Effect of biochar and compost application on nitrogen dynamics in organically managed nutrient-poor paddy soil system and in organic rice cultivation system

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Abstract. Nitrogen (N) is an essential plant nutrient, and its retention in the soil is beneficial to plant growth and productivity. High levels of N can leach from soil with organic amendments, particularly in water-rich paddy rice cultivation. Biochar has the potential to influence the soil N cycle. The study included four treatments applied to organically managed nutrient-poor paddy soil (S) and rice cultivation (R) systems, respectively over two growing seasons: biochar only (BA), compost only (CA), biochar and compost mixed at an equal rate (BC), and no amendment (control). Biochar produced from mangrove (*Rhizophora apiculata*) which obtained from slow pyrolysis in a traditional kiln, whereas compost generated from organic municipal solid waste. The results showed that, on average, BA and BC maintained NO_3^--N and NH_4^+-N in the soil and reduced absolute N leaching compared to the control and CA, respectively. System R maintained nitrogen better than system S. BA reduced N mass leaching by 27.25% in system S and by 59.21% in system R, compared to the control, while BC reduced N mass leaching by 24.85% in system S and by 58.48% in system R, compared to CA. However, the reduction in N_2O emission fluxes was not significant in both BA and BC in both seasons, although cumulative emission fluxes after a year of cultivation decreased significantly. BC significantly boosted water use efficiency relative to yield in system R. These results show that co-application of biochar and compost to nutrient-poor soil in an organically managed system substantially reduced N leaching and suggests that it could be an effective management option for organic rice cultivation in Thailand.

Keywords: Biochar, compost, nitrogen leaching, N_2O emission, nitrogen balance, organic rice cultivation.

INTRODUCTION

In Thailand, rice is the most favoured and widely cultivated crop. In recent years, Thai farmers have been recommended to adopt organic agricultural systems to achieve sustainability goals (FAO, 1999; NSO, 2019; OAE, 2019; TOTA, 2011). Biochar, a stable, solid carbonaceous by-product of biomass pyrolysis, is considered an organic material with several benefits. It has begun to play a critical role in agriculture

because of its potential to boost nutrient retention, and thus reduce soil nutrient leaching (Lehmann *et al.*, 2003; Lehmann, 2007; Steiner *et al.*, 2007; Steiner *et al.*, 2010). High leaching of essential plant nutrients depletes soil fertility and reduces crop yields, as well as directly affects surface and groundwater quality (Steiner *et al.*, 2010). The large internal surface area and high porosity of biochar enable it to absorb organic matter and nutrient molecules. Consequently, biochar may be able to stimulate microbial activity in the soil. The high surface charge density of biochar enables cation retention by cation exchange (Lehmann *et al.*, 2003; Lehmann *et al.*, 2006; Lehmann, 2007). Biochar has shown clear potential to influence the nitrogen (N) cycle (Clough and Condron, 2010); it is reported to have an impact on nitrification rates and ammonia (NH_3) adsorption and enhance ammonium (NH_4^+) storage (Clough and Condron, 2010; Singh *et al.*, 2010; Zheng *et al.*, 2012). Furthermore, biochar may be useful for reducing nitrate (NO_3^-) leaching that causes environmental contamination (Ding *et al.*, 2010; Liu *et al.*, 2017; Singh *et al.*, 2010). For instance, Liu *et al.* (2017) found that biochar promoted N use efficiency in sandy soil, but not in clay loam soil. However, the latter showed a rise in N fertilizer retention. Therefore, biochar was found to enhance both N fertilizer availability and actively reduce NO_3^--N leaching from clay loam soil. Biochar also reduces the loss of other essential plant nutrients through the deeper soil horizons that may cause environmental pollution (Asai *et al.*, 2009; Liu *et al.*, 2017; Singh *et al.*, 2010; Zhang *et al.*, 2012).

Some studies have reported the impact of biochar on greenhouse gas production as biochar potentially reduces the emission of greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O), during their cycles (Clough and Condron, 2010; Lehmann *et al.*, 2003; Liu *et al.*, 2012; Taghizadeh-Toosi *et al.*, 2011; Zhang *et al.*, 2012). In China, a field study investigating N_2O emissions in paddy cultivation found that total N_2O emissions decreased sharply by 40–51% and 21–28% in biochar-amended soils with and without N fertilization, respectively (Zhang *et al.*, 2010). Liu *et al.* (2012) also reported that biochar made with crop straw changed soil characteristics to reduce N_2O emission while improving soil fertility and rice productivity. In contrast, some studies have found no relationship between N_2O reduction and biochar (Scheer *et al.*, 2011; Verhoeven and Six, 2014).

Thus, biochar was found to either improve the availability or reduce the losses of the nitrogen. Accordingly, the study of nitrogen dynamics would be more thoroughly explored on the feasibility of biochar and its co-application of whether biochar could stimulate the cultivation system. Simultaneously, the practice of organic rice is becoming an alternative trend in Thailand. However, there has been very little research conducted on biochar application in the organic rice cultivation,

particularly in Thailand. Accordingly, the present study was carried out to determine the effect of biochar and compost application on soil N dynamics in a Thai organic rice system. Therefore, the aim of this study is to quantify the impact of application of biochar and compost, singly and in combination, on N balance, crop production, water use efficiency (WUE), greenhouse gas emissions, and soil quality in an organically managed nutrient-poor paddy soil (S) in comparison to a rice cultivation system (R) were estimated. This study contributes to the limited research on organic rice cultivation in Thailand by determining the potential benefits of co-application of biochar and compost as an alternative management option for improving the long-term capacity of paddy soils to retain essential nutrients.

MATERIALS AND METHODS

Soil and organic materials

Soil samples was obtained from Muang district, Ratchaburi province, Thailand (13° 35′ 25.537″ N, 99°43′ 42.974″ E; 19 m above sea level). It was classified as nutrient-poor clay soil (41% clay, 34% silt, and 25% sand). This region has been under rice cultivation for more than a decade. Surface soil was collected at 0 to 0.3 m of the soil profile. After collection, the soil sample was sun-dried, left for a month in the greenhouse with an air temperature of about 32°C before amending with compost and biochar at the ratio 1:5 based on experimental conditions. The soil texture was determined by the hydrometer method (Bouyoucos, 1962), and cation exchange capacity (CEC) was measured by the ammonium saturation method (Kitsopoulos, 1999). Soil organic matter (SOM) was measured by $FeSO_4$ titration (Arata *et al.*, 1976), and soil organic carbon (SOC) by a modified Walkley–Black acid dichromate digestion method (Soon and Abboud, 1991). Total N was measured by the Kjeldahl method (Bradstreet, 1954), NO_3^--N by cadmium reduction (Cortas and Wakid, 1990), and NH_4^+-N by the Nessler method (Crosby, 1968). Soil temperature was measured using a 1:1 soil:water suspension (Shirokova *et al.*, 2000), and soil pH and Eh were measured with an ion-selective electrode (pH/ORP combination sensor, YSI Professional Plus, Yellow Springs, OH, USA). The chemical and physical characteristics of the soil used in this study are given in Table 5.

Biochar commercially produced from mangrove (*Rhizophora apiculata*) was obtained from Samutsongkhram province, Thailand. It was produced by slow pyrolysis in a traditional kiln, in which the temperature was 500 to 700°C. The mangrove biochar was ground using a charcoal mill (size 1 to 3 mm). The average pore size of the biochar was approximately 10 µm. Biochar porosity and surface area size were

observed using scanning electron microscopy with energy dispersive X-ray spectroscopy (JCM-6000, JEOL Ltd., Japan). The basic properties of the biochar were obtained in triplicate, and the results are given in Table 5.

The compost used in the study was generated from organic municipal solid waste in Bangkok. It was produced under controlled conditions in a ventilated system at a temperature of 70°C and moisture control at 70% by weight, over 40 to 45 days. The texture of the compost ranged from coarse to fine particles. Compost characteristics, i.e., pH, organic matter, organic carbon, total N, and CEC, were measured as for biochar. The basic properties of the compost are given in Table 5.

Soil preparation and rice cultivation management

The study site was located at KMUTT, Bangkhuntian Campus (13° 34′ 34.3″N, 100° 26′ 34.5″E; 6.37 m above mean sea level), south Bangkok, about 5km inland from the Gulf of Thailand. The average temperature of the study site was approximately 31°C. The soil sample were carried out in twenty-four polyethylene containers (0.7 m W × 0.9 m L × 0.45 m H). Each container was installed a PVC tubing with a water tap at the bottom and fitted with a PVC end cap for collecting water leachate. The organically managed nutrient-poor paddy soil (S) system is in comparison to a rice cultivation system (R) for two seasons. The organically managed nutrient-poor paddy soil (S) system has the same field management as compared to a rice cultivation system (R). However, it does not cultivate rice. The rice system (R) was cultivated with *Oryza sativa* L. 'Pathumthani 1'. Rice was planted in trays two weeks before transplanting. The study period was from September to December 2017 for the first crop and May to August 2018 for the second crop.

The treatments included control without amendment (CT), biochar application (BA), compost application (CA), and biochar and compost co-application (BC) in the paddy soil system (SCT, SBA, SCA, and SBC, respectively) and the rice cultivation system (RCT, RBA, RCA, and RBC, respectively), giving a total of eight treatments. The treatments were replicated three times in a randomized complete block design.

Biochar was thoroughly applied once a year at a rate of 10 t ha^{-1} in the biochar application plots two weeks before transplanting the first crop. Wet compost was applied at a rate of 2 t ha^{-1} at a moisture content of 60% by weight in the compost application plots two weeks before transplanting in both seasons. Weeds were eliminated by hand, and all treatments were irrigated using a continuously flooded water management system.

Water intake was assessed once a week; water input was measured manually. The water level in the plots was usually kept 5 to 10 cm above the soil surface during seedling transplantation and until before harvest. The plots were always flooded during seed set to

increase the kernel size of panicles then allowed to dry out for harvest. Water use was compute as:

$$Wvol. = T_{ir} \; x \; Q_{constant} \tag{1}$$

Where $W_{vol.}$ is the volume of water (L), T_{ir} is the duration of irrigation (sec), and $Q_{constant}$ is a volume flow rate for this experiment (L sec^{-1}). The amount of water used was included in the calculation for WUE based on rice grain yield as below:

$$WUE = \frac{Ycrop}{Wvol.} \tag{2}$$

Where WUE is given as per crop (g m^{-2} L^{-1}) and Y_{crop} is rice grain yield (g m^{-2}).

Analysis of water leachate and leached N concentration

A free-drainage lysimeter was used to collect water leachate samples. Water samples were collected every two days during the first week of transplanting and once a week thereafter. During sample collection, the water taps on the PVC tubing were opened for an hour, and then closed after collection. Samples were kept in clean 200 ml plastic bottles and analyzed within 24 hours.

The absolute N mass leached, including NO_3^--N and NH_4^+-N, was analyzed with a water and wastewater multiparameter with chemical oxygen demand photometer (Model Hanna, HI83399, Hanna Instruments Ltd., United Kingdom). NO_3^--N was determined with the cadmium reduction method and NH_4^+-N with the Nessler method.

N$_2$O emission sampling, analysis and calculation

The closed-chamber method is used for simultaneous monitoring of N$_2$O. Two different chamber sizes (30 cm internal diameter × 50 cm or 100 cm height) were used depending on plant height in system R, and the 50-cm-high chamber used in system S. The chamber was made of opaque acrylic, and the stainless steel base was inserted into the soil surface before the first growing season and remained there until the end of the second season. Plant density was six plants per hill, with the hills spaced 25 cm apart. Gas samples were collected, once a week from 9.30 AM to 3.30 PM on every seven sampling day from fallow to harvest, in 20-ml vacuum vials at every 5-minute interval, wrapped in parafilm, and labeled at beside the bottle.

Gas concentrations were analyzed with a gas chromatograph equipped with an electron capture detector (ECD) and HayeSep Q packed column (Agilent 7890B, Agilent Technologies, Inc., USA) at 300°C for N$_2$O. Helium was used as the carrier gas for ECD at a flow rate of 20 ml min^{-1}.

N$_2$O flux is calculated for mass area^{-1} time^{-1}

(Nishimura *et al.*, 2008; Watanabe *et al.*, 2012). The gas collected from the chamber is converted to a mass or molecular basis using the ideal gas law. The conversion equation depends on the inside temperature of the chamber and enclosed air pressure. The ideal gas law equation is given as:

$$Ci = q_i \times M_i \times PRT \qquad (3)$$

Where C_i is mass volume^{-1} concentration (g m^{-3}), M_i is molecular weight (N_2O = 44 g), q_i is volume volume^{-1} concentration, P is atmospheric pressure within the chamber (assumed to be 1 atm), R is the universal gas constant (0.082058 L atm K^{-1} mol^{-1}), and T is air temperature within the chamber during sampling time (K).

The cumulative N_2O flux (Nishimura *et al.*, 2008) calculated using a linear portion of the gas concentration inside the chamber (ppm) changed over 15 minutes of sampling time:

$$F = \frac{dC}{dtVA} \qquad (4)$$

Where F is the cumulative flux (mg m^{-2} hr^{-1}), $\frac{dC}{dtVA}$ is the gas concentration rate increased or decreased by time (ppm min^{-1}), V is the volume of the chamber (m^3), and A is the area of soil enclosed by the chamber.

Total N_2O emissions during the year is calculated as:

$$Total_{N2O} = F_i \times D_i \qquad (5)$$

Where $Total_{N2O}$ is the total N_2O emission per year (g N_2O-N m^{-2} year^{-1}), F_i is the measured flux (g N_2O-N m^{-2} h^{-1}), D_i is the number of days (days), i is the sampling interval and n is the number of the sampling interval (Ma *et al.*, 2009)

While monitoring N_2O fluxes, soil Eh and soil pH were also measured at a depth of 0.1 m with an ion-selective electrode (pH/ORP combination sensor, YSI Professional Plus).

Rice grain yield and biomass sampling and analysis

Rice grain yield was determined for both inside and outside the chamber in every replicate plot after harvesting, and then the moisture content adjusted to approximately 14%. The biomass of aboveground parts (straw) was determined in both seasons after harvest. The wet weight was determined first and the samples were dried at 80 °C for 48 hours for obtaining the dry weight. The percent moisture content (eqn. 6) was computed based on the weight lost during the oven drying as:

$$MC_{wb} = \left(\frac{Wi - Wf}{Wi}\right) \times 100 \qquad (6),$$

Where MC_{wb} is the moisture content wet basis (%), W_i is the initial weight (wet weight) of rice grain yield (g) and W_f is the final weight (dry weight) of rice grain yield (g) (adapted from IRRI, n.d.).

Estimation of Nitrogen Balance

Nitrogen balance (Equation 7) was computed as follows:

$$Unknown\ N\ balance = N_{initial} - Average\ changes\ of\ N \qquad (7),$$

Where Unknown N balance = Unclassified N losses (NH$_4$ volatilization, denitrification, surface runoff, soil erosion, plant senescence, and crop N accumulated in system R (grain and biomass); due to the limitations and difficulty in measurement of some parameters, other N losses are unclassified, and we focused only on N leaching and N_2O emission); $N_{initial}$ = N initial soil before cultivation + N fertilization from biochar and compost (the amounts of N from irrigation water and biological N fixation were not considered due to insignificant values); Average changes of N = Average N losses of the two seasons (through NO_3^--N leaching + NH_4^+-N leaching + N_2O emission)

A positive N balance indicates that N is gained in the system, while a negative value indicates a loss (adapted from Sainju, 2017).

Statistical analysis

The data were analyzed by SPSS version 23 using the One-Way Analysis of Variance (ANOVA) (Stoline, 1981). Duncan's multiple range tests were used to identify statistically significant differences in the systems and treatment effects for two crop seasons at a confidence level of 99% (P < 0.01). The data are presented as mean ± standard deviation (SD) for n = 3.

RESULTS AND DISCUSSION

Effects of biochar and compost addition on NO_3^--N and NH_4^+-N leaching

The 1-hour collection of water in weeks 1–45 of the experiment was designed to simulate a weekly leaching. NO_3^--N and NH_4^+-N in paddy soil and rice cultivation systems varied considerably during the study period (Figure 2). The paddy soil system showed higher amounts of leachate of both forms of N all through the cultivation period, whereas the rice cultivation system had a higher amount of N leachate at the beginning of the season, which then dropped continuously during the cultivation period. The patterns were the same in both seasons. N leaching in the rice cultivation system was

Table 1. NO_3^--N and NH_4^+-N leaching during the week 1-45 of the organically managed nutrient-poor paddy soil (S) and rice cultivation (R) systems.

Cultivation system	First crop		Second crop		Average crop	
	Paddy soil (S)	Rice (R)	Paddy soil (S)	Rice (R)	Paddy soil (S)	Rice (R)
Treatment:	$g\ N\ m^{-3}\ crop^{-1}$					
NO_3^- - N leaching						
CT	0.221 b	0.026 a	0.201 b	0.011 c	0.211 b	0.019 b
CA	0.356 a	0.032 a	0.360 a	0.041 a	0.358 a	0.037 a
BC	0.239 b	0.016 ab	0.193 c	0.018 b	0.216 b	0.017 b
BA	0.167 c	0.009 b	0.165 d	0.006 c	0.166 c	0.008 c
NH_4^+ - N leaching						
CT	0.381 c	0.076 c	0.364 c	0.022 c	0.373 c	0.049 c
CA	0.708 a	0.186 a	0.667 a	0.117 a	0.688 a	0.152 a
BC	0.612 b	0.114 b	0.534 b	0.073 b	0.573 b	0.094 b
BA	0.280 d	0.061 d	0.237 d	0.006 d	0.259 d	0.034 d

The values are mean (n=6). SD did not indicate in this table due to the value < 0.01
Different letters denote significant differences (P < 0.01) between treatments of each system.

lower than in the paddy soil system, in general, due to plant uptake of N for growth (Lea and Azevedo, 2006).

The average NO_3^--N leachate in the paddy soil system ranged from 0.166 to 0.358 g N m^{-3} $crop^{-1}$, whereas in the rice cultivation system it ranged from 0.008 to 0.037 g N m^{-3} $crop^{-1}$. The average NH_4^+-N leachate was 0.259 to 0.688 g N m^{-3} $crop^{-1}$ and 0.034 to 0.152 g N m^{-3} $crop^{-1}$ in the paddy soil system and the rice cultivation system, respectively (Table 1). In both systems, we found a significantly higher reduction in NO_3^--N and NH_4^+-N leaching ($p < 0.01$) in the co-application treatment than in the compost treatment. The average amount of NO_3^--N leachate in the co-application treatment decreased by 39.66% and 54.05% in the paddy soil system and the rice cultivation system, respectively, compared to that in the compost treatment. The average amount of NH_4^+-N leachate in the co-application treatment also decreased by 16.71% and 38.16% in the paddy soil system and the rice cultivation system, respectively, compared to that in the compost treatment.

High levels of N leachate, in the form of NO_3^--N and NH_4^+-N, were observed in the compost treatment in both the paddy soil system and the rice cultivation system due to the compost containing a high amount N. N leaching was reduced in both systems in the biochar and compost co-application treatment. In addition, the biochar treatment also showed the lowest level of leaching than all the other treatments. These findings show that biochar addition can lead to retention of N in the soil and reduced leaching from the columns (Figure 3 and Table 1). Consequently, our results confirm that biochar can capture N from the soil due to its nitrogen adsorption capacity, which initially from biochar feedstock and the pyrolysis temperature (Dempster *et al.*, 2012; Lehmann *et al.*, 2003). Furthermore, the particle size of biochar

also results in the potential impacts on nitrogen retention that reduce the leaching from the soil vice versa (Lehmann *et al.*, 2003). This study supported the conclusion of Clough *et al.* (2013) that nitrogen shall be adsorbed by biochar, which thereby desorbed from the water infiltration. This situation can increase the residence time of NO_3^- availability in the soil. On the other hand, it is better for plant uptake of NO_3^-.

Dempster *et al.* (2012) reported that sandy soil amended with *Eucalyptus* biochar placed in lysimeter pots showed an increase in NO_3^- absorption potential and a reduction in cumulative NO_3^- leaching by 25% after fertilized and watered for 21 days compared to a control treatment. NH_4^+ was also reduced (from 15.0 to 12.9 mg pot^{-1}) after 21 days of fertilization. Thus, adsorption of N by biochar leads to a decrease in leaching of NO_3^- and NH_4^+. Yao *et al.* (2012) studied the mechanism of NO_3^- retention in sandy soil amended with biochar made from peanut hulls and Brazilian pepperwood in a column leaching experiment. After flushing the column over four days, they found that biochar reduced NO_3^- leaching by 34%. Kameyama *et al.* (2012) have suggested that biochar amendment of soil potentially increases hydraulic conductivity or preferential flow around larger particles, thereby increasing N leaching, although some studies have shown no effect of biochar (Ding *et al.*, 2010; Schulz and Glaser, 2012).

Organic applications increase the capacity of soil to retain N as both NO_3^--N and NH_4^+-N. However, biochemical processes are involved in controlling NO_3^- leaching through the soil column. Therefore, it is difficult to anticipate NO_3^- retention by biochar in the soil system. In addition, biochar itself has a substantial capacity to adsorb NO_3^- and NH_4^+ from the soil solution. It can reduce the rate of N mineralization and

NO_3^--N leaching from the soil column due to adsorption of NH_4^+ and organic nitrogen produced during mineralization of soil organic matter (Downie, 2007; Dünisch, 2007; Liu *et al.*, 2017; Singh *et al.*, 2010; Yao *et al.*, 2012). In addition, NO_3^--N may be lost via other pathways, such as denitrification and immobilization (Clough *et al.*, 2013).

Effect of biochar and compost addition on N_2O emissions

The trends in temporal variation in N_2O flux were similar in the two systems throughout the cultivation period. However, the flux increased or decreased alternately due to different biological processes depending on the growing conditions of this study, such as moisture, water content, climate, N availability, and the competition between microbes and weeds (Figure 4). N_2O emission is naturally favored under aerobic conditions; in this study, the flux was high during the fallow period. In the paddy soil system, all treatments showed a similar trend. However, in the rice cultivation system, N_2O fluxes immediately dropped during the first week of transplanting, then slightly increased until the growth of the tillering stage, especially in the RCA treatment. N_2O fluxes increased during the reproductive phase in the following weeks. Tillering and reproductive stages are the active stages in rice production, and supply a high level of O_2 from photosynthesis and produce higher amounts of N_2O from the nitrification process (Minami, 2000; Pathak, 1999).

This study results support other studies which concluded that wood and poultry manure biochar (Singh *et al.*, 2010), bamboo processing biochar (Wang *et al.*, 2013), maize (*Zea mays* L.) straw biochar (Jia *et al.*, 2012) reduced N_2O fluxes. The average N_2O emission flux was significantly lower ($p < 0.01$) with biochar amendment in both paddy soil and rice cultivation systems (Figure 5). The average N_2O emission flux in the paddy soil system ranged from 608.17 to 812.25 mg N_2O m^{-2} crop^{-1}, whereas in the rice cultivation system, it ranged from 459.79 to 569.52 mg N_2O m^{-2} crop^{-1} (Table 2). The average N_2O emission fluxes were lower in the rice cultivation system than in the paddy soil system due to direct plant uptake of N as NO_3^- (Giles *et al.*, 2012). The co-application treatment showed significantly lower ($p < 0.01$) N_2O emission fluxes on average compared to the compost treatment, which was approximately 13.48% and 8.21% in the paddy soil system and rice cultivation system, respectively. Results for the biochar treatment also demonstrate the positive effects of biochar addition. It had the lowest N_2O fluxes on average—19.23% compared to the control in the paddy soil system and 9.16% in the rice cultivation system (Table 2).

Biochar application was associated with a significant reduction in N_2O fluxes, while compost addition resulted in either higher N_2O emissions or higher rice yield due to the higher organic content in the soil. Biochar has the potential to reduce N_2O emissions in the field by increasing N retention in the soil (Abel *et al.*, 2013; Van *et al.*, 2010). N_2O is generally produced during biological processes of microorganisms. It is usually generated from nitrification of NH_4^+ under aerobic conditions. It can also be produced from denitrification of NO_3^- under anaerobic conditions (Bremner and Blackmer, 1981). In addition, application of organic fertilizer such as compost also promotes N_2O emission (Czepiel *et al.*, 1996; He *et al.*, 2001; Wang *et al.*, 2013). The nitrifier or denitrifier uses organic carbon compounds as electron donors for cellular synthesis or composition, or as energy. Therefore, organic compounds can cause an increase in the denitrification rate (Pathak, 1999), which results in higher N_2O emissions.

Furthermore, treatments in the rice cultivation system during the flooded period had lower N_2O emissions compared to those in the paddy soil system due to unfavorable condition for nitrification and direct uptake of NO_3^- by rice plants for their growth (Pathak, 1999; Smith *et al.*, 1983). Rice plants supply O_2 from photosynthesis at the rhizosphere. The process results in the promotion of nitrification, which increases NO_3^- as the primary product and N_2O as its by-product (Pathak, 1999). This affects NO_3^- availability and the magnitude of denitrification because NO_3^- is the main substrate that is reduced to form N_2O (Giles *et al.*, 2012).

Grain yield and water use efficiency

Rice grain yield increased in response to biochar and compost application. The average grain yield in the two seasons was 45.34 to 67.67 g m^{-2} crop^{-1}. The RCA treatment showed a significantly improved yield by about 42.26% compared to the control (RCT; $p < 0.01$), whereas biochar addition improved grain yield in the RBC treatment only by about 4.91% compared to the RCA treatment. Yield in the RBA treatment was boosted by 4.76% compared to the control treatment, confirming that biochar can also have a positive effect on productivity. This turn occurred as a result of variations in the water holding capacity, nutrition in the soil, and activities of microbial, which varying upon the soil types. However, the first-season crop was not affected by biochar addition, but a significant change ($p < 0.01$) was observed in the RBC treatment in the second-season crop (Table 3 and Figure 6). A significant change in grain yield found in the latter crop due to the interaction of biochar addition, which was related to the soil water. Hence, biochar, which blended in the soil, adsorbed nitrogen, in its pores resulted in higher N uptake for plants.

Liu *et al*. (2016) found that rice straw biochar application resulted in a considerable improvement in yield, 8.5 to 10.7% higher than the yield in the control

Table 2. N$_2$O emissions of the first and second crop seasons, and average crop of the organically managed nutrient-poor paddy soil (S) and rice cultivation (R) systems.

Cultivation system	*N$_2$O Emissions*					
	First crop		**Second crop**		**Average crop**	
	Paddy soil (S)	**Rice (R)**	**Paddy soil (S)**	**Rice (R)**	**Paddy soil (S)**	**Rice (R)**
Treatment:	*mg N$_2$O m^{-2} crop^{-1}*					
CT	773.21 ± 61.69 b	520.37 ± 27.23 ab	732.78 ± 26.83 b	491.89 ± 31.96 ab	752.99± 44.26 b	506.13 ± 29.32 c
CA	831.04 ± 80.37 a	576.20 ± 8.80 a	793.45 ± 112.50 a	562.90 ± 41.99 a	812.25± 96.44 a	569.52 ± 23.80 a
BC	740.60 ± 98.60 b	534.50 ± 29.65 a	664.96 ± 19.71 c	511.10 ± 30.20 ab	702.78 ± 59.16 c	522.77 ± 11.19 b
BA	651.77 ± 56.17 c	467.47 ± 11.70 b	564.56 ± 73.77 d	452.11 ± 35.55 b	608.17 ± 64.97 d	459.79 ± 13.42 d

The values are mean ± SD (n=6).
Different letters denote significant differences (P < 0.01) between treatments of each system.

Table 3. Grain yield and water use efficiency (WUE) of the rice cultivation (R) system.

Cultivation system	**First crop**		**Second crop**		**Average crop**	
	Grain yield	**WUE**	**Grain yield**	**WUE**	**Grain yield**	**WUE**
Treatment:	*g m^{-2} crop^{-1}*	*g m^{-2} L^{-1} crop^{-1}*	*g m^{-2} crop^{-1}*	*g m^{-2} L^{-1} crop^{-1}*	*g m^{-2} crop^{-1}*	*g m^{-2} L^{-1} crop^{-1}*
CT	45.00 ± 4.36 b	0.1903 ± 0.02 b	45.67 ± 2.08 c	0.1893 ± 0.01 d	45.34 ± 3.22 d	0.1898 ± 0.01 d
CA	58.67 ± 4.04 a	0.2473 ± 0.02 a	70.33 ± 2.89 b	0.2903 ± 0.01 b	64.50 ± 3.47 b	0.2688 ± 0.01 b
BC	59.33 ± 4.94 a	0.2523 ± 0.02 a	76.00 ± 3.00 a	0.3180 ± 0.01 a	67.67 ± 3.97 a	0.2852 ± 0.01 a
BA	46.33 ± 4.04 b	0.1981 ± 0.02 b	48.67 ± 1.53 c	0.2066 ± 0.01 c	47.50 ± 2.79 c	0.2024 ± 0.01 c

The values are mean ± SD (n=6).
Different letters denote significant differences (P < 0.01) between treatments.

under cold waterlogged conditions. The definite increase of yield were associated with hardwood biochar and the charing possessed with high major plant nutrient, for instance, nitrogen content (Spokas *et al.*, 2012). However, not all studies have shown that biochar application to the soil leads to improved crop yield. Some studies reported no immediate correlation between plant productivity and biochar application (David, 2015; de Melo Carvalho *et al.*, 2013; Schulz *et al.*, 2014; Van *et al.*, 2010). Yield improvement was caused by compost addition. Other studies also reported an increase in productivity in response to addition of organic materials. The study of Jones *et al.* (2012) found no difference on biochar application in the first year after performed a three-year field of various species on agronomic crops. The contrast of crop performances was affected by the biochar application in the second and third years. Similar to the study of Uzoma *et al.* (2011) conducted an experiment of cow manure biochar applied in the sandy soil effect to the maize plant. Both maize yield and N uptake increased with the rate of biochar application in the latter period, which indicates the N release from biochar. Furthermore, in Hall and Bell's (2015) long-term study, wheat straw and chicken manure biochar and compost treatments significantly increased crop yield by about 8% during the first three seasons. However, there was no change in crop yield in the organic amendment treatments in the following seasons. Therefore, biochar and compost led to an increase in crop yield when nutrient availability in the soil was high and due to direct addition of nutrients, which disappeared over time. In the long-term, crop yield was unchanged. These results suggest that research should have a greater focus on the effects of biochar on rice yield in the long term.

Both grain yield and WUE responded positively to biochar addition. Table 3 shows the average WUE based on rice grain yield after two growing seasons. Addition of compost (RCA and RBC treatments) led to a doubling of yield compared to the treatments that did not receive compost (RCT and RBA) as the organic fertilizer contributed high levels of nutrients to the soil. WUE was significantly higher ($p < 0.01$) in biochar addition treatments. RBC had the highest WUE relative to yield; it was 6.10% higher in RBC than in the RCA treatment. Similarly, biochar addition (RBA) also had a positive effect on WUE compared to the RCT treatment; it was 6.64% higher than in the treatments not receiving biochar (Table 3 and Figure 7). Accordingly, this study suggests that the most effective soil conditions for WUE are in the RBC treatment. This outcome supports the findings of numerous studies which concluded that biochar has the potential to affect WUE. Batool *et al*. (2015) studied the possibility of biochar and gypsum increasing the WUE of *Abelmoschus esculentus* L. Moench. The biochar treated plants showed significantly improved WUE, by approximately 60% throughout the experiment ($p \leq 0.01$), compared to the control. Li *et al*. (2015) also reported that biochar application at a rate of 40 t ha^{-1} m^{-2} had the highest positive impact on the growth, yield, and WUE of winter wheat; it was also useful for enhancement of root growth.

Effects of biochar and compost addition on soil nitrogen balance

The Nitrogen (N) balance in the soil typically provides a quantitative framework for N inputs, outputs, and retention that focuses on sustainable productivity of agriculture, soil, and the environment. N balance, therefore, reflects the changes in total N in the soil during cultivation. A positive N balance refers to system-induced N, which enhances crop yield. Unused N in the soil as residue could be lost to the environment by denitrification, leaching, surface runoff, soil erosion, or N_2O emission. N losses can be minimized by increasing N retention (Janzen *et al.*, 2013; Ross *et al.*, 2008). Thus, soil N balance and the effects of inferred N losses are soil characteristics of potential interest for agronomic benefit (Clough *et al.*, 2010; Clough *et al.*, 2013; Zheng *et al.*, 2012).

This study assessed N balance from the absolute changes in N mass, in the form of NO_3^--N, NH_4^+-N, and N_2O-N (Table 4). In the compost treatment, initial N increased due to compost addition, whereas in the co-application treatment it increased due to incorporation of both compost and biochar. The number of changes in N in terms of NO_3^--N, NH_4^+-N, and N_2O–N vary for several reasons, for instance, growing conditions, irrigation management, rice variety, cultivation system, and additional inputs of organic material such as compost and

biochar. In this study, an unknown N balance was computed from average N after two growing seasons. The average N mass balance for the two seasons showed a positive unknown N balance in all treatments in both the paddy soil system and the rice cultivation system. The unknown N balance of the paddy soil system ranged between +0.842 and +2.147 m^2/crop. In contrast, in the rice cultivation system, it ranged from +1.921 to +2.878 m^2/crop; this was higher than in the paddy soil system as the N is converted to grain and rice biomass (Table 4).

In the SBC treatment, the unknown N was significantly higher (81.47%) compared to that in SCA ($p < 0.01$), while in the SBA treatment, biochar retained more (78.47%) unknown N than the control. In the rice cultivation system, RBC also showed a significantly increased ($p < 0.01$) level (by approximately 35.13%) of unknown N compared to RCA. Moreover, the unknown N in RBC converted N into the form of rice grain yield and biomass, and in which the volume of plant materials was the highest ($p < 0.01$) compared to all other treatments. In addition, the biochar in the RBA treatment enabled higher circulation of N (42.76%) due to the macropore (approximately 10 μm) size distribution and the surface area of mangrove biochar (Figure 1), which result to producing a higher volume of grain and biomass compared to the control.

The unknown N in the compost treatment in both systems was the lowest, suggesting that N mass was lost from other pathways much more than in other treatments. These findings also suggest that compost has no ability to hold N in the cycle. In addition, the sudden increase in initial N may be a result of organic fertilizer application (Biey *et al.*, 2000; Mamo *et al.*, 1999). However, aerobic decomposition of organic fertilizer results in humified organic compounds and decreased nutrient availability (Nahm, 2005) leading to higher losses through leaching overtime. Soil and organic fertilizer generally have the capacity to retain nutrients (Anderson *et al.*, 2014; Palm *et al.*, 1997) even though the amounts vary according to the suitability or stability of conditions. In contrast, biochar treatments led to the retention of N in the cycle and the doubling or increasing of the unknown N balance. Co-application of biochar and compost had a positive impact on N storage compared to the compost-only treatment. These findings can be summarized as retention of higher unknown N to circulate in the cycle due to the addition of biochar to the systems. Similar results were obtained by Steiner *et al.* (2008) in a field trial in central Amazon, in which two successive sorghum (*Sorghum bicolor* L. Moench) crops were harvested, to demonstrate the effect on N retention of charcoal and compost application. N retention in biomass was significantly higher in the compost treatment in the first season and in the charcoal treatment in the second season. Organic amendments increased the retention of applied N, and the recycling N was taken up by crops (Steiner *et al.*, 2008).

Table 4. Nitrogen (N) balances of the organically managed nutrient-poor paddy soil (S) and rice cultivation (R) systems.

Treatments	N initial	Changes of N			Unknown N balance	Grain yield	Biomass (Dry weight)
	$g\ m^{-2}$	$g\ NO_3^-\ m^{-2}\ crop^{-1}$	$g\ NH_4^+\ m^{-2}\ crop^{-1}$	$g\ N_2O\ m^{-2}\ crop^{-1}$		$g\ m^{-2}\ crop^{-1}$	$g\ m^{-2}\ crop^{-1}$
SCT	2.54	0.211 b	0.373 c	0.753 b	+ 1.203	-	-
SCA	2.70	0.358 a	0.688 a	0.812 a	+ 0.842	-	-
SBC	3.02	0.216 b	0.573 b	0.703 c	+ 1.528	-	-
SBA	3.18	0.166 c	0.259 d	0.608 d	+ 2.147	-	-
RCT	2.59	0.019 b	0.049 c	0.506 c	+ 2.016	45.34 ± 3.22 d	407.00 ± 41.86 d
RCA	2.68	0.037 a	0.152 a	0.570 a	+ 1.921	64.50 ± 3.47 b	655.50 ± 55.65 b
RBC	3.23	0.017 b	0.094 b	0.523 b	+ 2.596	67.67 ± 3.97 a	727.34 ± 56.53 a
RBA	3.38	0.008 c	0.034 d	0.460 d	+ 2.878	47.50 ± 2.79 c	465.17 ± 47.94 c

The values are mean (n=6). S.D. did not indicate in some parameters due to the value < 1
Different letters denote significant differences (P < 0.01) between treatments of each system.

Clough and Condron (2010) suggested that biochar may have the ability to manipulate N cycling rates in soil systems by influencing nitrification rates and ammonia adsorption and by increasing NH_4^+ storage. Biochar is further implicated in the reduction of N losses through N_2O and NO_3^- leaching (López-Cano *et al.*, 2016). The results of this study confirm this by showing lower N losses in the biochar and co-application treatments due to the macropore of mangrove biochar (Figure 1) can be absorbed nutrient in its pores.

Co-application of biochar and compost is recommended as optimal in sustainable agriculture to farmers in Thailand. This study confirms that co-application is the most reasonable compromise between rice cultivation components and productivity. In other words, compost, an environmentally-friendly material, helps increase productivity, whereas biochar helps improve soil fertility, support productivity, and has a positive effect as a measure to mitigate greenhouse gases.

Effects of biochar and compost addition on soil properties

The mangrove biochar used in this study was 23.43% C and 0.39% N by mass, and contained 40.40% organic matter (OM). Figure 1 shows the surface area characteristics and porosity of the mangrove biochar. The macropore of mangrove biochar is approximately ten (10) μm. The Bangkok municipal solid waste compost used in this study was 7.11% C and 0.81% N on a dry weight basis (Table 5). Soil properties (OM, OC, total N, NO_3^-, NH_4^+) were changed positively after a year of biochar and compost addition (Table 5). The rice cultivation system had higher OM than the paddy soil system in all treatments due to nutrient circulation by deep-rooted plants and soil macro- and microfauna, which coincided with the period of nutrient demand by the plants. Therefore, returning organic matter to the soil as well as growing or rotating crops can maintain the right level of OM. All of the biochar and co-application treatments significantly increased OC in both systems (p < 0.01), in contrast to the compost treatment in both systems. This suggests that biochar may facilitate carbon, while compost cannot maintain it in the soil. Total N in the co-application treatment was significantly higher than in the other treatments except for SCA. However, total N in the rice cultivation system was less than in the paddy soil system due to plant uptake of nutrients. The variation in NO_3^--N and NH_4^+-N in both systems may be due to nitrifying bacteria in the soil affecting the nitrification process. However, adding organic materials can significantly increase and maintain N in both systems more than in the control. Biochar addition (the biochar and co-application treatments) significantly increased (p < 0.01) the CEC of both systems possibly due to
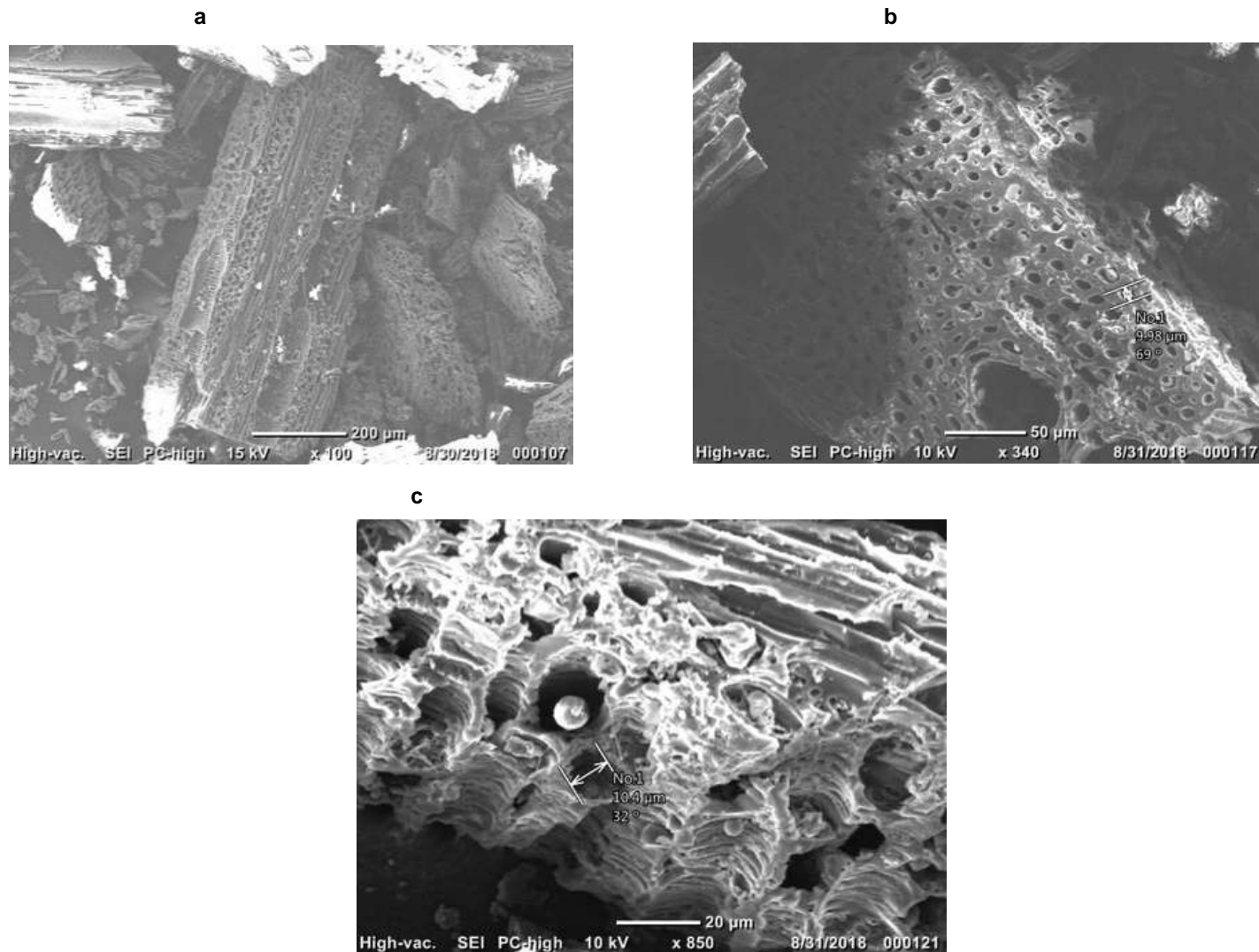
a

b

c

Figure 1. Scanning Electron Microscope (SEM) of Mangrove Biochar (a) Surface area and (b-c) Macropore size.

the high surface area of biochar and charge density. However, there was no treatment or system effect on bulk density (Table 5).

Greenhouse gas emissions

Biochar offers a way to reduce atmospheric CO_2 levels and improve food productivity by increasing soil fertility (Amonette, 2010). Woolf *et al.* (2010) suggested that biochar production can sustainably offset the world's greenhouse gas emissions by 12%. Moreover, approximately half of the biochar in the soil may potentially mitigate climate change depending on carbon capture and storage (Amonette, 2010). In addition to considering the N pathway, this study measured CH_4 and N_2O as indicators of greenhouse gas emissions in paddy fields and analyzed their global warming potential (GWP).

In this study, after two growing seasons, total GWP increased more in the rice cultivation system than in the paddy soil system (Table 6). Total GWP of the paddy soil system was 3.939 to 6.159 t CO_2-eq ha^{-1} year^{-1}, whereas the aggregate GWP of the rice cultivation system was 6.068 to 7.985 t CO_2-eq ha^{-1} year^{-1}. The substantial difference between the two systems may result from activities of rice plants leading to higher emissions, microorganism movement in the soil, along with increasing of the application rates (Feng *et al.*, 2012; Xu *et al.*, 2013). Application of compost as an organic fertilizer that contains high nutrient levels itself resulted in significantly higher ($p < 0.01$) GWP in the compost and co-application treatments compared to the control treatment in both systems. However, biochar addition also significantly reduced ($p < 0.01$) GWP, as shown by the co-application treatment in both systems (Table 6). That is, SBC reduced GWP by 12.49%, which was significantly more ($p < 0.01$) than the reduction in SCA. At the same time, SBA reduced GWP by 19.80% compared

Table 5. Chemical and physical properties of Ratchaburi's paddy soil, biochar, compost and treated soils after a year of cultivation.

Treatments	OM	OC	Total N	NO₃⁻ - N	NH₄⁺ - N	CEC	BD
	%			*mg kg⁻¹*		*cmolc kg⁻¹*	*g cm⁻³*
Before cultivation							
Soil	0.96	0.55	0.04	5.60	5.60	20.8	-
Biochar	40.40	23.43	0.39	-	-	93.58	-
Compost	52.26	7.11	0.81	-	-	51.62	-
After a year of cultivation							
SCT	1.13 c	0.54 c	0.03 c	3.17 d	5.50 b	21.80 d	1.39 b
SCA	1.91 ab	0.60 c	0.10 a	6.12 b	3.87 c	24.50 b	1.50 a
SBC	2.40 a	1.34 a	0.14 a	5.25 c	6.23 a	25.30 a	1.40 b
SBA	1.43 bc	0.85 b	0.07 b	7.12 a	2.43 d	23.60 c	1.16 c
RCT	1.33 b	0.75 d	0.03 c	2.90 d	4.63 a	22.70 d	1.32 c
RCA	2.79 ab	1.02 c	0.08 ab	6.17 b	3.73 b	25.70 b	1.21 d
RBC	3.98 a	1.67 a	0.09 a	7.17 a	3.77 b	27.97 a	1.40 a
RBA	2.46 ab	1.34 b	0.06 bc	6.06 c	2.80 c	24.83 c	1.37 b

The values are mean (n=3), and SD did not indicate in this table due to the value < 1
[a] SOM = soil organic matter; SOC = soil organic carbon; CEC = cation exchange capacity; BD = bulk density

Figure 2. Seasonal variation of NO₃⁻- N and NH₄⁺- N leaching after two crop seasons of the organically managed nutrient-poor paddy soil (S) and rice cultivation (R) systems.

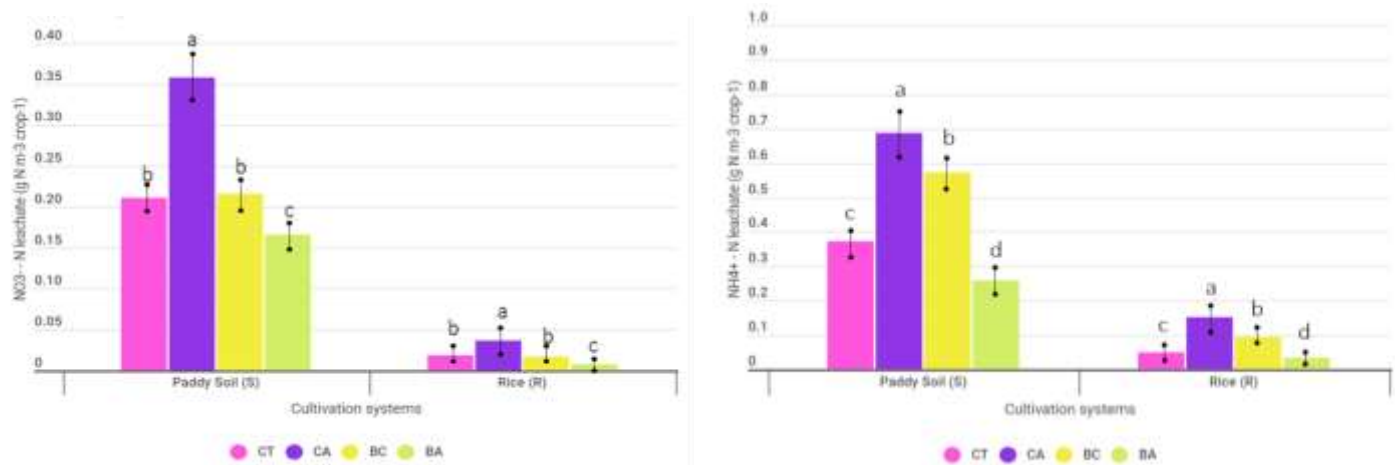**Figure 3.** Average NO_3^-- N and NH_4^+- N leaching after two crop seasons of the organically managed nutrient-poor paddy soil (S) and rice cultivation (R) systems.

Figure 4. Seasonal variation of N_2O emission fluxes after two crop seasons of the organically managed nutrient-poor paddy soil (S) and rice cultivation (R) systems.
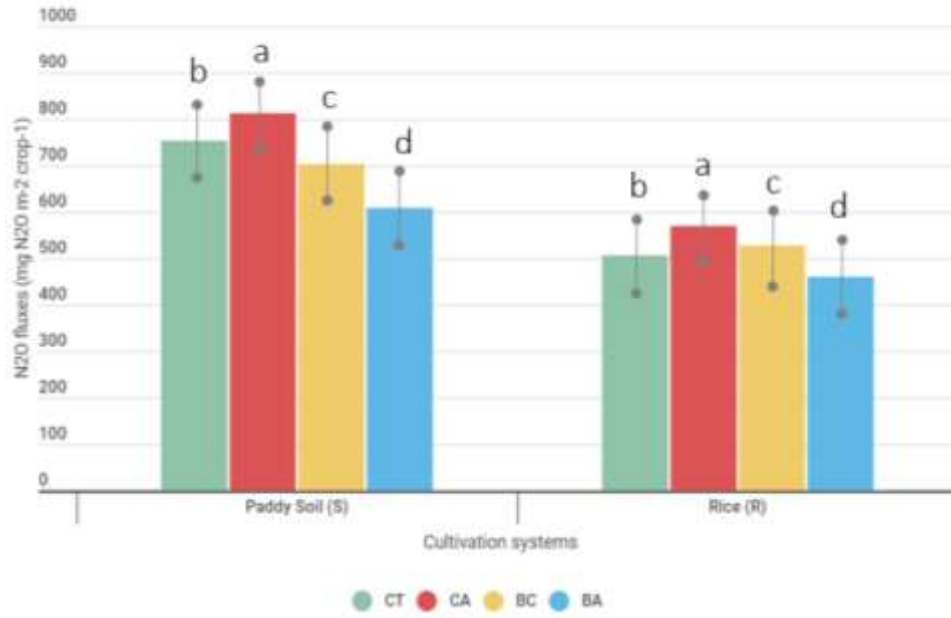
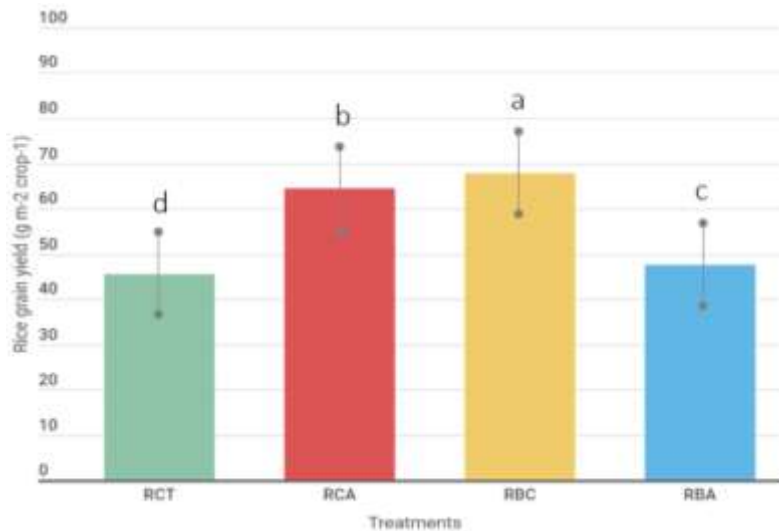**Figure 5.** Average N_2O emission fluxes after two crop seasons of the organically managed nutrient-poor paddy soil (S) and rice cultivation (R) systems.

Figure 6. Average grain yield of the rice cultivation (R) system after two crop seasons.

to the control (SCT) treatment, which also supports that biochar has the capacity to reduce GWP. In the rice cultivation system, RBC reduced GWP significantly more ($p < 0.01$) than the RCA treatment; this was a 7.94% greater reduction. Moreover, RBA also showed a 13.39% greater reduction in GWP than RCT. Biochar addition (the biochar and co-application treatments) showed positive results leading to the conclusion that biochar is effective in reducing the GWP of the rice cultivated under both systems.

Liu *et al.* (2016) also reported that biochar has the potential to reduce the carbon footprint of rice cultivation by significant soil carbon sequestration without increasing N_2O and CH_4 emissions. However, application of biochar may produce adverse conditions for methanogenic archaea in the soil, depending on increased aeration. Enhancing soil aeration may increase CH_4 oxidation, leading to a reduction in CH_4 emissions from paddy fields (Feng *et al.*, 2012) and lower GWP values. Xu *et al.* (2013) reported that carbon introduced at the planting
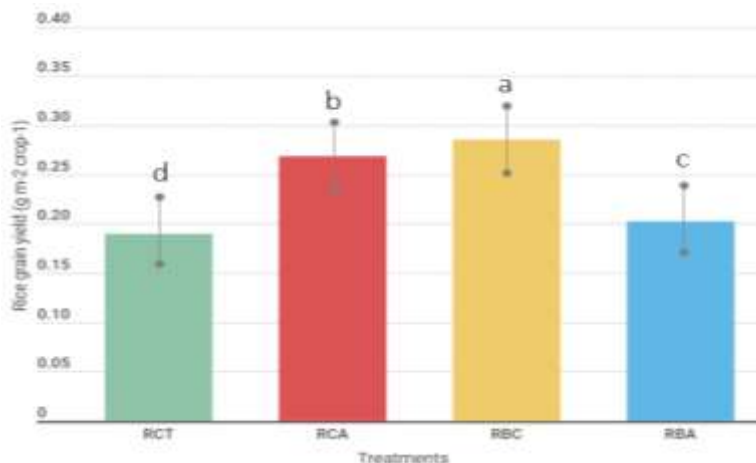
Figure 7. Average water use efficiency (WUE) of the rice cultivation (R) system after two crop seasons

Table 6. Annual greenhouse gas (GHG) emissions and global warming potential (GWP) of the organically managed nutrient-poor paddy soil (S) and rice cultivation (R) systems.

Cultivation system	Paddy soil (S)			Rice (R)		
	CH_4	N_2O	Total GWP	CH_4	N_2O	Total GWP
Treatment:	$t\ CO_2\text{-eq. }ha^{-1}\ year^{-1}$					
CT	0.244 c	4.669 b	4.912 c	3.868 c	3.138 c	7.006 c
CA	1.124 a	5.036 a	6.159 a	4.454 a	3.531 a	7.985 a
BC	1.033 b	4.357 c	5.390 b	4.110 b	3.241 b	7.351 b
BA	0.168 d	3.771 d	3.939 d	3.217 d	2.851 d	6.068 d

The values are mean (n = 6). S.D. did not indicate in this table due to the value < 1
Different letters denote significant differences (P < 0.01) between treatments of each seasonal crops.

stage, through increased irrigation, and higher greenhouse gas emission coefficients would lead to a larger carbon footprint. Consequently, the factors that drive the carbon footprint of rice cultivation are generally influenced by soil properties, cultivars, water management practices, fertilization, and the cropping system (Xu *et al.*, 2013; Xu *et al.*, 2019).

CONCLUSION

Adding biochar to compost can reduce N leachate in organically managed nutrient-poor paddy soil (S) and rice cultivation (R) systems. NO_3^--N and NH_4^+-N leachate losses were lower in the rice cultivation system than in the paddy soil system. Biochar incorporated into the soil may enhance N retention in the cycle. Furthermore, biochar can reduce N_2O emissions in both systems, even when incorporated with high-N material such as compost.

This organic management practice showed a positive unknown N balance, meaning that N is circulated and sufficient to be sustained in the cultivation system. Not applying biochar may lead to a high likelihood of losing

nitrogen, resulting in imbalanced and ultimately low nutrient levels in the soil for a longer term. Compared to traditional practices, biochar and compost application is favorable for maintaining the N balance. Therefore, co-application of compost and biochar is highly recommended as an effective management practice in organic rice cultivation in nutrient-poor soils to prevent nitrogen loss from leaching, reduce N_2O emissions, maintain rice grain yield, and improve WUE.

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