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Research Article

Enhanced Growth and Yield in Boro Rice through Optimized Biochar Application Rates

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Abstract— The research was conducted from December 2022 to June 2023 to investigate the growth and yield performance of two boro rice varieties under various biochar application rates, aiming to determine the optimum rate. This comprehensive study utilized two rice varieties: BRRI dhan86 (V_1) and BRRI dhan96 (V_2). Five treatments of biochar were applied: T_1 (Biochar 10 t ha⁻¹), T_2 (Biochar 8 t ha⁻¹), T_3 (Biochar 6 t ha⁻¹), T_4 (Biochar 4 t ha⁻¹), and T_5 (Biochar 2 t ha⁻¹). The experiment used a Randomized Complete Block Design (RCBD) with five replications. Results showed significant improvements in all parameters with increasing biochar application, particularly at the highest rates (T_4, T_5). Both varieties exhibited enhanced growth and yield, with BRRI dhan96 (V_2) outperforming BRRI dhan86 (V_1) across most traits. The highest grain yield was observed in V_2 with 7.75 t ha⁻¹ at T_5, representing a 30.3% increase compared to the T_1. The study found that biochar application improves soil structure, nutrient retention, and water-holding capacity, contributing to better plant performance. Thus, T_4 and T_5 can be considered an optimal rate for enhancing rice productivity under the tested conditions as they do not differ significantly. These findings support biochar as a sustainable soil amendment for improving crop yield and suggest that further research is needed to explore its long-term impacts and cost-effectiveness across different soil types and climatic conditions.

Keywords— Biochar application, Rice yield enhancement, Sustainable agriculture, Soil improvement, Optimal treatment rates, Organic Farming.

1. Introduction

Biochar, a carbon-rich material produced from the pyrolysis of organic biomass under low-oxygen conditions, has garnered substantial interest in recent years as a potential solution to various agricultural challenges. Its distinct physical and chemical properties, such as a highly porous structure and the ability to retain nutrients, make it a valuable soil amendment. The benefits of biochar application extend to improving soil fertility, enhancing nutrient retention, boosting water-holding capacity, and promoting beneficial microbial activity in the soil [1]. Such attributes are particularly relevant in the context of sustainable agriculture, where the focus is on increasing productivity while maintaining or enhancing environmental health [2].

In South Asia, Boro rice (*Oryza sativa* L.) represents a critical crop cultivated during the dry season and plays a central role in food security for millions of people. Unlike the monsoon-fed Aman rice, Boro rice requires significant irrigation due to the season’s dry conditions. This reliance on water, coupled with the need for substantial chemical inputs like fertilizers and pesticides, creates a challenging environment for farmers who must balance high yields with sustainable practices [3]. These challenges are further compounded by issues such as soil degradation, nutrient loss, and the economic strain associated with expensive inputs [4]. Thus, there is a pressing need for innovative practices that can optimize resource use, improve soil health, and enhance crop productivity without exacerbating environmental impacts.

Integrating biochar as a soil amendment in Boro rice cultivation offers a promising pathway to addressing these challenges. Research has shown that biochar application can lead to improved soil structure, increased cation exchange capacity (CEC), and better nutrient and water retention [5]. These enhancements create a more conducive environment for plant growth, which can be particularly beneficial during the dry season when water is scarce. Biochar’s ability to modulate soil pH and provide a habitat for beneficial soil microorganisms further contributes to its role in promoting sustainable crop production [6]. Such properties are critical for Boro rice, which requires optimal nutrient and water management to achieve high yields.

Moreover, biochar’s role in carbon sequestration adds an important dimension to its use in agriculture. By stabilizing carbon in the soil, biochar contributes to the reduction of atmospheric CO_2 levels, aligning with global efforts to mitigate climate change [7]. This function is particularly relevant as agricultural practices continue to adapt to the challenges posed by changing climate conditions, which include increased frequency of droughts and unpredictable rainfall patterns. Integrating biochar into soil management practices can thus serve the dual purpose of enhancing food security and contributing to environmental sustainability.

However, despite the recognized benefits of biochar, significant knowledge gaps remain, particularly in understanding the optimal application rates for specific crops under different environmental conditions. The performance of biochar in agricultural settings can vary widely depending on its feedstock source, pyrolysis conditions, and the rate at which it is applied [8]. For instance, biochar produced from woody biomass may exhibit different properties compared to biochar derived from agricultural residues, influencing its impact on soil and crop productivity [9]. Additionally, the interaction between biochar and soil type is a critical factor in determining its efficacy. Sandy soils, which are more prone to nutrient leaching, may benefit more from biochar application than clay-rich soils, where nutrient retention is already relatively high [10].

This research article aims to investigate the effects of different biochar application rates on the growth and yield performance of Boro rice. By conducting a comprehensive evaluation of key agronomic parameters such as plant height, tiller number, chlorophyll content, grain yield, and biomass production, the study seeks to pinpoint the most effective biochar dosage for maximizing productivity. These insights are essential not only for improving the efficiency of biochar use but also for supporting the broader objective of sustainable agriculture.

The economic feasibility of biochar application is another critical aspect of this study. While the environmental benefits of biochar are well-documented, its adoption by farmers depends significantly on its cost-effectiveness [11]. Understanding the balance between input costs and yield improvements will be vital for promoting biochar as a practical solution for smallholder farmers who often operate under tight financial constraints. The findings from this research can inform best practices for biochar use in Boro rice production and help guide policymakers in developing strategies that encourage sustainable farming.

This research seeks to bridge the gap in knowledge regarding the optimal application rates of biochar for Boro rice cultivation. By exploring its effects on crop growth, yield performance, and soil health, this study will provide valuable insights for farmers, researchers, and policymakers looking to harness biochar's potential for sustainable agriculture. The anticipated outcomes include improved resource management, enhanced crop productivity, and a contribution to long-term soil health. Furthermore, by demonstrating the practical benefits of biochar, this research aims to support its broader adoption and encourage sustainable agricultural practices that can withstand the challenges of a changing world.

2. Materials and Methods

2.1 Experimental soil and weather: The experimental field was characterized by a level, of well-drained terrain that was situated above flood-prone areas and classified as medium-high land. The soil was sandy loam with a pH of 8.2. The location experienced a subtropical climate with relatively high temperatures and significant rainfall during the kharif season (November to March). In contrast, the Rabi season (November to March) featured limited rainfall and cooler temperatures.

2.2 Collection of biochar: The biochar used in the study was sourced from a local market at Khorkhori Bazar, Rajshahi. It was made from maize straw through slow pyrolysis at temperatures ranging from 400 to 500°C in an oxygen-limited environment.

2.3 Variety and Experimental treatments: BRRI dhan86 and BRRI dhan96 were used in the present experiment. BRRI dhan86 (V_1) and BRRI dhan96 (V_2) were collected from the Bangladesh rice research institute (BRRI). There are five rates of biochar were applied: T_1 (Biochar 2 t ha^{-1}), T_2 (Biochar 4 t ha^{-1}), T_3 (Biochar 6 t ha^{-1}), T_4 (Biochar 8 t ha^{-1}), and T_5 (Biochar 10 t ha^{-1}).

2.4 Cultivation techniques: Healthy seeds were soaked for 24 hours, allowed to sprout in darkness, and then sown in a prepared seedbed on 31 December 2022. The seedbed was regularly maintained through weeding, irrigation, and pest control measures. Before transplanting, the field was flooded to decompose weeds, then plowed and leveled. The final field preparation and layout for transplanting were completed on 16 February 2023. NPK fertilizers (urea, TSP, MoP) were applied according to BARI recommendations during the crop growth phase. Seedlings were uprooted and transplanted on 16 February 2023 using conventional methods. Intercultural practices included gap filling, manual weeding, herbicide use, flood irrigation, and pest management. Rice stem borer and green leaf hopper infestations were controlled with Furadan and Sumithion. Regular monitoring ensured healthy plant growth with vigorous tillering and no lodging. Data collection was done from five randomly selected hills per plot. The crop reached full maturity and was harvested on 1 June 2023. Post-harvest, the crop from each plot was bundled, labeled, and threshed separately. The grains and straw were sun-dried to a 14% moisture content, and yields were calculated in tons per hectare. The field maintained good health throughout the growing period, with no significant disease issues.

2.5 Collection of experimental data: The data recording procedure involved measuring plant height from five randomly selected plants in each plot at maturity. Total tillers, including both effective and non-effective, were counted from the same plants. Chlorophyll levels were measured using a SPAD-502 meter. At maturity, yield data were collected by uprooting five hills per plot, excluding border rows, and harvesting the crop from a 1m² area. Yield parameters recorded included panicle length, number of grains per panicle, filled and unfilled grains per panicle, 1000-grain weight, grain yield, straw yield, biological yield, and harvest index. Grain and straw yields were measured, dried, and converted to tons per hectare. Biological yield was calculated by summing grain and straw yields, and the harvest index was determined as the ratio of economic yield to biological yield.

2.6 Statistical analysis: The collected data were analysed statistically using the analysis of variance technique and a least significant difference (LSD; at 0.05 level of probability) test was applied to assess the differences between the means using IBM SPSS Statistics for Windows, Version 28. Correlation heatmap and relative abundance analysis are prepared by Origin Pro software.

3.1 Plant height: The varietal differences, treatments and interaction in plant height were found at harvest shown in **Table 1**. Both rice varieties, V_1 (BRRI dhan86) and V_2 (BRRI dhan96) differed significantly, V_2 (93.57 cm) was considered the largest plant height while the smallest height was obtained in V_1 (87.00 cm). At harvest, the maximum plant height was observed in T_5 (86.59 cm) and reduced by 2.49, 2.89, 4.35 and 6.04% in T_4, T_3, and T_2 respectively but significantly reduced by 7.37% in T_1(84.48cm).

Table 1. Growth parameters of rice under different biochar rates.

Variety	Plant Height (cm) at harvest	Leaf Number (90 DAT)	Chlorophyll Content (60 DAT)	Tiller Number	Effective Tiller	Non-Effective Tiller
$\mathbf{V_1}$	87±1.27b	46.76±2.15b	42.6±0.74b	17.78±0.44b	14±0.38	3.78±0.14
$\mathbf{V_2}$	93.57±1.2a	50.93±1.31a	48.65±0.89a	17.31±0.56a	13.37±0.48a	3.94±0.15
LS	0.05	0.05	0.05	NS	NS	NS
Treatment						
$\mathbf{T_1}$	86.59±2.83b	42.95±3.89b	43.53±2.07b	15.66±0.44c	12.13±0.35b	3.53±0.14
$\mathbf{T_2}$	89.41±3.04ab	46.81±1.99ab	45.23±1.38b	17.12±0.67bc	13.42±0.55b	3.7±0.24
$\mathbf{T_3}$	90.78±2.09ab	51.79±2.45a	44.16±1.44b	17.4±0.97bc	13.59±0.98b	3.81±0.19
$\mathbf{T_4}$	91.15±1.77ab	49.24±1.53ab	46.17±1.42ab	17.98±0.55ab	13.77±0.38b	4.22±0.26
$\mathbf{T_5}$	93.48±1.5a	53.44±2.76a	49.04±2.13a	19.56±0.33a	15.52±0.12a	4.04±0.24
LS	0.05	0.05	0.05	0.05	0.05	NS
Interaction						
$\mathbf{V_1T_1}$	82.37±4.15c	36.72±4.88b	39.29±0.84e	15.9±0.64b	12.48±0.47b	3.42±0.2
$\mathbf{V_1T_2}$	85.51±2.73bc	44.99±3.29ab	43.16±1.53de	17.29±0.11ab	13.65±0.35ab	3.64±0.41
$\mathbf{V_1T_3}$	87.32±2.59abc	50.89±5.04a	41.84±1.49cde	17.87±1.52ab	14±1.41ab	3.87±0.23
$\mathbf{V_1T_4}$	88.08±0.25abc	46.92±2.39ab	43.99±1.74bcde	18.56±0.83ab	14.35±0.35ab	4.21±0.5
$\mathbf{V_1T_5}$	91.72±1ab	54.29±2.81a	44.74±1.31bcd	19.27±0.42a	15.52±0.23a	3.76±0.2
$\mathbf{V_2T_1}$	90.82±2.24abc	49.19±3.62a	47.77±1.68bc	15.42±0.71b	11.78±0.51b	3.64±0.23
$\mathbf{V_2T_2}$	93.32±4.86ab	48.62±2.38a	47.3±1.71bc	16.94±1.48ab	13.18±1.15ab	3.75±0.34
$\mathbf{V_2T_3}$	94.23±1.79ab	52.7±1.93a	46.47±1.66bcd	16.94±1.49ab	13.18±1.63ab	3.75±0.34
$\mathbf{V_2T_4}$	94.22±2.49ab	51.57±0.79a	48.36±1.49b	17.4±0.7ab	13.18±0.51ab	4.22±0.3
$\mathbf{V_2T_5}$	95.24±2.66a	52.59±5.42a	53.33±1.6a	19.85±0.53a	15.52±0.12a	4.33±0.41
LS	0.05	0.05	0.05	0.05	0.05	NS

In each column, lowercase lettering is used to show the significant differences between different types of treatment at P<0.05 level as per DMRT. Values show mean of three replicates ± standard errors (SE), DAT=Days after transplanting, LS=Level of Significance, NS=Non-significant, V_1=BRRI dhan86 and V_2=BRRI dhan96, T_1=Biochar 2 t ha^{-1}, T_2=Biochar 4 t ha^{-1}, T_3=Biochar 6 t ha^{-1}, T_4=Biochar 8 t ha^{-1}, and T_5=Biochar 10 t ha^{-1}.

For interaction, V_2T_5 showed the highest result whereas V_1T_1 exhibited the lowest result.

3.2 Leaf number: **T**here were remarkable varietal differences, treatments and interactions observed in leaf numbers at different DAT. At 90 DAT V_2 had the maximum leaf number (50.93) which was significantly 8.98% higher than V_1 and had the minimum leaf number (46.76). As for treatments, the most significant number was seen in T_5 (53.43) which was remarkably decreased by 19.62% and 12.40 % in T_1 and T_2, respectively (Table 1).

3. Results

The findings of this study are presented in tables 1 to 4 and figures 1 to 2. Various rates of biochar were used to assess rice cultivars' growth, yield, and yield-contributing characteristics.

3.3 Chlorophyll Content: The SPAD values did not significantly differ at 60 DAT. This finding demonstrated that at 60 DAT, the largest value was recorded in T_5 (49.03) which was slightly reduced by 5.83% in T_4 but significantly decreased by 9.95, 7.75 and 11.23% in T_3, T_2 and T_1, respectively. The interaction between V_2 and T_5 exhibited the best result whereas V_1T_1 showed the lowest result (Table 1).

3.4 Tiller hill^{-1}: For the tiller number per hill, variety V_1 had the highest value at 17.78, while V_2 had the lowest at 17.30. Comparing the treatments, T_1 had the lowest tiller number at 15.66. T_2 showed an increase of 9.28% over T_1 with a value of 17.12, and T_3 had a slight improvement over T_2 by 1.69% with a value of 17.40. T_4 continued the upward trend with a 3.32% increase over T_3, reaching 17.98. T_5 had the highest tiller number at 19.56, representing an 8.78% increase over T_4 and a 24.85% increase over T_1. For interactions, the highest tiller number was recorded for V_2T_5 at 19.85, while the lowest was in V_2T_1 at 15.42 (Table 1).

3.5 Effective tiller: For effective tillers per hill, variety V_1 had the highest value at 14, while V_2 had the lowest at 13.37. Comparing the treatments, T_1 had the lowest number of effective tillers at 12.13. T_2 showed an increase of 10.57% over T_1 with a value of 13.41, while T_3 had a slight improvement of 1.3% over T_2 with a value of 13.59. T_4 continued this trend with a 1.29% increase over T_3, reaching 13.76. T5 had the highest number of effective tillers at 15.52, showing a 12.73% increase over T_4 and a 27.9% increase over T_1. For interactions, the highest effective tiller number was seen in both V_1T_5 and V_2T_5 at 15.52, while the lowest was in V_2T_1 at 11.78 (Table 1).

3.6 Non-effective tiller: For non-effective tillers per hill, variety V_2 had the highest value at 3.94, while V_1 had the lowest at 3.78. Among the treatments, T_1 had the lowest number of non-effective tillers at 3.53. T_2 showed a 4.82% increase over T_1 with a value of 3.70, while T_3 had a 2.97% increase over T_2, reaching 3.81. T_4 had the highest value at 4.22, showing a 10.76% increase over T_3 and a 19.54% increase over T_1. T_5 showed a slight decrease from T_4 with a value of 4.04, representing a 4.27% reduction from T_4 but still a 14.43% increase over T_1. For interactions, the highest number of non-effective tillers was recorded in V_2T_5 at 4.33, while the lowest was in V_1T_1 at 3.42 (Table 1).

3.7 Total dry matter (TDM): For total dry matter at 30, 60, and 90 DAT (days after transplanting), variety V_2 showed the highest values at all stages, with 152.75 g m^{-2} at 30 DAT, 337.40 g m^{-2} at 60 DAT, and 580.81 g m^{-2} at 90 DAT, while variety V_1 had lower values of 148.88, 321.30, and 566.85 g m^{-2} at the respective stages. Among treatments, T_5 had the highest total dry matter at all stages: 177.38 g m^{-2} at 30 DAT, 392.15 g m^{-2} at 60 DAT, and 640.79 g m^{-2} at 90 DAT. T_1 had the lowest values at each stage with 129.92, 285.20, and 529.27 g m^{-2}. The increase in total dry matter from T_1 to T_5 was 36.5% at 30 DAT, 37.5% at 60 DAT, and 21.1% at 90 DAT. In terms of interaction, the highest dry matter was recorded for V_2T_5 at 30, 60, and 90 DAT with 177.65, 419.98, and 666.85 g m^{-2} respectively, while the lowest values were observed in V_1T_1 with 124.06, 284.28, and 529.49 g m^{-2} at the respective stages (Table 2).

3.8 Crop growth rate (CGR): For crop growth rate (CGR) between 30-60 DAT and 60-90 DAT, variety V_2 had the highest CGR at both stages, with 6.16 g m^{-2} day^{-1} at 30-60 DAT and 8.11 g m^{-2} day^{-1} at 60-90 DAT, while variety V_1 had lower values of 5.75 and 8.18 g m^{-2} day^{-1}, respectively. Among treatments, T_5 had the highest CGR at both stages, with 7.16 g m^{-2} day^{-1} between 30-60 DAT and 8.29 g m^{-2} day^{-1} between 60-90 DAT. T_1 had the lowest CGR at 30-60 DAT with 5.18 g m^{-2} day^{-1}, and T_4 had the lowest CGR at 60-90 DAT with 7.79 g m^{-2} day^{-1}. The increase in CGR from T_1 to T_5 was 38.3% at 30-60 DAT and 2.8% at 60-90 DAT. In terms of interaction, the highest CGR between 30-60 DAT

Table 2. Total Dry Matter (TDM) and Crop Growth Rate (CGR) of rice under different biochar rates.

Variety	Total Dry Matter (30 DAT)	Total Dry Matter (60 DAT)	Total Dry Matter (90 DAT)	Crop Growth Rate (30-60 DAT)	Crop Growth Rate (60-90 DAT)
V_1	148.88±6.82b	321.3±13.78b	566.85±12.87b	5.75±0.45	8.18±0.54
V_2	152.75±5.86a	337.4±15.86a	580.81±18.41a	6.16±0.41	8.11±0.4
LS	0.05	0.05	0.05	NS	NS
Treatment					
T_1	129.92±9.57b	285.2±10.29b	529.27±19.96b	5.18±0.4	8.14±0.86
T_2	138.13±7.49b	306.55±16.07b	558.96±12.79b	5.61±0.49	8.41±0.9
T_3	152.75±7.09ab	324.07±14.55b	567.57±31.31b	5.71±0.61	8.12±0.79
T_4	155.9±8.97ab	338.79±28.73ab	572.56±17.89b	6.1±1.02	7.79±1
T_5	177.38±4.92a	392.15±21.2a	640.79±19.25a	7.16±0.58	8.29±0.1
LS	0.05	0.05	0.05	NS	NS
Interaction					
V_1T_1	124.06±7.4b	284.28±19.58b	529.49±40.02b	5.34±0.7	8.17±1.85
V_1T_2	137.68±13.99ab	301.02±18.25b	552.16±16.62b	5.44±0.79	8.37±1.14
V_1T_3	152.38±15.59ab	321.54±22.77b	566.67±31.89ab	5.64±1.17	8.17±0.84
V_1T_4	153.2±18.61ab	335.34±58.1ab	571.2±28.27ab	6.07±2.02	7.86±2.21
V_1T_5	177.11±1.72a	364.32±11.15ab	614.72±11.86	6.24±0.33	8.35±0.1
V_2T_1	135.79±19.2b	286.12±12.07b	529.04±19.76b	5.01±0.54	8.1±0.5
V_2T_2	138.58±9.21ab	312.07±30.45b	565.76±22.26b	5.78±0.75	8.46±1.65
V_2T_3	153.11±2.87ab	326.6±23.11ab	568.48±62.32ab	5.78±0.7	8.06±1.56
V_2T_4	158.61±6.99ab	342.24±27.18ab	573.92±28.27ab	6.12±1.05	7.72±0.24
V_2T_5	177.65±10.86a	419.98±36.71a	666.85±32.13a	8.08±0.86	8.23±0.2
LS	0.05	0.05	0.05	NS	NS

In each column, lowercase lettering is used to show the significant differences between different types of treatment at P<0.05 level as per DMRT. Values show mean of three replicates ± standard errors (SE), DAT=Days after transplanting, LS=Level of Significance, NS=Non-significant, V_1=BRRI dhan86 and V_2=BRRI dhan96, T_1=Biochar 2 t ha^{-1}, T_2=Biochar 4 t ha^{-1}, T_3=Biochar 6 t ha^{-1}, T_4=Biochar 8 t ha^{-1}, and T_5=Biochar 10 t ha^{-1}.

was recorded in V_2T_5 with 8.08 g m^{-2} day^{-1}, and the highest CGR between 60-90 DAT was also in V_2T_2 with 8.46 g m^{-2} day^{-1}. The lowest values were observed in V_2T_1 with 5.01 g m^{-2} day^{-1} for 30-60 DAT and V_2T_4 with 7.72 g m^{-2} day^{-1} for 60-90 DAT (Table 2).

3.9 Panicle length (cm): For panicle length, variety V_2 had the highest value at 25.26 cm, while variety V_1 had the lowest at 24.95 cm. Among the treatments, T_5 had the longest panicle length at 26.20 cm, followed by T_4 with 25.99 cm. T_3 had a slightly shorter panicle length of 24.76 cm, and T2 showed a value of 24.63 cm. T_1 had the shortest panicle length at 23.94 cm. The increase in panicle length from T_1 to T_5 was 9.24%. In terms of interaction, the highest panicle length was recorded in V_1T_5 at 26.44 cm, while the lowest was observed in V_1T_1 at 23.31 cm (Table 3).

3.10 Grains panicle^{-1}: The highest number of grains per panicle was observed in variety V_1, with 93.14 grains, while variety V_2 had slightly fewer grains at 92.32. Among the treatments, T_5 resulted in the highest grain count per panicle, with 100.05 grains, followed by T_4 with 96.64 grains. T_3 produced 94.36 grains, and T_2 had 89.75 grains, while T_1 had the lowest number of grains per panicle at 82.86. The increase from T_1 to T_5 was 20.6%. In terms of interaction, the highest grain count was found in V_1T_5 with 101.02 grains, while the lowest was in V_1T_1 with 82.12 grains (Table 3).

3.11 Effective and Non-effective grains panicle^{-1}: Variety V_2 showed a slightly higher number of effective grains per panicle at 77.52, compared to V_1, which had 77.15 grains. For non-effective grains, however, variety V_1 had more, with 15.99, while V_2 had 14.81. Among the treatments, T_5 had the highest number of effective grains per panicle at 82.23, followed by T_4 with 80.18 grains, and T_1 had the lowest at 69.88 grains. T_5 also produced the highest number of non-effective grains, with 17.82, while T_1 had the lowest at 12.99. The increase in effective grains from T_1 to T_5 was 17.7%, and for non-effective grains, the increase was 37.5%. For interactions, the highest effective grain count was recorded in V_2T_5 with 82.57 grains, while V_1T_1 had the lowest with 69.25 grains. For non-effective grains, V_1T5 had the highest count at 19.13, and V_1T_1 again had the lowest with 12.87 (Table 3).

3.12 1000-grain weight (g): Variety V_2 had the highest 1000-grain weight at 24.99 g, slightly exceeding V_1, which had 24.65 g. Among the treatments, T_5 resulted in the highest 1000-grain weight at 26.07 g, followed by T_4 with 25.44 g. T_3 showed 24.83 g, while T_2 had 24.47 g. T_1 had the lowest 1000-grain weight at 23.30 g, with a 12% increase in weight

Table 3. Yield contributing characters of rice under different biochar rate

Variety	Panicle Length (cm)	Grain Panicle^{-1}	Effective Grain Panicle^{-1}	Non-Effective Grain Panicle^{-1}	1000-Grain Weight (g)
V_1	24.95±0.43b	93.14±2.44	77.15±1.93	15.99±0.77a	24.65±0.41
V_2	25.26±0.37a	92.32±2.34	77.52±2.08	14.81±0.52b	24.99±0.31
LS	0.05	NS	NS	0.05	NS
Treatment					
T_1	23.94±0.53	82.86±2.16b	69.88±1.65b	12.99±0.93c	23.3±0.5a
T_2	24.63±0.51	89.75±4.01ab	75.46±3.98ab	14.29±0.46bc	24.47±0.51bc
T_3	24.76±0.61	94.36±3.61a	78.93±3.11ab	15.43±1.14abc	24.83±0.59abc
T_4	25.99±0.46	96.64±2.39a	80.18±2.32a	16.46±0.71ab	25.44±0.31ab
T_5	26.2±0.63	100.05±2.32a	82.23±2.06a	17.82±0.85a	26.07±0.28a
LS	NS	0.05	0.05	0.05	0.05
Interaction					
V_1T_1	23.31±0.8	82.12±2.57c	69.25±2.66	12.87±0.82c	22.93±0.92c
V_1T_2	24.36±0.84	89.63±3.44abc	75.63±3.06	14±0.9bc	24.19±0.68abc
V_1T_3	24.38±0.61	95.1±5.92abc	79.04±5.15	16.06±1.88abc	24.64±1.17abc
V_1T_4	26.24±0.71	97.83±4.96abc	79.95±4.78	17.88±0.6ab	25.45±0.56ab
V_1T_5	26.44±0.8	101.02±4.5a	81.88±3.96	19.13±1.37a	26.03±0.39a
V_2T_1	24.57±0.6	83.6±4.03bc	70.5±2.47	13.1±1.92c	23.68±0.52c
V_2T_2	24.9±0.73	89.86±8.28abc	75.28±8.35	14.58±0.41bc	24.74±0.86abc
V_2T_3	25.13±1.16	93.62±5.45abc	78.81±4.67	14.8±1.61bc	25.01±0.57abc
V_2T_4	25.74±0.71	95.44±1.58abc	80.41±1.98	15.03±0.39bc	25.42±0.39ab
V_2T_5	25.97±1.15	99.09±2.4ab	82.57±2.31	16.51±0.23abc	26.1±0.48a
LS	NS	0.05	NS	0.05	0.05

In each column, lowercase lettering is used to show the significant differences between different types of treatment at $P<0.05$ level as per DMRT. Values show mean of three replicates ± standard errors (SE), DAT=Days after transplanting, LS=Level of Significance, NS=Non-significant, $V_{1=}$BRRI dhan86 and V_2=BRRI dhan96, T_1=Biochar 2 t ha^{-1}, T_2=Biochar 4 t ha^{-1}, T_3=Biochar 6 t ha^{-1}, T_4=Biochar 8 t ha^{-1}, and T_5=Biochar 10 t ha^{-1}.

from T_1 to T_5. For the interactions, the highest 1000-grain weight was recorded in V_2T_5 at 26.10 g, while the lowest was in V_1T_1 at 22.93 g (Table 3).

3.13 Grain yield (t ha^{-1}): Variety V_2 had the highest grain yield at 6.92 t ha^{-1}, surpassing V_1, which had 5.75 t ha^{-1}. Among the treatments, T_5 produced the highest grain yield at 7.21 t ha^{-1}, followed by T_4 with 6.63 t ha^{-1}. T_3 showed 6.22 t ha^{-1}, while T_2 had 6.09 t ha^{-1}, and T_1 had the lowest yield at 5.53 t ha^{-1}, with a 30.3% increase from T_1 to T_5. In terms of interaction, the highest yield was recorded in V_2T_5 with 7.75 t ha^{-1}, while the lowest was in V_1T_1 with 4.73 t ha^{-1} (Table 4).

3.14 Straw yield (t ha^{-1}): The highest straw yield was recorded in variety V_2, with 9.20 t ha^{-1}, exceeding V_1, which had 7.65 t ha^{-1}. Among the treatments, T_5 produced the highest straw yield at 9.59 t ha^{-1}, followed by T_4 at 8.82 t ha^{-1}. T_3 yielded 8.28 t ha^{-1}, while T_2 had 8.09 t ha^{-1}, and T_1 had the lowest yield at 7.35 t ha^{-1}, showing a 30.7% increase from T_1 to T_5. When examining interactions, V_2T_5 achieved the highest yield at 10.31 t ha^{-1}, while V_1T_1 had the lowest at 6.28 t ha^{-1} (Table 4).

3.15 Biological yield (t ha^{-1}): The highest biological yield was observed in variety V_2, which had 16.11 t ha^{-1}, compared to V_1 with 13.40 t ha^{-1}. Among the treatments, T_5 resulted in the highest biological yield at 16.80 t ha^{-1}, followed by T_4 at 15.45 t ha^{-1}. T_3 produced 14.50 t ha^{-1}, while T_2 had 14.18 t ha^{-1}, and T_1 had the lowest yield at 12.87 t ha^{-1}, with a 30.7% increase from T_1 to T_5. Regarding the interaction, the highest yield was recorded in V_2T_5 with 18.07 t ha^{-1}, while V_1T_1 had the lowest at 11.01 t ha^{-1} (Table 4).

3.16 Harvest index (%): The harvest index for both varieties, V_1 and V_2, was identical at 42.92%. Among the treatments, the harvest index values were also similar, with T_1 showing 42.93%, T_2 at 42.92%, T_3 at 42.91%, T_4 at 42.92%, and T_5 at 42.92%. For the interaction, the highest harvest index was observed in V_1T_1 and V_1T_2, both at 42.93%, while the lowest was in V_2T_3 with 42.91%. However, the differences between all treatments and interactions were minimal, indicating little variation in the harvest index across all conditions (Table 4).

3.17 Relative Abundance: The relative abundance graph illustrates the effects of varying biochar application rates on agronomic traits for two rice varieties. Each treatment combination shows the proportional contribution of plant height, leaf number, chlorophyll content, tiller number, panicle length, grain panicle^{-1}, effective grain panicle^{-1}, and yields components. Notably, increasing biochar rates appear to enhance yield-related parameters, such as grain yield, particularly at higher levels (T_4 and T_5). This trend suggests a positive response of both rice varieties to biochar, with specific improvements in traits crucial for productivity, such as effective tillering and panicle characteristics. These results provide insights into optimizing biochar application rates to

Table 4. Yield of rice under different rates of biochar

Variety	Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Biological Yield (t ha^{-1})	Harvest Index (%)
V_1	5.75±0.22	7.65±0.29	13.4±0.51	42.92±0.01
V_2	6.92±0.21	9.2±0.28	16.11±0.49	42.92±0
LS	0.05	0.05	0.05	NS
Treatment				
T_1	5.53±0.51c	7.35±0.67a	12.87±1.18c	42.93±0.01
T_2	6.09±0.38bc	8.09±0.5bc	14.18±0.88bc	42.92±0.01
T_3	6.22±0.4bc	8.28±0.53bc	14.5±0.93bc	42.91±0.01
T_4	6.63±0.21ab	8.82±0.28ab	15.45±0.49ab	42.92±0.01
T_5	7.21±0.26a	9.59±0.34a	16.8±0.6a	42.92±0.01
LS	0.05	0.05	0.05	NS
Interaction				
V_1T_1	4.73±0.44d	6.28±0.59d	11.01±1.03d	42.93±0.01
V_1T_2	5.54±0.19cd	7.37±0.25cd	12.91±0.44cd	42.93±0.02
V_1T_3	5.61±0.6cd	7.46±0.8cd	13.07±1.39cd	42.91±0.01
V_1T_4	6.22±0.12bc	8.28±0.16bc	14.5±0.27bc	42.92±0.01
V_1T_5	6.66±0.09abc	8.86±0.12abc	15.53±0.21abc	42.92±0.01
V_2T_1	6.32±0.67bc	8.41±0.89bc	14.73±1.56bc	42.92±0.01
V_2T_2	6.63±0.62abc	8.81±0.83abc	15.44±1.45abc	42.92±0.06
V_2T_3	6.83±0.25abc	9.09±0.34sbc	15.92±0.6abc	42.91±0.01
V_2T_4	7.04±0.21ab	9.36±0.28ab	16.4±0.49ab	42.93±0.02
V_2T_5	7.75±0.16a	10.31±0.21a	18.07±0.36a	42.92±0.01
LS	0.05	0.05	0.05	NS

In each column, lowercase lettering is used to show the significant differences between different types of treatment at P<0.05 level as per DMRT. Values show mean of three replicates ± standard errors (SE), DAT=Days after transplanting, LS=Level of Significance, NS=Non-significant, V_1=BRRI dhan86 and V_2=BRRI dhan96, T_1=Biochar 2 t ha^{-1}, T_2=Biochar 4 t ha^{-1}, T_3=Biochar 6 t ha^{-1}, T_4=Biochar 8 t ha^{-1}, and T_5=Biochar 10 t ha^{-1}.

improve growth and yield outcomes in rice cultivation, contributing to sustainable agricultural practices (Figure 1).

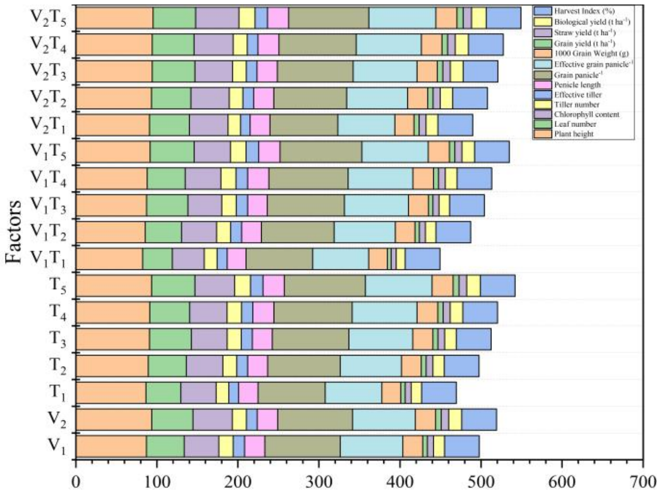

Figure 1. Relative Abundance analysis for the important parameter of this study

3.18 Pearson Correlation: The Pearson correlation analysis of the data reveals the relationships between different important parameters of this study, indicating how changes in one variable might be associated with changes in another. A significant positive relationship was observed with the yield and growth parameters of rice under various rates of biochar application (Figure 2).

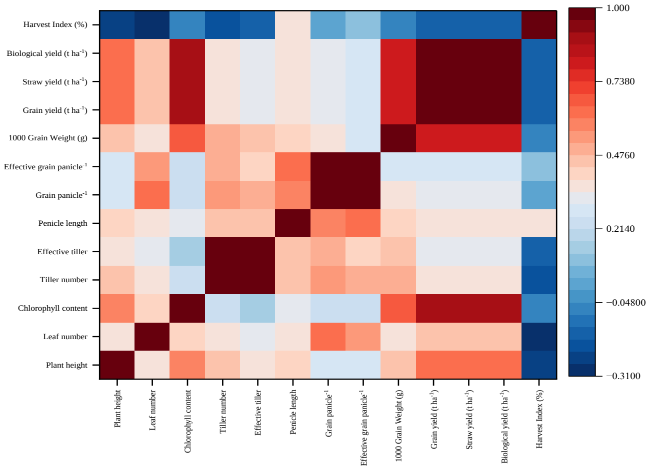

Figure 2. Heat map of Pearson Correlation analysis, range of colour showing positive and negative correlation.

4. Discussion

This study investigated the effect of biochar application on the growth, yield, and yield-contributing traits of two rice cultivars, with biochar applied at five different rates (2 t ha⁻¹, 4 t ha⁻¹, 6 t ha⁻¹, 8 t ha⁻¹, and 10 t ha⁻¹). The findings highlight the significant impact of both rice variety and biochar application on various agronomic parameters, with varying responses observed across treatments. Both varietal and treatment effects were significant for plant height, with V_2 exhibiting a taller stature (93.57 cm) compared to V_1 (87.00 cm). These results are consistent with previous studies where certain rice varieties were observed to have increased growth under optimized nutrient conditions [12]. Similarly, the application of biochar at higher rates (T_5) resulted in the tallest plants (86.59 cm), although a reduction in plant height was noted at lower biochar rates (T_1–T_4). These findings align with reports indicating that biochar can enhance plant growth by improving soil structure and nutrient availability [13]. The leaf number, significantly higher in V_2 at 90 DAT (50.93), also increased with higher biochar rates, particularly T_5 (53.43), suggesting a potential enhancement of photosynthetic capacity due to improved soil conditions [14]. Chlorophyll content, as measured by SPAD values, was highest in T_5 (49.03), which corresponds with the improved plant growth and nutrient uptake observed at higher biochar rates [15]. Tiller number and effective tillers per hill showed marked improvements with increasing biochar levels, with the highest values recorded in T_5 (19.56 and 15.52, respectively). These results support the findings by [16], who suggested that biochar application can enhance tillering by improving soil aeration and nutrient cycling . Interestingly, the varietal differences in tiller production, with V_1 outperforming V_2 in tiller number but the reverse for effective tillers, reflect the distinct growth characteristics of these cultivars. Total dry matter (TDM) production was consistently higher in V_2, which also responded more positively to biochar treatments, particularly at T_5. The increases in TDM from T_1 to T_5 (21.1% at 90 DAT) corroborate studies by [1], who reported enhanced biomass production in crops treated with biochar due to improved nutrient and water retention. Similarly, the crop growth rate (CGR) between 30–60 DAT and 60–90 DAT showed significant improvements in T_5, with V_2 recording the highest CGR at both stages. This suggests that biochar not only enhances early growth but also sustains it through the later stages of development [13]. Panicle length and the number of grains per panicle were both significantly increased under T_5, aligning with the other's findings, they reported that biochar improved panicle development by increasing soil fertility [17]. Grain yield was also significantly higher in T_5, with a 30.3% increase compared to T_1, and was greatest in V_2 (7.75 t ha⁻¹). These results are consistent with studies showing that biochar improves soil conditions, leading to enhanced nutrient availability and ultimately higher crop yields [18]. The highest straw yield was also observed under T_5, with V_2 recording the greatest biological yield (18.07 t ha⁻¹), confirming that biochar has the potential to increase overall plant productivity [19]. The harvest index (HI) remained relatively unchanged across all treatments, which is consistent with other studies where biochar's primary effect was on biomass production rather than on the allocation of resources to grain production [20]. Although slight differences in HI were noted, these were not significant, suggesting that while biochar enhances overall plant growth and yield, it does not significantly affect the proportion of biomass allocated to grain formation.

5. Conclusion and Future Scope

The results of this study demonstrate that the application of biochar significantly enhances rice growth, yield, and related agronomic traits. Biochar, particularly at higher application rates (T_4, T_5), improved key parameters such as plant height, leaf number, tiller dynamics, chlorophyll content, dry matter production, panicle length, and grain yield. The positive effects were more pronounced in the BRRI dhan96 (V_2) variety, which exhibited greater growth and productivity compared to BRRI dhan86 (V_1). These findings suggest that biochar improves soil structure, nutrient availability, and water retention, contributing to better plant development and increased yield potential. The results highlight the potential of biochar as a sustainable soil amendment for enhancing rice production, especially in nutrient-deficient soils. With a significant increase in grain yield (30.3% under the highest biochar treatment), biochar application offers a promising approach to improving food security in rice-growing regions. Further research is needed to explore the long-term impacts of biochar on soil health and its interaction with different rice varieties under diverse environmental conditions. Nevertheless, this study supports the use of biochar as an effective agricultural practice to optimize rice productivity while promoting soil sustainability.

Conflict of Interest

The authors have no conflict of interest in this article.

Authors' Contributions

Author-1 wrote the first draft of the manuscript, researched the literature and conceived the study. Author-2 was involved in data collection and assisted in manuscript writing, Author-3 the corresponding author, was involved in protocol development gaining ethical approval, patient recruitment, and data analysis revising the final draft of the manuscript. Both 2nd & 3rd authors reviewed and edited the manuscript and approved the final version of the manuscript.

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