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Reducing nitrogen fertilizer combined with biochar amendment improves soil quality and increases grain yield in the intensive rice cultivation system

Vu Van Long [a,*], Tran Van Dung [b]

[a] Faculty of Natural Resources-Environment, Kien Giang University, Kien Giang, 91752, Vietnam

[b] Faculty of Soil Science, College of Agriculture, Can Tho University, Can Tho, 94100, Vietnam

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Author(s)

V.V.Long *

T.V.Dung

* Corresponding author

Abstract

Intensive rice cultivation for a long time resulted in increasing soil degradation and less yield. This study aimed to evaluate effects of the combining reducing nitrogen fertilizer (N) with biochar amendment on soil chemical properties, rice growth parameters, and grain yield in the rice cultivation system in the Mekong Delta region, Vietnam (VMD). Field experiment was designed in the split-plot design with two factors, including N fertilizer (main plot) and biochar (sub-plot). Two N fertilizer rates were: (N_{50})—50 kg N ha^{-1} and (N_{100})—100 kg N ha^{-1}, which is the farmer's practice. Biochar was amended with three rates: no applied biochar (B_0), 5 t ha^{-1} (B_5), and 10 t ha^{-1} (B_{10}). The results indicated that reducing N fertilizer by 50% combined 5–10 t biochar ha−1 resulted in maintaining soil pH, soil electrical conductivity, soil organic carbon, cation exchange capacity, and rice biomass. Applying biochar at a rate of 5–10 t ha^{-1} significantly increased the available N, available P, and rice height compared to the treatment with no applied biochar (B_0). Rice yield in the treatments applied with 5–10 t ha^{-1} was significantly higher than the treatment without the use of biochar by 11.6–14.7%. The findings of this study confirmed that reducing 50% N fertilizer combined with 5 t ha^{-1} or 10 t ha^{-1} of biochar could improve soil available N, available P, rice growth, and grain yield in intensive rice cultivation systems in the VMD region.

Keywords: Biochar, nitrogen, Oryza sativa L., paddy soil, phosphorus, soil fertility.

Introduction

In the intensive rice production system in the Vietnamese Mekong Delta (VMD) region, farmers often use a large amount of N fertilizer to gain a high yield (Dung et al., 2021). However, this application could increase fertilizer costs and high-risk environmental pollution. In addition, rice plant often takes up only 40–50% of N fertilizer applied, and the remaining N fertilizer will be lost through NH_3 and N_2O volatilization, or runoff to the water environment (Wulf et al., 2002; Choudhury and Khanif, 2004; Weil and Brady, 2017).

Soil degradation, which is the loss of soil functions capacity to reduce soil fertility and soil biodiversity, is the most serious problem in the world (Brusseau et al., 2019). It causes industrial, commercial pollution, and especially in agricultural production because of the rapidly increasing demand for food and fiber (Kopittke et al., 2019). Over the years, soil degradation leads to reduce rice growth and loss of grain yield. The intensification of rice production is already resulting in acidification, salinization, loss of organic matter, decline of nutrients availability, and increase greenhouse gas emission (Scharlemann et al., 2014; Shcherbak et al., 2014; Kopittke et al., 2017; Dung et al., 2022).

Biochar has been known as a biomaterial that can improve soil characteristics such as water content, soil pH, cation exchange capacity (CEC), and soil organic carbon (SOC) (Jaafar et al., 2015; Bass et al., 2016; Bera et al., 2016). Its effect is dependent on some factors such as soil types (Anthrosols, Ferrasols, or Acrisols) and the amount used (5, 10, 15, or 20 tons of biochar ha^{-1}) (Agegnehu et al., 2017). The application of biochar results

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in reducing soil compaction, increasing field capacity (Chan et al., 2008; Abel et al., 2013), soil pH, organic matter, nutrients availability, and cations exchangeable (Glaser et al., 2002; Laird et al., 2010; Thies et al., 2015), and microorganisms biomass (Chan et al., 2008; Shah et al., 2021). Besides, the increase of plant growth and yield as affected by biochar amendment was reported in some previous studies. A number of studies reported that the application resulted in increased maize yield by 98–150% (Uzoma et al., 2011), wheat (Solaiman et al., 2010), peanut (Agegnehu et al., 2015), and rice (Asai et al., 2009; Bakar et al., 2015; Ali et al., 2021). The crop yield increased in the treatment applied biochar due to increasing soil pH, available soil nutrients, and nutrient uptake capacity (Agegnehu et al., 2017). However, the information about reducing N fertilizer combined with biochar in the paddy rice system in the VMD region was limited.

We hypothesized that the application of biochar could enhance some soil chemical properties and macro-nutrients such as N, P, and K without rice yield loss under reducing N fertilizer conditions. Therefore, this study aimed to determine the effects of N fertilization combined biochar amendment on (i) some soil chemical characteristics such as pH, EC, SOC, and CEC; (ii) availability of macronutrients including N, P, and K; and (iii) growth, rice biomass, and grain yield of paddy rice.

Material and Methods

Soil and biochar properties

The field experiment was conducted at the intensive rice (3 crops per year) area in Giuc Tuong commune, Chau Thanh district, Kien Giang province, which is located in the Vietnamese Mekong Delta (VMD) region (9°57'43.0" N, 105°11'18.1" E). The soil in the experimental area was classified as Dystric Gleysols (IUSS Working Group WRB, 2015). At the depth of 0–20 cm, the soil is acidic (pH 4.90), and soil EC is 0.50 mS cm^{-1}. Soil organic carbon (6.47 %C) ranged in high level for paddy rice (Metson, 1961). Soil texture was silty clay, with the clay contents around 54.45%. Biochar used in this study was a commercial product of Mai Anh Co., Dong Thap province, Vietnam, which was made from rice husk, have a total porosity of 92.3%, according to Phuong et al. (2020a). The characteristics of experimental soil and biochar are presented in Table 1.

Table 1. Experimental soil (0–20 cm) and biochar properties in this study

Characteristics	Soil	Biochar
Sand (%)	1.84	-
Silt (%)	43.71	-
Clay (%)	54.45	-
pH	4.90	7.70
EC (mS cm^{-1})	0.50	4.10
Organic carbon (%C)	6.47	47.1
Total N (%)	0.27	0.47
Available N (mg kg^{-1})	39.90	nd
Total P (% P_2O_5)	0.18	nd
Available P (mg kg^{-1})	3.89	800.00
CEC ($cmol_{(+)}$ kg^{-1})	17.10	6.50
Exchangeable K ($cmol_{(+)}$ kg^{-1})	0.38	12.90

EC: electrical conductivity; CEC: cation exchange capacity; nd: not detected

Experimental design, treatments, and management

The field experiment was conducted in a split-plot design with 3 replicates, while N fertilizer rate was the main factor and biochar amendment was the sub-factor. Two N fertilizer rates were 50 kg N ha^{-1} (N_{50}) and 100 kg N ha^{-1} (N_{100}) as the farmer's practices. Three biochar amendments included no applied biochar (B_0), applied biochar with a rate of 5 t ha^{-1} (B_5), and 10 t ha^{-1} (B_{10}).

Dai Thom 8 rice variety, which was the local variety has a growth duration of 90–95 days, was used for this experiment. Each treatment plot was covered in an area of 25 m^2 (5 m × 5 m), separated by 0.3 m height of soil bund. A plastic was installed between plots to minimize hydrological connectivity between each plot. The rate of P and K fertilizers was 60 P_2O_5-30K_2O (kg $ha^{-1}cr^{-1}$) in all plots. Phosphorus fertilizer was applied all before sowing, and urea fertilizer was topdressed at 10, 20, and 45 days after sowing (DAS) while potassium fertilizer at 20 and 40 DAS.

Soil sampling and analyses

At the prior to experiment and harvest stage, soil samples were collected to determine the soil characteristics. Its were taken at the depth of 0–20 cm in the field. The pipette method was used to analyze the contents of clay, silt, and sand (Kroetsch and Wang, 2008). Soil pH and EC were determined in 1:2.5 (w:v) filtered soil:water suspensions, measured using pH meter and EC meter, respectively. Soil organic carbon (%C) was determined by the Walkley and Black method (Walkley and Black, 1934). Available soil P was determined as Olsen-P by extracting the soil with 0.5*M* $NaHCO_3$ (Olsen and Sommers, 1982). Soil total P concentration was measured by molybdate colorimetric method (Murphy and Riley, 1962). Total N was analyzed by Kjeldahl digestion, and available soil N was analyzed by extracting soils with KCl 2M at 1:10 ratio, measured by the Spectrophotometer in 650 nm. Cation exchange capacity and exchangeable K were determined by the NH_4OAc extraction method.

Rice growth parameters and grain yield collection

Rice height was collected at active tillering (20 DAS), panicle initiation (45 DAS), heading (60 DAS), and flowering (75 DAS) stages. Biomass was calculated from samples in an area of 0.25 m^2 (0.5 × 0.5 m) at the harvest stage. Grain yield was collected in an area of 5 m^2 of each plot. Grains were separated, treated, air-dried, and then weighed. Grain moisture was also determined at weighing or by grain moisture tester. The final grain yield at 14% of the moisture was then calculated based on the weight and the determined moisture

Statistical analysis

The effect of N fertilizer (N) and biochar rates (B) and their interaction on soil properties and rice parameters were determined by analysis of variance using R (V4.0.5) statistical software. Only treatments with significant differences were submitted to the Tukey comparison test (LSD < 0.05).

Results

Soil chemical properties

Table 2 showed the effects of combining N fertilizer with biochar amendment on soil characteristics. The results showed that reducing N fertilizer by 50% did not significantly affect soil pH, EC, SOC, and CEC compared to the treatments applied 100 kg N ha^{-1}. Similarly, there were no significant difference in pH, EC, SOC, and CEC in the treatments applied 5–10 t biochar ha^{-1} (B_5 and B_{10}) compared to the treatments without received biochar amendment (B_0). This study confirmed that reducing N fertilizer by 50% combined with 5–10 t biochar ha^{-1} amended did not significantly affect soil chemical properties.

Table 2. Effects of nitrogen fertilizer and biochar on soil properties

Treatments	pH	EC, mS cm^{-1}	SOC (%C)	CEC ($cmol_{(+)}kg^{-1}$)
N_{50}	4.51±0.08 [a]	0.55±0.09 [a]	8.05±0.79 [a]	15.2±0.54 [a]
N_{100}	4.50±0.06 [a]	0.51±0.10 [a]	8.41±0.79 [a]	15.3±0.61 [a]
B_0	4.50±0.07 [a]	0.55±0.11 [a]	7.84±0.99 [a]	15.4±0.77 [a]
B_5	4.49±0.04 [a]	0.54±0.08 [a]	8.19±0.64 [a]	15.2±0.54 [a]
B_{10}	4.53±0.09 [a]	0.50±0.09 [a]	8.66±0.55 [a]	15.1±0.38 [a]
F test (N)	ns	ns	ns	ns
F test (B)	ns	ns	ns	ns
F test (N×B)	ns	ns	ns	ns
LSD	0.08	0.16	1.31	1.08
CV(%)	0.95	16.4	8.47	3.78

The value after ± showed the standard deviation of the mean of three replications; means in a column for each factor followed by the same letter are not significantly different; ns mean P > 0.05; N and B treatments are explained in the text.

Marco nutrients availability

The results indicated that the soil N, P, and K availability in the treatment that applied 50 kg N ha^{-1} were not significantly different compared to the treatment received 100 kg N ha^{-1} (Table 3). However, available N in the B_{10} treatment was varied in 15.5 mg kg^{-1}, significantly higher than the B_0 and B_5 treatments (11.4 and 12.4 mg kg^{-1}, respectively). Besides, applying biochar at a rate from 5 to 10 t ha^{-1} significantly increased available P compared to the treatment with no applied biochar ($P < 0.05$). This study also indicated that applying 5–10 t biochar ha^{-1} did not significantly change soil exchangeable K compared to treatment without biochar amended (Table 3). The finding of this study demonstrated that reducing N fertilizer by 50% combined with 5–10 t biochar ha^{-1} could significantly increase available N and available P while exchangeable K is maintained.

Table 3. Effects of nitrogen fertilizer and biochar on macro nutrients

Treatments	Available N (mg kg^{-1})	Available P (mg P kg^{-1})	Exchangeable K (cmol$_{(+)}$kg^{-1})
N_{50}	11.6±2.71 ^{a}	13.0±2.30 ^{a}	0.16±0.04 ^{a}
N_{100}	14.6±2.22 ^{a}	13.6±3.53 ^{a}	0.14±0.03 ^{a}
B_0	11.4±1.87 ^{b}	10.1±1.61 ^{b}	0.13±0.01 ^{a}
B_5	12.4±1.20 ^{b}	14.1±1.20 ^{a}	0.14±0.01 ^{a}
B_{10}	15.5±2.12 ^{a}	15.8±2.02 ^{a}	0.18±0.05 ^{a}
F test (N)	ns	ns	ns
F test (B)	*	***	ns
F test (N×B)	*	**	ns
LSD	3.56	2.63	0.07
CV(%)	14.4	10.5	24.8

The value after ± showed the standard deviation of the mean of three replications; means in a column for each factor followed by the same letter are not significantly different; means in a column for each factor followed by the different letters are not significantly different; ns means P >0.05; * means P <0.05; ** means P <0.01; *** means P <0.001; N and B treatments are explained in the text.

Rice growth

The results showed no significantly different in rice height between the two N fertilization treatments at the various growth stages (Table 4). However, rice height in the treatments applied 5–10 t biochar ha^{-1} (B_5 and B_{10}) were significantly greater than the treatment no received biochar in 40 DAS, 60 DAS, and 75 DAS ($P < 0.05$). In general, this study indicated that reducing 50 kg N ha^{-1} combined with 5–10 t biochar ha^{-1} could significantly increase plant height compared to the treatments with no received biochar (B_0) or 100 kg N ha^{-1}.

Table 4. Effects of nitrogen fertilizer and biochar on rice height at the various growing stages

Treatments	Active tillering (25 DAS)	Panicle initiation (40 DAS)	Heading (60 DAS)	Flowering (75 DAS)
N_{50}	42.6±2.56 ^{a}	66.4±5.96 ^{a}	85.9±5.07 ^{a}	108±4.65 ^{a}
N_{100}	42.0±2.60 ^{a}	68.8±4.78 ^{a}	87.6±3.16 ^{a}	107±5.84 ^{a}
B_0	41.8±3.21 ^{a}	64.3±7.73 ^{b}	84.0±5.75 ^{b}	102±3.49 ^{b}
B_5	42.8±2.93 ^{a}	70.4±3.63 ^{a}	88.2±3.11 ^{a}	112±1.76 ^{a}
B_{10}	42.3±1.49 ^{a}	68.1±1.73 ^{ab}	88.0±1.91 ^{a}	110±3.31 ^{a}
F test (N)	ns	ns	ns	ns
F test (B)	ns	*	*	***
F test (N×B)	ns	*	*	*
LSD	6.01	7.84	5.55	4.24
CV(%)	7.55	6.16	3.40	2.10

The value after ± showed the standard deviation of the mean of three replications; means in a column for each factor followed by the same letter are not significantly different; means in a column for each factor followed by the different letters are not significantly different; ns means P >0.05; * means P <0.05; *** means P <0.001; N and B treatments are explained in the text.

Rice straw biomass and yield

The effects of N and biochar amendment on biomass and grain yield are shown in Table 5. The rice biomass ranged from 17.0 to 17.9 t ha^{-1} in the treatments applied 50–100 kg N ha^{-1} and varied between 14.5 and 19.5 t ha^{-1} in the biochar amended treatments. In the harvest stage, rice biomass in the treatments applied with 50 and 100 kg N ha^{-1} did not differ significantly, neither among the treatments applied with 0, 5, and 10 t biochar ha^{-1}.

Table 5. Effects of nitrogen fertilizer and biochar on rice height at the various growing stages

Treatments	Rice biomass (t ha^{-1})	Grain yield (t ha^{-1})
N_{50}	17.0±3.03	5.96±0.63 ^{a}
N_{100}	17.9±4.75	6.03±0.41 ^{a}
B_0	14.5±2.40	5.52±0.53 ^{b}
B_5	19.5±4.51	6.32±0.36 ^{a}
B_{10}	18.3±3.04	6.15±0.27 ^{a}
F test (N)	ns	ns
F test (B)	ns	**
F test (N×B)	ns	*
LSD	7.42	0.65
CV(%)	22.6	5.79

The value after ± showed the standard deviation of the mean of three replications; means in a column for each factor followed by the same letter are not significantly different; means in a column for each factor followed by the different letters are not significantly different; ns means P >0.05; * means P <0.05; ** means P <0.01; * means P <0.001; N and B treatments are explained in the text.

Similarly, the results showed that rice yield in the treatment reduced N fertilizer by 50% varied around 5.96 t ha^{-1}, and was not a significant difference compared with treatment received 100 kg N ha^{-1} as the farmer's practice (6.03 t ha^{-1}). However, rice yield in the treatments applied 5–10 t biochar ha^{-1} ranged from 6.15–6.32 t ha^{-1}, significantly higher than the treatment no received biochar (5.52 t ha^{-1}). The results indicated that the biochar application at a rate of 5–10 t ha^{-1} could significantly increase grain yield compared to no applied biochar by 11.4–14.5%. The findings of this study demonstrated that the combination of 50 kg N ha^{-1} with 5–10 t biochar ha^{-1} could reduce the N fertilizer amount and increase rice yield compared to traditional rice cultivation.

Discussion

In this study, experimental soil has the C:N varied around 24.0 (organic carbon and N contents were 6.27 %C and 0.27 %N, respectively). In this C:N level, available soil N may be released into soil solution throughout the processes of decomposition rice straw residues or mineralization (Weil and Brady, 2017; Kopittke et al., 2020; Dung et al., 2022). It explained why the organic carbon and available N contents in the treatment that applied 50 kg N ha^{-1} did not differ significantly compared to the treatment that applied 100 kg N ha^{-1}. This results were in agreement with Dung et al. (2021) studied the effects of reduced N fertilizer on two rice varieties in the VMD region. Dung et al. (2021) reported that applying 50 kg N ha^{-1} could maintain the number of tillers, rice height, and grain yield of OM5451 and OM6976 compared to the traditional cultivation applied 100 kg N ha^{-1}.

pH is the most important factor in the soil has directly affected the availability of soil nutrients (Weil and Brady, 2017). The change in soil pH is most dependent on the pH of biochar and soil pH. Previous studies reported that applying biochar in the low soil pH such as Ferrasols or Acrisols could significantly increase soil pH (Glaser et al., 2002; Lehmann et al., 2003; Chan et al., 2007; Li et al., 2015; Thies et al., 2015), but did not differ significantly in the near-neutral soil (Lashari et al., 2013). Besides, the application of biochar at a rate of 5–10 t ha^{-1} resulted in no differ significantly different in soil EC, SOC, exchangeable K, and CEC compared to the treatment with no received biochar may be due to the low biochar application rates (Lashari et al., 2013). Agegnehu et al. (2017) reported that the rate of biochar application higher than 39 t ha^{-1} resulted in significantly increased soil pH in the neutral soil. Similarly, some previous studies have also shown that applying the biochar at a rate of 50 t ha^{-1} could improve the soil pH, EC, exchangeable K, SOC, and CEC (Van Zwieten et al., 2010; Rajkovich et al., 2012; Schulz and Glaser, 2012; Abel et al., 2013; Biederman and Harpole, 2013; Abiven et al., 2015; Sánchez-García et al., 2016). The other reasonable explanation for did not change in these soil characteristics is closely correlated to the short time of biochar application. According to Griffin et al. (2017), applying biochar was not significantly affect exchangeable soil K in the first two years. However, the amount of K in treatments applied biochar was significantly higher than the treatment with no applied biochar after three years (Griffin et al., 2017).

Our study indicated that the application of biochar from 5 to 10 t ha^{-1} resulted in significantly higher available N and available P contents than the treatment without biochar. This study is in line with some previous studies which have reported that N available content significantly increased in the treatment applied biochar at a rate of 15 t ha^{-1} or higher (Vaccari et al., 2015; Bera et al., 2016; Cao et al., 2018; Ullah et al., 2018; Ali et al., 2021). Applying biochar in the soil could be enhanced the mineralization process of the soil because of the high C content in biochar (Weil and Brady, 2017). According to Phuong et al. (2020b), the availability of P was significantly higher in the treatments applied biochar at a rate of 5–10 t ha^{-1} due to the mineralization of soil organic P to inorganic P, increasing P availability. The findings of this study agree Ullah et al. (2018) and Ali et al. (2021), who reported that biochar amendment enhances soil available P compared to the soil without biochar. Nitrogen and phosphorus, which are the macronutrient of plant, helps enhance plant growth in all soil types (Weil and Brady, 2017). According to Ali et al. (2021), the increase in rice yield was highly positively correlated with the soil chemical properties such as N and P available contents. This study showed that applied biochar in a rate of 5–10 t ha^{-1} resulted in significantly higher N and P available contents, and it explained why the significantly higher rice height and grain yield compared to the treatment without biochar. Similarly, the positive effect of biochar on rice yield was reported by previous studies (Dong et al., 2015; Ali et al., 2021). The findings of this study indicated that reducing N fertilizer by 50% combined biochar at a rate of 5–10 t ha^{-1} could improve soil quality and increase rice yield compared to the no applied biochar.

Conclusion

This study indicated that reducing N fertilizer by 50% did not significantly affect soil properties, rice growth, and yield. Applying biochar in a rate of 5–10 t ha^{-1} resulted in significantly higher N and P availability, rice height, and grain yield than without biochar admended. The combining of 50 kg N ha^{-1} with biochar in a rate of 5–10 t ha^{-1} may be recommended in the same paddy rice soil conditions. Further research is required to evaluate the effects of biochar as soil amendment combined N fertilizer on soil quality, C sequenstration, greenhouse gases emissions on the rice cultivation system in the VMD region.

References

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., Wessolek, G., 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma* 202-203: 183–191.

Abiven, S., Hund, A., Martinsen, V., Cornelissen, G., 2015. Biochar amendment increases maize root surface areas and branching: a shovelomics study in Zambia. *Plant and Soil* 395: 45–55.

Agegnehu, G., Bass, A.M., Nelson, P.N., Muirhead, B., Wright, G., Bird, M.I., 2015. Biochar and biochar-compost as soil amendments: Effects on peanut yield, soil properties and greenhouse gas emissions in tropical North Queensland, Australia. *Agriculture, Ecosystems & Environment* 213: 72–85.

Agegnehu, G., Srivastava, A., Bird, M.I., 2017. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied Soil Ecology* 119: 156–170.

Ali, I., Zhao, Q., Wu, K., Ullah, S., Iqbal, A., Liang, H., Zhang, J., Muhammad, I., Khan, A., Khan, A.A., 2021. Biochar in combination with nitrogen fertilizer is a technique: to enhance physiological and morphological traits of Rice (Oryza sativa L.) by improving soil physio-biochemical properties. *Journal of Plant Growth Regulation* 41: 2406–2420.

Asai, H., Samson, B.K., Stephan, H.M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., Horie, T., 2009. Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. *Field Crops Research* 111(1-2): 81–84.

Bakar, R.A., Razak, Z.A., Ahmad, S.H., Seh-Bardan, B.J., Tsong, L.C., Meng, C.P., 2015. Influence of oil palm empty fruit bunch biochar on floodwater pH and yield components of rice cultivated on acid sulphate soil under rice intensification practices. *Plant Production Science* 18(4): 491–500.

Bass, A.M., Bird, M.I., Kay, G., Muirhead, B., 2016. Soil properties, greenhouse gas emissions and crop yield under compost, biochar and co-composted biochar in two tropical agronomic systems. *Science of the Total Environment* 550: 459–470.

Bera, T., Collins, H., Alva, A., Purakayastha, T., Patra, A., 2016. Biochar and manure effluent effects on soil biochemical properties under corn production. *Applied Soil Ecology* 107: 360–367.

Biederman, L.A., Harpole, W.S., 2013. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB Bioenergy* 5(2): 202–214.

Brusseau, M.L., Pepper, I.L., Gerba, C.P., 2019. Environmental and Pollution Science. Academic Press. UK. 656p.

Cao, Y., Gao, Y., Qi, Y., Li, J., 2018. Biochar-enhanced composts reduce the potential leaching of nutrients and heavy metals and suppress plant-parasitic nematodes in excessively fertilized cucumber soils. *Environmental Science and Pollution Research* 25: 7589–7599.

Chan, K., Van Zwieten, L., Meszaros, I., Downie, A., Joseph, S., 2007. Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research* 45(8): 629–634.

Chan, K., Van Zwieten, L., Meszaros, I., Downie, A., Joseph, S., 2008. Using poultry litter biochars as soil amendments. *Australian Journal of Soil Research* 46(5): 437–444.

Choudhury, A., Khanif, Y., 2004. Effects of nitrogen and copper fertilization on rice yield and fertilizer nitrogen efficiency: A 15N tracer study. *Pakistan Journal of Scientific and Industrial Research* 47(1): 50–55.

Dong, D., Feng, Q., Mcgrouther, K., Yang, M., Wang, H., Wu, W., 2015. Effects of biochar amendment on rice growth and nitrogen retention in a waterlogged paddy field. *Journal of Soils and Sediments* 15: 153–162.

Dung, T.V., Tan, D.B., Khanh, T.H., Gale, D., Long, V.V., 2021. Effect of Gluconacetobacter diazotrophicus inoculation and reduced nitrogen fertilizer on yield and growth parameters of rice varieties. *Journal of Seed Science* 43: e202143029.

Dung, T.V., Thu, T.A., Long, V.V., Da, C.T., 2022. Decomposition of rice straw residues and the emission of CO_2, CH_4 under paddy rice and crop rotation in the Vietnamese Mekong Delta region–A microcosm study. *Plant, Soil and Environment* 68: 29–35.

Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–a review. *Biology and Fertility of Soils* 35: 219–230.

Griffin, D.E., Wang, D., Parikh, S.J., Scow, K.M., 2017. Short-lived effects of walnut shell biochar on soils and crop yields in a long-term field experiment. *Agriculture, Ecosystems & Environment* 236: 21–29.

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome. 192p. Available at [Access date: 08.09.2022]: http://www.fao.org/3/i3794en/I3794en.pdf

Jaafar, N.M., Clode, P.L., Abbott, L.K., 2015. Soil microbial responses to biochars varying in particle size, surface and pore properties. *Pedosphere* 25(5): 770–780.

Kopittke, P.M., Dalal, R.C., Finn, D., Menzies, N.W., 2017. Global changes in soil stocks of carbon, nitrogen, phosphorus, and sulphur as influenced by long-term agricultural production. *Global Change Biology* 23(6): 2509–2519.

Kopittke, P.M., Dalal, R.C., Hoeschen, C., Li, C., Menzies, N.W., Mueller, C.W., 2020. Soil organic matter is stabilized by organo-mineral associations through two key processes: The role of the carbon to nitrogen ratio. *Geoderma* 357: 113974.

Kopittke, P.M., Menzies, N.W., Wang, P., McKenna, B.A., Lombi, E., 2019. Soil and the intensification of agriculture for global food security. *Environment International* 132: 105078.

Kroetsch, D., Wang, C., 2008. Particle size distribution. In: Soil sampling and methods of analysis, Carter, M.R., Gregorich, E.G. (Eds.), CRC Press and Taylor and Francis Group: Boca Raton, Florida. pp. 713–725.

Laird, D., Fleming, P., Wang, B., Horton, R., Karlen, D., 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma* 158(3-4): 436–442.

Lashari, M.S., Liu, Y., Li, L., Pan, W., Fu, J., Pan, G., Zheng, J., Zheng, J., Zhang, X., Yu, X., 2013. Effects of amendment of biochar-manure compost in conjunction with pyroligneous solution on soil quality and wheat yield of a salt-stressed cropland from Central China Great Plain. *Field Crops Research* 144: 113–118.

Lehmann, J., da Silva, J.P., Steiner, C., Nehls, T., Zech, W., Glaser, B., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil* 249: 343–357.

Li, B., Fan, C., Xiong, Z., Li, Q., Zhang, M., 2015. The combined effects of nitrification inhibitor and biochar incorporation on yield-scaled N2O emissions from an intensively managed vegetable field in southeastern China. *Biogeosciences* 12: 2003–2017.

Metson, A.J., 1961. Methods of chemical analysis for soil survey samples. Soil Bulletin, New Zealand Department of Scientific & Industrial Research, New Zealand. 207p.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta* 27: 31–36.

Olsen, S.R., Sommers, L.E., 1982. Phosphorus. In: Methods of soil analysis. Part 2 Chemical and microbiological properties. 2nd edition. Page, A.L., Miller, R.H., Keeney, D.R., (Eds.). American Society of Agronomy Inc., Madison, WI, USA. pp. 403-430.

Phuong, N.T.K., Khoi, C.M., Ritz, K., Linh, T.B., Minh, D.D., Duc, T.A., Sinh, N.V., Linh, T.T., Toyota, K., 2020a. Influence of rice husk biochar and compost amendments on salt contents and hydraulic properties of soil and rice yield in salt-affected fields. *Agronomy* 10(8): 1101.

Phuong, N.T.K., Khoi, C.M., Ritz, K., Sinh, N.V., Tarao, M., Toyota, K., 2020b. Potential use of rice husk biochar and compost to improve P availability and reduce GHG emissions in acid sulfate soil. *Agronomy* 10(5): 685.

Rajkovich, S., Enders, A., Hanley, K., Hyland, C., Zimmerman, A.R., Lehmann, J., 2012. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Biology and Fertility of Soils* 48: 271–284.

Sánchez-García, M., Sánchez-Monedero, M., Roig, A., López-Cano, I., Moreno, B., Benitez, E., Cayuela, M., 2016. Compost vs biochar amendment: a two-year field study evaluating soil C build-up and N dynamics in an organically managed olive crop. *Plant and Soil* 408: 1–14.

Scharlemann, J.P., Tanner, E.V., Hiederer, R., Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Management* 5(1): 81–91.

Schulz, H., Glaser, B., 2012. Effects of biochar compared to organic and inorganic fertilizers on soil quality and plant growth in a greenhouse experiment. *Journal of Plant Nutrition and Soil Science* 175(3): 410–422.

Shah, T., Tariq, M., Muhammad, D., 2021. The influence of added biochar on soil microbial biomass in a less fertile alkaline calcareous soil under different management practices. *Soil and Environment* 40: 27–37.

Shcherbak, I., Millar, N., Robertson, G.P., 2014. Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. *PNAS* 111(25): 9199–9204.

Solaiman, Z.M., Blackwell, P., Abbott, L.K., Storer, P., 2010. Direct and residual effect of biochar application on mycorrhizal root colonisation, growth and nutrition of wheat. *Australian Journal of Soil Research* 48(7): 546–554.

Thies, J.E., Rillig, M.C., Graber, E.R., 2015. Biochar effects on the abundance, activity and diversity of the soil biota. In: Biochar for environmental management: Science, Technology and Implementation, Lehmann, J., Joseph, S. (Ed.), Routledge. pp. 359–422.

Ullah, Z., Akmal, M.S., Ahmed, M., Ali, M., Khan, A.Z., Ziad, T., 2018. Effect of biochar on maize yield and yield components in rainfed conditions. *International Journal of Agronomy and Agricultural Research (IJAAR)* 12(3): 46–51.

Uzoma, K., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., Nishihara, E., 2011. Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil Use and Management* 27(2): 205–212.

Vaccari, F., Maienza, A., Miglietta, F., Baronti, S., Di Lonardo, S., Giagnoni, L., Lagomarsino, A., Pozzi, A., Pusceddu, E., Ranieri, R., Valboa, G., Genesio, L., 2015. Biochar stimulates plant growth but not fruit yield of processing tomato in a fertile soil. *Agriculture, Ecosystems & Environment* 207: 163–170.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K., Downie, A., Rust, J., Joseph, S., Cowie, A., 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil* 327: 235–246.

Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science 37: 29–38.

Weil, R., Brady, N.C., 2017. The nature and properties of soils. Pearson Publisher. 1104p.

Wulf, S., Vandré, R., Clemens, J., 2002. Mitigation options for CH_4, N_2O and NH_3 emissions from slurry management. Non-CO2 greenhouse gases: scientific understanding, control options and policy aspects. Proceedings of the Third International Symposium, Maastricht, Netherlands, 21–23 January 2002. Millpress Science Publishers, pp. 487–492.