi.org/10.1007/s11356-017-8551-2>
- Yang L, Wu Y, Wang Y, An W, Jin J, Sun K, Wang X (2021) Effects of biochar addition on the abundance, speciation, availability, and leaching loss of soil phosphorus. *Sci Total Environ* 758:143657. <https://doi.org/10.1016/j.scitotenv.2020.143657>
- Yang X, Vancov T, Penuelas J, Sardans J, Singla A, Alrefaei A, Song X, Wang W (2022) Optimal biochar application rates for mitigating global warming and increasing rice yield in a subtropical paddy field. *Exp Agric* 1–17. <https://doi.org/10.1017/S0014479721000259>
- Yang S, Xiao Yn, Sun X, Ding J, Jiang Z, Xu J (2019) Biochar improved rice yield and mitigated CH<sub>4</sub> and N<sub>2</sub>O emissions from paddy field under controlled irrigation in the Taihu Lake Region of China. *Atmospheric Environ* 200:69–77. <https://doi.org/10.1016/j.atmosenv.2018.12.003>
- Yun J-J, Park J-H, Acharya B, Park J-H, Cho J-S, Kang S-w (2022) Production of pelleted biochar and its application as an amendment in paddy condition for reducing methane fluxes. *Agriculture* 12:470. <https://doi.org/10.3390/agriculture12040470>
- 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>
- 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>

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