Ilmu Pertanian (Agricultural Science)

http://journal.ugm.ac.id/jip

Vol. 9 No. 3 December, 2024: 147–157| DOI: doi.org/10.22146/ipas.75250

The effect of a combination of nitrogen and phosphorus fertilization with bamboo biochar rate on the growth and productivity of rice

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Article Info

Received : 8th June 2022
Revised : 30th June 2023
Accepted: 20th December 2024

Keywords:
Ammonium, bamboo biochar, Kontiki, nitrate, rice yield

Abstract

The combination of fertilizer treatment with biochar has shown to be a sustainable and ecologically friendly method of increasing soil fertility and crop productivity. However, its combined impact on nutrient availability and rice yield is still unclear. This study aimed to investigate the effect of bamboo biochar produced by the Kontiki method in combination with nitrogen and phosphorus fertilization on nutrient availability in the soil and the productivity of rice. The treatment factors included the fertilizer combination factor (B) consisting of B1 (N + P fertilizer + Biochar), B2 (N fertilizer + Biochar), B3 (P fertilizer + Biochar), and B4 (Biochar + no fertilizer), and the biochar dose factor (F) comprising F0 (0 tons ha^{-1}), F1 (5 tons ha^{-1}), and F2 (10 tons ha^{-1}), resulting in 36 experimental plots with 12 treatment combinations. Measurement of ammonium and nitrate concentration in the soil started on the 15th day after planting, following the measurement of the growth of rice plant biomass with an interval of 15 days. The measurement of available P in the soil was started on day 45 after planting and continued until harvesting time with the same time intervals as the measurements of ammonium and nitrate. The study found that combining bamboo biochar treatment with nitrogen and phosphorus fertilizer greatly boosted the availability of nitrogen (ammonium and nitrate) and availability of P in the soil. Treatment combinations improved lowland rice yield ($P < 0.05$) by increasing plant height, number of tillers, dry weight of shoots and roots, grain weight per clump, 1000-grain weight, and grain yield.

INTRODUCTION

Lowland rice is the staple food for more than 3 billion people in the world (Dauda and Dzivama, 2004; Olaleye et al., 2004; Oladele et al., 2019) and is the most important crop cultivated in Indonesia among maize and soybean (Ministry of Agriculture, 2021). However, it faced various productivity issues due to the decline of land resources quality caused by the overuse of non-environmentally friendly chemical fertilizers, which led to a decrease in environmental quality and, ultimately, land degradation. Fertilization problems commonly become a limiting factor for increasing plant productivity, especially in lowland rice. Fertilizers are often applied excessively and inefficiently, but this is not always followed by an increase in production; in some cases, it even leads to a decrease in production, as seen in nitrogen and phosphorus fertilization. Excessive application of N fertilizer could acidify the soil and accelerate the loss of nutrients (Guo et al., 2010). Ammonium (NH_4^+) and nitrate (NO_3^-) are the two forms of nitrogen fertilizer available in the soil.

Nitrogen in soil is highly mobile due to leaching and can be carried away by surface water, potentially contaminating surface and groundwater, or can be lost through evaporation and emission (Chen et al., 2015; Fan et al., 2017; Russo et al., 2017). In saturated

How to cite: Mahyudi, Purwanto, B.H., Hanudin, E. (2024). The effect of a combination of nitrogen and phosphorus fertilization with bamboo biochar rate on the growth and productivity of rice. *Ilmu Pertanian (Agricultural Science)*, 9(3), pp. 147–157.

ISSN 0126-4214 (print) ISSN 2527-7162 (online)

Inceptisols and Entisols, the ammonium content and soil solution that seeped into the soil were higher than that of nitrate (Mulyani et al., 2001). Aggria et al. (2012) reported that the concentration of ammonium (NH_4^+) in flooded soil was higher than in dry soil, which is contrast to nitrate (NO_3^-) that was higher in dry soil. Furthermore, phosphorus (P) is a macronutrient that is also required in significant quantities; however, the quantity of P in plants is less than that of nitrogen (N).

Phosphorus is mainly absorbed by plants in the form of primary orthophosphate ions ($H_2PO_4^-$) and secondary orthophosphate ions (HPO_4^{2-}). It is slightly absorbed in the form of pyrophosphate and metaphosphate and in the form of water-soluble organic phosphates compounds such as nucleic acids and phytin. Phosphorus is assimilated in the form of inorganic ions and rapidly converts to organic phosphate compounds. Phosphorus is a mobile nutrient that can be transported between plant tissues. The optimum level of P in plants during vegetative growth was 0.3–0.5% of the dry weight of plant (Rosmarkam and Yuwono, 2002). The efficiency of P fertilizer is generally very low, at approximately 10%, as it can only be assimilated by plants through root interception and diffusion in a short distance (< 0.02 cm). Most of the P fertilizer that is not absorbed by plants is not leached away but becomes stable P, unavailable to plants. It is then fixed as Al-P and Fe-P in acidic soils (pH < 5.5) and as Ca-P in alkaline soils (pH > 6.5) (Pitaloka, 2004).

Numerous studies have recommended the utilization of biochar as a soil amendment. Biochar is a carbon-rich soil material produced from organic raw materials through a pyrolysis process, which has specific characteristics such as high surface area, high porosity, and high cation exchange capacity (Xia et al., 2019; Guo et al., 2022). According to Gani (2009), the use of biochar was more effective in nutrient retention and in increasing its availability to plants compared to other organic materials such as compost or manure. Therefore, the use of biochar is expected to minimize the negative impact of excessive use of chemical fertilizers so as not to pollute the environment and could increase fertilization efficiency, increase carbon absorption, improve soil physic-chemical, increase rhizosphere microbial community biodiversity, and improve soil nutrient retention (Joseph et al., 2015; Hosseini et al., 2016; Nguyen et al., 2018). The objective of this research was to determine the optimal dosage of biochar in conjunction with nitrogen and phosphorus fertilizers to enhance the growth and yield of lowland rice. This would result in a rise in the quality and quantity of lowland rice production, as well as an increase in the income of farmers.

MATERIALS AND METHODS

Field experimental description

The research was carried out from February to May 2021 at the Center for Agrotechnology Innovation, Universitas Gadjah Mada, located in Kalitirto Village, Berbah District, Sleman Regency, Yogyakarta. This region is situated at an elevation of 124 meters above sea level and has a typical tropical monsoon climate, characterized by an annual average temperature of 25.1°C and a yearly precipitation of 2681 mm. The soil type was Inceptisol (67% sand, 20% dust, and 16% clay) with the following soil characteristics: pH 6.53, C-organic 1.76%, N-total 0.15%, P-available 6.23%, and LCM 15.52 me/100g.

Biochar source and production

Biochar was produced using the Kontiki pyrolysis process at a temperature of 600°C, employing a cooling system involving immersion in water. The process was carried out at the experimental field of the Faculty of Agriculture at Universitas Gadjah Mada, Banguntapan, Bantul, Yogyakarta. Upon drying, the biochar was powdered and pulverized. The attributes of the bamboo biochar utilized in this investigation are presented in Table 1.

Experimental design

The experimental design employed a Completely Randomized Block Design (CRBD) for lowland rice, incorporating two treatment factors: the fertilizer combination factor (B) consisting of B1 (N + P fertilizer + Biochar), B2 (N fertilizer + Biochar), B3 (P fertilizer

Table 1. Characteristics of bamboo biochar

Material	pH H_2O (1:5)	C-Fix	P-Total (%)	N-Total (%)	K-Total (%)
Bamboo Biochar	10.13	40	0.1	0.21	0.33

+ Biochar), and B4 (Biochar + no fertilizer), and the biochar dose factor (F) comprising F0 (0 tons ha^{-1}), F1 (5 tons ha^{-1}), and F2 (10 tons ha^{-1}). The treatments were replicated three times, resulting in 36 experimental plots with 12 treatment combinations. This study used Ciherang variety rice seeds in rice fields with irrigation systems. The dose of fertilizers used was based on the recommended dose of 300 kg ha^{-1} for Urea fertilizer and 150 kg ha^{-1} for SP-36 fertilizer which was converted into experimental plots with an area of 2 meters × 2.5 meters to 150 grams $plot^{-1}$ and 75 grams $plot^{-1}$ applied in two stages. The initial stage of fertilizer was soaked with charcoal based on the treatments (N + P + biochar), (N + biochar), and (P + biochar), while the second stage was applied directly to the experimental plot by integrating it into the soil at 35 days after planting (DAP).

Soil sampling and observation parameter

Observations of plant and soil parameters (plant height, tiller number, N-available, P-available, and soil pH) were measured at the age of 15, 30, 45, 60, and 75 days after planting (DAP), except for available P, which was carried out at 45 days after planting (DAP) until harvest. Soil samples taken for analysis were the pH, NH_4^+, NO_3^-, and available P. Plant parameters were measured following soil sampling, while production parameters were measured after harvesting time.

Statistical analysis

The experimental data were subjected to Analysis of Variance (ANOVA) using the "R" application to find out which mean value had a significant effect on the observed parameters. If the effect of treatment was very significant or significant then it would be proceeded to performing the Least Significant Difference (BNT) test to find out the significantly different treatments.

RESULTS AND DISCUSSION

The concentration of ammonium, nitrate, and P-available in soil

All treatments showed a decreasing trend of ammonium and nitrate concentrations in the soil from 15 to 75 days after planting (DAP) (Figure 1). The combined treatment of N + P + biochar at a rate of 5 tons ha^{-1} exhibited the greatest ammonium content at 15 DAP; however, it was not substantially different from the treatment with just N fertilizer or the combination of N and biochar at the same dosage. At 75 DAP, the control treatment, which lacked nitrogen (N) and phosphorus (P) fertilization and biochar addition, did not exhibit significant differences across all treatments, except for the combination treatment of N + P + biochar at a rate of 10 tons per hectare and the combination treatment of N fertilizer + biochar at the same rate, which demonstrated significant differences. The use of biochar may influence nitrogen transformation in the soil (Zhang et al., 2021) and might enhance the absorption capacity of NH_4^+ in the soil (Xiao et al., 2017; He et al., 2019). The combined treatment of N + P + biochar at a dosage of 10 tons ha^{-1} exhibited

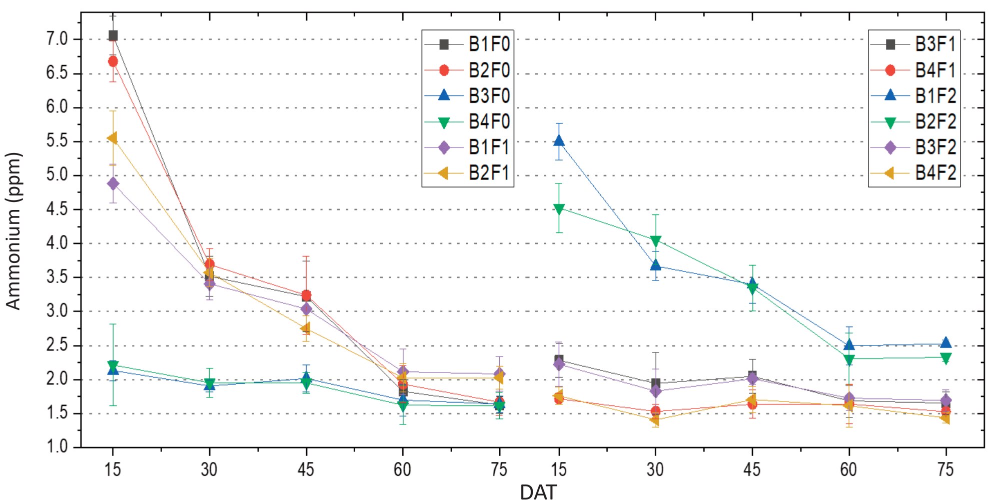

Figure 1. Ammonium (NH_4^+) concentration in soil of rice under combined treatment of N and P fertilization with varying rates of biochar application

the greatest concentration of NH_4^+ at 75 DAP. The higher the pyrolysis temperature during the biochar manufacturing process, the higher the pore volume and surface area of the biochar produced (max. 700 °C) (Xu et al., 2019; Yin et al., 2021).

The concentration of nitrate in the soil showed the same decreasing trend as that of NH_4^+ from 15 to 75 DAP. However, at 45 DAP, some treatments experienced an increase in concentration due to the 2nd stage of fertilizer application at 35 DAP, followed by a subsequent decrease in concentration at the next observation (Figure 2). The combination of N + P fertilizers without biochar exhibited the highest nitrate concentration, which was significantly higher compared to the combination of the N + P fertilizers with a biochar dosage of 10 tons ha^{-1}, which showed a lower nitrate concentration. He et al. (2019) and Xiao et al. (2017) reported that biochar could increase the absorption capacity of NH_4^+ and NO_3^- in the soil. Additionally, Feng and Zhu (2017) and Xie et al. (2020) stated that the application of biochar reduced the formation of nitrate in the soil by suppressing the nitrification process, so that the production of N_2O could be suppressed. The concentration of NO_3^- in the soil at 60 and 75 DAP showed a small trend concentration of nitrate, indicating that the concentration of NO_3^- in the soil had lost either through the volatilization process or due to leaching, or it was even more likely to become N_2O emissions. The concentration of NO_3^- in the soil produced by the nitrification process was responsible for the high emission of N_2O (Lan et al., 2017; Xie et al., 2020). Nitrate was very unstable in flooded soil conditions, which would be easily lost as N_2O and N_2 through the denitrification process within a few days after inundation (Ponnamperuma, 1977).

Available P in the soil showed different concentrations and tended to decrease over time (Figure 3). All combination treatments of N + P fertilizer with biochar showed a significant difference compared to the control treatment, which involved fertilization without biochar application. The combination treatment of N + P + biochar at a dosage of 5 tons ha^{-1} exhibited the highest available P concentration relative to the treatment without P fertilization; however, it did not significantly differ from the combination treatment of N + P + biochar at 10 tons ha^{-1}, the combination treatment of N + P + biochar at 0 tons ha^{-1}, or the combination treatment of P + biochar fertilizer at dosages of 0, 5, and 10 tons ha^{-1}. The concentration of available P showed a very significant difference between the fertilization treatment combined with biochar and the treatment without biochar. This might be because bamboo biochar could increase the bioavailability of phosphorus, which was in agreement with a study by Song et al., (2019) that the application of biochar combined with compound fertilizers into paddy fields could increase the availability of P and reduce soil phosphatase. Moreover, Mabagala and Mng'ong'o (2022) suggested that the extensive application of organic fertilizers or other materials such as biochar can increase the availability of organic matter and positively affect P availability, particularly in soils in tropical climates.

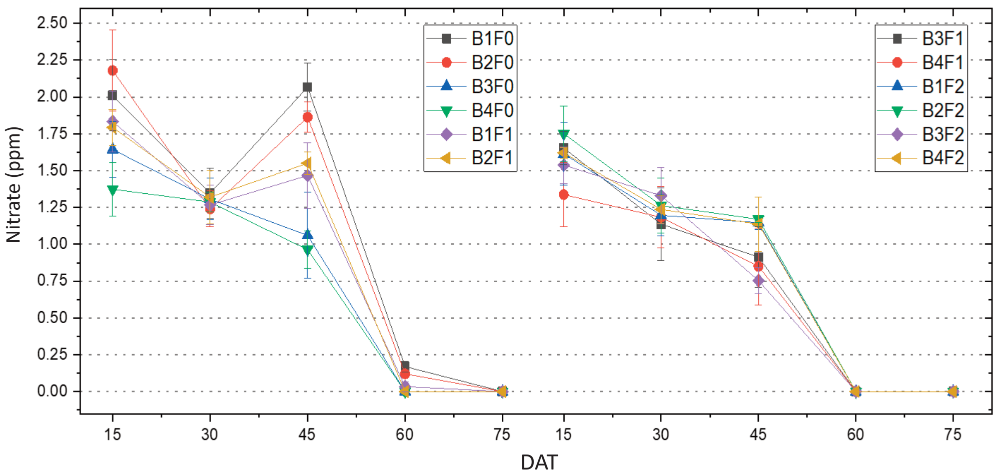

Figure 2. Nitrate (NO_3^-) concentration in soil of rice under combined treatment of N and P fertilization with varying rates of biochar application

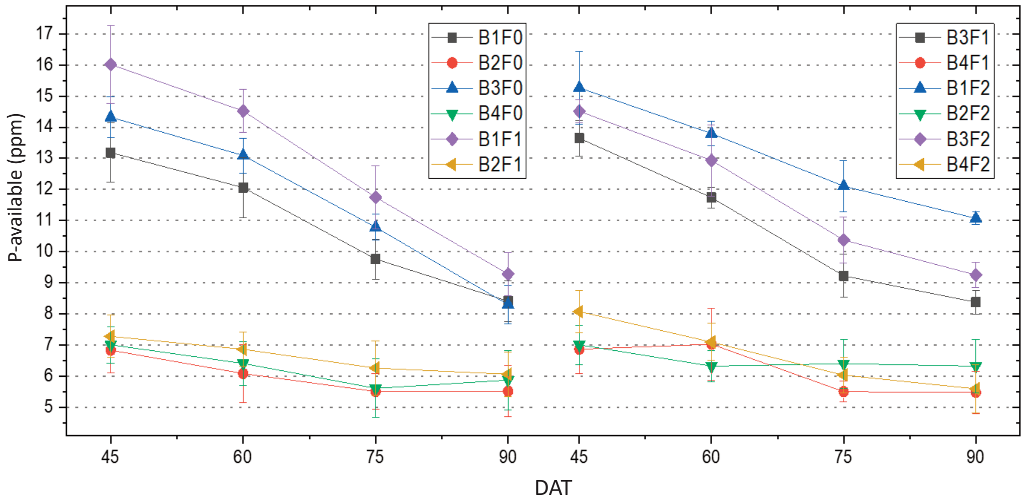

Figure 3. Concentration of P-available in soil of rice under combined treatment of N and P fertilization with varying rates of biochar application

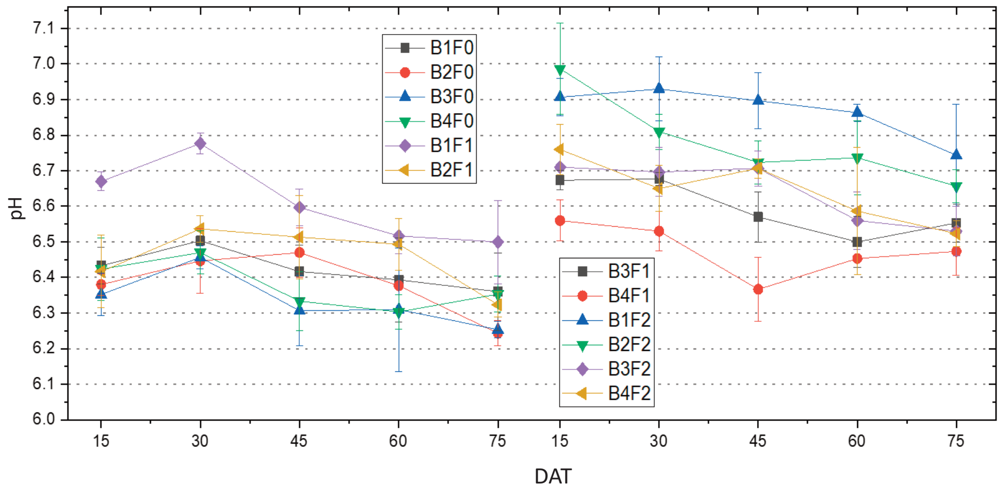

Figure 4. Soil pH (H_2O) of rice under combination treatment of N and P fertilization with varying rates of biochar application

Soil pH

The combination treatment of N + P + biochar at a dosage of 10 tons ha^{-1} and the combination treatment of N + biochar at a dosage of 5 tons ha^{-1} exhibited the highest pH value of 6.9 at 15 DAP, maintaining stability up to 75 DAP (Figure 4). This suggests that the application of biochar increased the soil's pH, likely due to the elevated pH value of bamboo biochar. According to Aamer et al. (2021), the increase in soil pH by biochar application was caused by the abundance of alkaline-charged carbonate groups in bamboo biochar. The increase in soil pH by biochar can increase the induction of enzymes responsible for the denitrification process, thereby reducing N_2O production (Obia et al., 2015). Additionally, biochar plays a direct role in the abundance of microbes that produce the nosZ gene which facilitates the conversion of N_2O to N_2, further suppressing N_2O production (Aamer et al., 2021). Ibrahim et al. (2022) also emphasized that the application of biochar to the soil can significantly increase soil pH.

The growth and biomass production of rice

Plant height and the number of tillers showed significant differences between the treatments. All treatments differed markedly from the control, which had no nitrogen fertilizer and included a biochar dosage, ranging from 15 to 60 days after planting (Figure 5 and Figure 6). Plants reached the maximum height at 75 (DAP), with the treatment of N + P + biochar fertilizer at a rate of 10 tons per hectare exhibiting the greatest height among all treatments, followed by the combination of N fertilizer and bamboo biochar at the same dosage. The tallest rice plants reached 109 cm with the N + P + bamboo biochar fertilizer treatment at a dosage of 10 tons ha^{-1}, followed by the N fertilizer + bamboo biochar treatment at the same dosage, resulting in a height of 105 cm. The mean tiller count was 71 for the combination of fertilizer N and bamboo biochar at a dosage of 10 tons ha^{-1}, followed by a combined treatment of fertilizer N, P, and biochar at the same dosage, which yielded a total of 66 tillers in rice plants. This indicated that the application of biochar combined with fertilization had a potency to increase the plant height of the rice plant compared to the fertilization treatment without the application of biochar. These results were in line with the research by Yin et al. (2021) reporting that the application of fertilizer-enriched biochar in paddy fields enhanced the growth components of rice plants, including root biomass, plant height, and the number of tillers, ultimately boosting the rice yields.

The average dry weight of rice plant shoots across all treatments did not substantially vary from the control treatment, which involved no fertilization

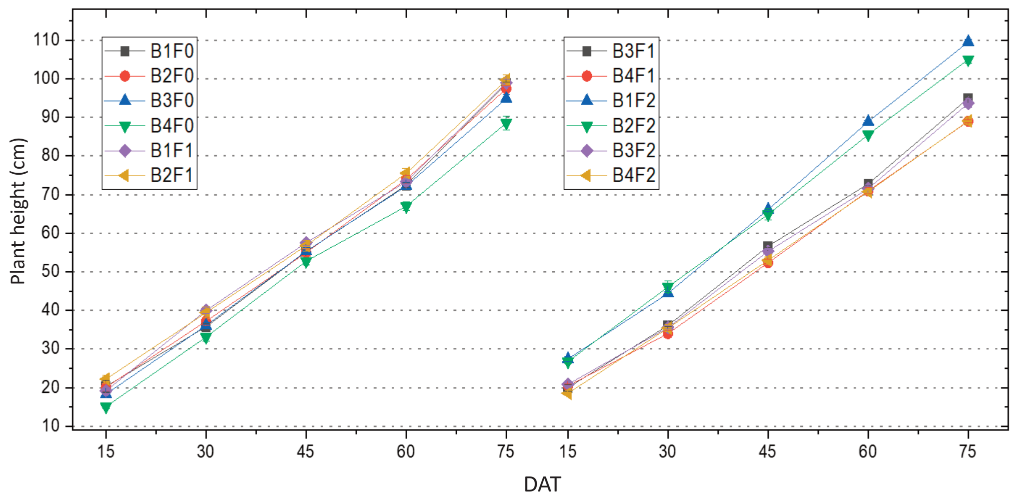

Figure 5. Plant height of rice under combined treatment of N and P fertilization with varying rates of biochar application

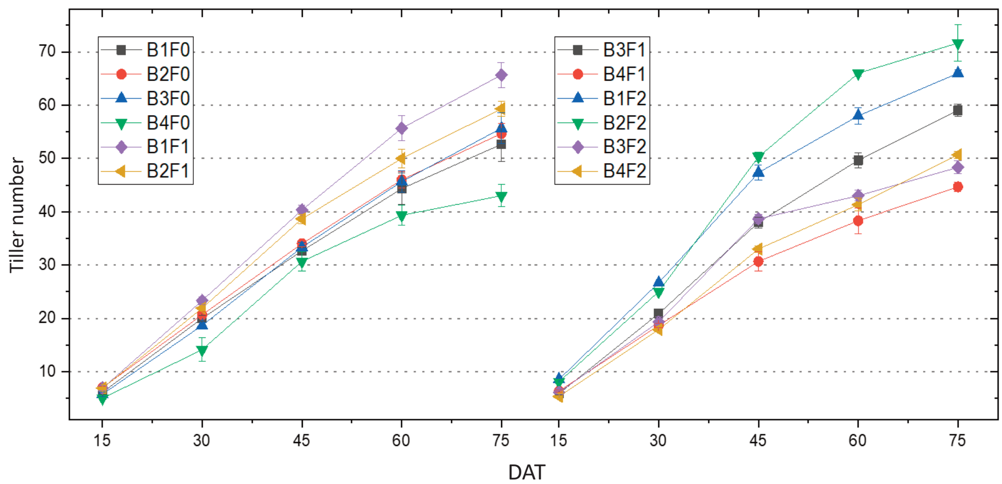

Figure 6. Tiller number of rice under combined treatment of N and P fertilization with varying rates of biochar application

and no biochar (Figure 7). However, it is markedly distinct from the combination treatment of N + P + biochar fertilizer at a dosage of 10 tons ha⁻¹, the combination treatment of N + P + biochar at a dosage of 5 tons ha⁻¹, and the combination treatment of N + biochar at a dosage of 10 tons ha⁻¹. However, it is markedly different from the combination treatment of N + P + biochar fertilizer at a dosage of 10 tons ha⁻¹, the combination treatment of N + P + biochar at a dosage of 5 tons ha⁻¹, and the combination treatment of N + biochar at a dosage of 10 tons ha⁻¹. Meanwhile, the means of dry weight of roots in all treatments were not significantly different from the control without fertilization and the addition of biochar, except for the combination treatment of N + P + biochar fertilizer at a dose of 10 tons ha⁻¹ and the combination treatment of N + biochar fertilizer at a dose of 10 tons ha⁻¹ which showed a significant difference with the control treatment. The integration of fertilizer with biochar significantly enhanced plant biomass. The result of this study indicated that applying fertilizer and biochar at rates of 5 and 10 tons per hectare enhanced rice biomass output compared to the control treatment without fertilization and biochar supplementation. In agreement with the research of Chew et al. (2022), the application of compound fertilization combined with the application of biochar significantly increased rice biomass. Furthermore, Chan et al. (2007) suggested that fertilization without the addition of biochar had no effect on increasing crop yields, and vice versa if only the addition of biochar without fertilization had no effect on increasing plant productivity even though the biochar given reached 100 tons ha⁻¹. Additionally, Ibrahim et al. (2022) reported that biochar amendments at different rates generally increased root and shoot dry weight compared to untreated soils.

Rice yield

Grain weight per clump of rice was measured at harvest by separating the panicle from the grains, which were then calculated manually. The maximum grain weight per clump was observed with the application of the N + P + biochar combination at a dosage of 10 tons ha⁻¹, which is attributed to the nutrient provision for plant growth throughout both vegetative and generative stages, as reflected in the increased rice biomass and productivity (Figure 8). Conversely, the control treatment, which lacked nitrogen and phosphorus fertilization, as well as biochar application, exhibited the lowest grain weight per clump due to the absence of nutrient supply for rice plant growth. This was in line with the research by Zhang et al. (2021) which stated that the yield of rice grain can be increased by biochar treatment combined with balanced fertilization according to plant needs. Additionally, Case et al. (2012) and Wang et al. (2018) suggested that biochar improved plant growth conditions due to its high surface area and porous structure that could enhance cation exchange capacity and soil properties, contributing to increased plant productivity (Agegnehu et al., 2016). Therefore, biochar was considered as an important organic material to maintain production and reduce environmental

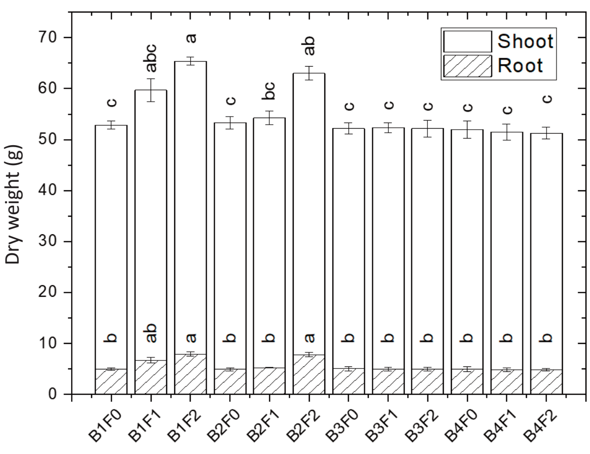

Figure 7. Dry weight of shoot and root of rice under combined treatment of N and P fertilization with varying rates of biochar application

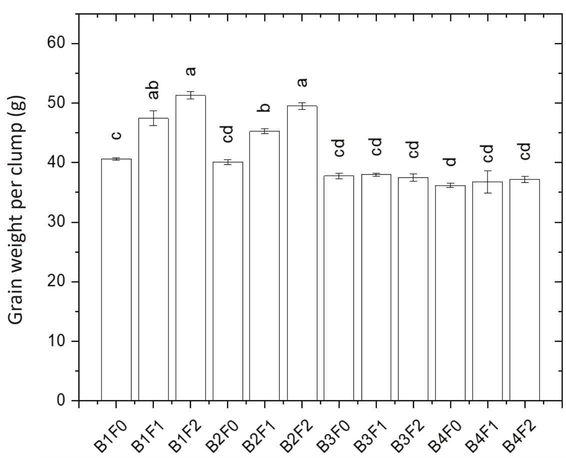

Figure 8. Grain weight per clump of rice under combined treatment of N and P fertilization with varying rates of biochar application

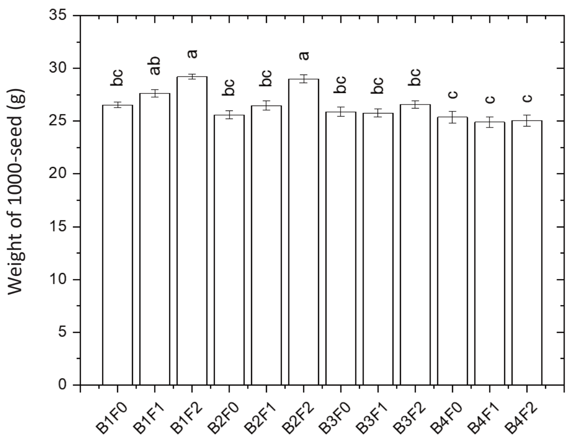

Figure 9. Weight of 1000-seed of rice under combined treatment of N and P fertilization with varying rates of biochar application

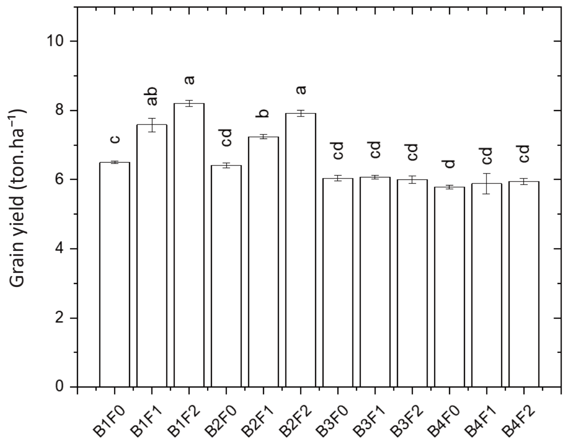

Figure 10. Grain yield of rice under combined treatment of N and P fertilization with varying rates of biochar application

risks (Barrow, 2012).

The combination treatment of N and P + biochar at a dose of 10 tons ha^{-1} showed the highest weight value of 1000 grains of rice followed by a combination treatment of N + biochar fertilizer at a dose of 10 tons ha^{-1} and a combination treatment of N + P + biochar at a dose of 5 tons ha^{-1} compared to all treatments (Figure 9). The combination of N and P fertilizer with biochar likely improved plant development by increasing the availability of essential nutrients. Nitrogen and phosphorus were consistently available as biochar's ability to bind nutrients and and release them slowly aligned with plant needs. This was due biochar's richness in functional groups as well as its high surface area and pore structure. Consistent with the findings of Wang et al. (2018), the biochar amendment enhanced plant growth conditions owing to its elevated surface area and porous structure, which augmented cation exchange capacity and improved soil properties, thereby contributing to increased plant productivity.

The research findings and analysis of variance indicated that the treatment combining N + P fertilizers with a biochar application of 10 tons ha^{-1} was significantly different from the control group, which lacked fertilization and biochar application; however, it was not significantly different from the treatment combining N + P fertilizers with biochar at 10 tons ha^{-1} and the treatment combining N fertilizer with biochar at 10 tons ha^{-1}. The combination treatment of N + P + biochar at a dose of 10 tons ha^{-1} had the highest value among all treatments whereas this treatment had a grain yield of 8.21 tons ha^{-1}, followed by a combination treatment of 7.92 ton ha^{-1} and a combination of N + P fertilizer with biochar at a dose of 5 tons ha^{-1} with a weight of 7.59 tons ha^{-1}. The control treatment without fertilization and biochar had a dry grain weight of only 5.79 tons ha^{-1}; the fertilization treatment without biochar had a harvested dry grain weight of 5−6 tons ha^{-1}; and the application of biochar without fertilization both at the doses of 5 and 10 tons ha^{-1} had a grain yield ranging from 4–6 tons ha^{-1}. This showed that nitrogen and phosphorus fertilization treatment according to the recommended dose combined with the application of biochar at a dose of 10 tons ha^{-1} had the potential to increase rice production yields based on grain yield. The results of this study were in agreement with some previous studies such as the research of Joseph et al. (2013) and Yao et al. (2015) who stated that the application of biochar-based compound fertilizer (BCF) had the potential to increase crop yields, vegetable quality, and fertilizer use efficiency while reducing pesticide inputs and greenhouse gas emissions. In addition, the benefits of applying biochar with a certain particle size combined with balanced fertilization could increase crop yields and improve soil properties (Thomas, 2021). The increase in dry biomass due to the application of biochar could be explained by the increased availability and uptake of nutrients in the soil and/or plants (Almaroai and Eissa 2020; Karimi et al., 2020; Kocsis et al., 2020) and increased soil physio-chemical properties (Bashir et al., 2019; El-Naggar et al., 2019).

CONCLUSIONS

The utilization of biochar in lowland rice effectively preserved nutrient availability in the soil, particularly nitrogen and phosphorus. The integration of fertilization and bamboo biochar dosage may enhance biomass yield and rice plant productivity compared to treatments which lacked biochar, as reflected in metrics such as plant height, tiller count, dry weight of shoots and roots, and yield components including clump grain weight, 1000-grain weight, and grain yield in tons per hectare. It is recommended that further research focusing on the mechanism of biochar in increasing fertilization efficiency and its impact on plant physiology is conducted.

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