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BIOCHAR IN CONJUNCTION WITH REDUCED DOSES OF MINERAL FERTILIZERS INCREASED YIELD ATTRIBUTES AND YIELD OF RICE (CV. BRRI DHAN29)

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Abstract

Recently, biochar (BC) applied in optimized quantities has emerged as an effective organic amendment for improving the physico-chemical features of the soil along with boosting the yield attributes of cereals. In the research field of Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur a field experiment was directed to assess the impact of BC implication united with reduced doses of recommended chemical fertilizers (RDF including N, P, K and S) on the growth and yield of rice (cv. BRRI dhan29). It was comprised of five treatments viz. T_1= Recommended doses of RDF, T_2 = BC 10 t ha^{-1}, T_3 = BC 10 t ha^{-1} + half RDF, T_4= Biochar 7.5 t ha^{-1} + half RDF and T_5 = BC 5 t ha^{-1} + half RDF. The experimental design was the regular arrangement of Randomized Complete Block Design (RCBD) along with four replications. The T_1 treatment recorded the maximum plant height (103.00 cm) and the number of tillers hill^{-1} (26.10) which remained statistically identical to T_3. Likewise, T_3 out performed rest of regimes by recording the highest values of panicle length (24.89 cm), grains number panicle^{-1} (195.40), filled grains number panicles^{-1} (191.10), and 1000-grain weight (25.53 g). Moreover, the same treatment recorded for grain yield (7.82 tha^{-1}) and straw yield (8.76 t ha^{-1}) which was statistically at par to T_1 (7.46 and 8.72 t ha^{-1}, respectively). Furthermore, T_3 also remained superior as for as biological yield (16.58 t ha^{-1}) of rice was concerned. The outcomes of this trial reveal that BC (10 t ha^{-1}) application have potential to reduce CF dose up to 50% for improving the yield attributes and grain output of rice. (cv. BRRI dhan29).

Key words: Biochar, Pyrolysis, Synergistic effect, Integrated nutrient management.

Introduction

In mid-November 2022, there were 8 billion people on the planet, compared to only 2.5 billion in 1950 and is predicted to increase by roughly 9.7 billion by 2050 (Anon., 2022). Food insecurity has been aggravated due to the COVID-19 pandemic from 2020 and ongoing Russia-Ukraine war. Nevertheless, to guarantee food and nutritional security, it appears inevitable to boost crop productivity per unit of land area.

Universally, rice (*Oryza sativa* L.) is the most significant cereal that are grown for human consumption (Islam *et al*., 2021a, 2022; Alim *et al*., 2023; Alam *et al*., 2024), and contributing as a paramount food for the people of Southeast Asia accounting for over 76% of the calorific intake (Zhao *et al*., 2020). Asian contributes more than 90% of the global rice production, and rice accounts for more than a quarter of the world caloric intake. Therefore, increasing rice production in a sustainable way can improve global food security. Bangladesh, which ranks third among the world's rice producers after China and India, produced 38.3 million tons of rice in 2022-2023 (Anon., 2023). The national average for Bangladesh is 3.25 t/ha, which is marginally greater than the 3.18 t ha^{-1} average to far considerably less than Japan (5.00 t ha^{-1}) and China (4.74 t ha^{-1}) (Anon., 2022). A considerable gap exists between the current yield and the genetic potential of existing rice genotypes, necessitating the development of contemporary farming practices.

Chemical fertilizers (CF) are crucial commodities that can boost rice yields, specifically in Bangladesh, but their utilization efficacy is alarmingly inadequate. In contrast, fertilizer utilization efficiency is negatively affected by excessive fertilizers consumption (Zhang *et al*., 2008) and degrades the soil quality (Zhu *et al*., 2005). It is almost established that neither inorganic fertilizers nor sole organic input can contribute higher yield (Jobe, 2003). Due to our climatic conditions and higher cropping intensity, the organic matter reserve in soil declines rapidly. Therefore, to ensure higher yield along with maintaining sustainable soil productivity, joint application of inorganic and organic fertilizers would be alternative approach (Mahajan *et al*., 2008). Efficient use of crop residues, farm wastes, and another one strategy to regulate soil fertility and health is to add nutrients and possibly soil amendments (DeLuca *et al*., 2006). In this setting, the coordinated application of CF and BC has emerged as a biologically viable strategy to boost rice yield. The BC is a solid byproduct that is produced when organic matter is thermally oxidized in an oxygen-limited milieu, serves as a medium with fertilizing properties, contributing to increased rice production (Anon., 2014). This beneficial relationship between inorganic fertilizers and carbon black has been deemed as a "synergistic impact" (Steiner *et al.*, 2007). Even though BC materials do not have plenty of nutrients, it could hold five times as much water as they weigh. During the field trials crops performed well when BC was applied conjointly with recommended fertilizers. Extensive investigation has been done by researchers regarding the use of BC as an amendment to enhance the fertility of paddy soil (Ly *et al.*, 2015; Si *et al.*, 2018; Kumputa *et al.*, 2019). To achieve optimal rice crop yields, a strategic approach involves combining BC with fertilizers. This combination aims to optimize rice production by minimizing the overall reliance on chemical fertilizers for plant development. Rice is being cultivated extensively with more inorganic fertilizers that are expensive too. When integrated into the soil, BC enhances fundamental chemical, biological, and physical attributes. This simultaneous improvement contributes to increased yield including crop biomass (Kookana *et al.*, 2011; Latawiec *et al.*, 2017). The BC, also referred to as black carbon, is a byproduct of pyrolysis with versatile agricultural benefits. Its application can enhance crop yields, decrease the need for fertilizers, and improve water and nutrient retention in the topsoil over an extended period. This is achieved through the minimization of nutrient leaching from the root zones of crops. The integration of BC into agricultural practices holds the promise of improving crop yields while concurrently mitigating negative environmental impacts (Spokas *et al.*, 2012). Ippolito *et al.*, (2012) showed that adding BC in conjunction with inorganic fertilizers to extremely worn and unfertile soils significantly improved crop development and yield. BC 10 t ha^{-1} increases the rice yield at about 57% (Zhang & Zaitun, 2012). The addition of BC into the soil has been shown to enhance various aspects of plant roots, including increased root biomass, improved root morphology, elevated concentrations of nutrients in roots, and the promotion of beneficial root-associated microbes (Vanek & Lehmann, 2015; Xiang *et al.*, 2017). Besides, BC effect on rice grain yield has remained inconsistent probably owing to varying quantities of application and raw material used for its preparation, consequently there has been limited adoption of BC as an organic amendment for rice cultivation.

Nonetheless, there is a scarcity of research regarding the influence of BC on soil health, plant growth, yield, and fertilizer use efficiency specifically for boro rice. Aiming to fill this knowledge vacuum, the current study examined how BC affected the characteristics of the soil attribute, yield and the effectiveness of fertilizer application in boro rice (cv. BRRI dhan29).

Material and Method

Location and duration: In the year 2017 the trial was conveyed at the Hajee Mohammad Danesh Science and Technology University research field in Dinajpur, Bangladesh (25°38" N latitude and 88°41" E longitude). The Old Himalayan Piedmont Plain (AEZ-1) is the region's Agro-ecological Zone, according to Anon., (2018), and the trial site is 37.5 meters above sea level.

Weather condition: During the crop growing phase, average values of climatic data for the study site, including temperature, precipitation (mm), and relative humidity (RH %), are illustrated in (Fig. 1; Table 1). The mean monthly maximum temperatures ranged from 27.6 to 34.3°C, with an average of 31.10°C, while the mean monthly minimum temperatures varied between 8.0 and 22.3°C, averaging 15.18°C. Relative humidity ranged from 69% to 79%, and total precipitation was 474 mm averaging 94.8 mm during the normal growth period.

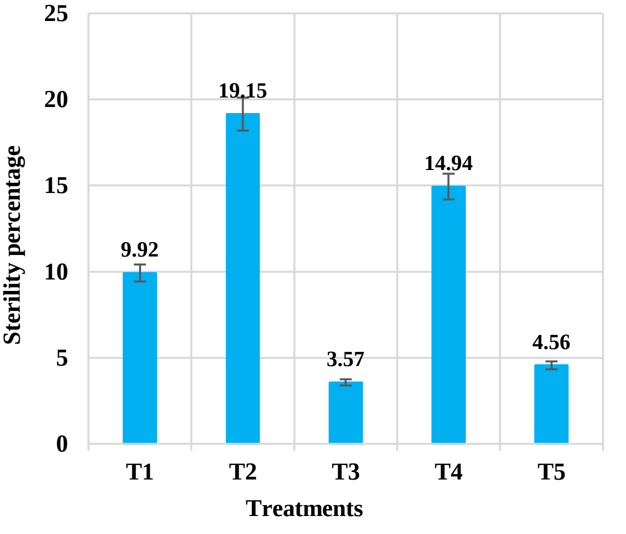

Fig. 1. Shows the effect of BC and inorganic fertilizers on unfilled grain $panicle^{-1}$ vs treatment.

Soil properties: The experimental plot was positioned on medium-high ground with sandy loam texture and a pH of 5.87. The soil composition included 0.91% organic matter, 0.09% total nitrogen (N), 14.60 µg g^{-1} available phosphorus (P), 0. 15 meq $100g^{-1}$ available potassium (K), and 8.60 ppm available sulfur (S) based on the pre-sowing soil tests conducted at 0-15 cm depth. Table 2 gives a thorough summary of the examined soil's characteristics.

Materials used

Plant material: The test crop utilized in this study was BRRI dhan29, selected for its role as the planting material. In 1994, Bangladesh Rice Research Institute (BRRI) developed it specifically for the boro rice season, BRRI dhan29 is recognized as an essential high-yielding variety. With a height ranging from 90 to 100 cm, a robust stem that minimizes lodging, and tolerance to leaf and sheath blight diseases, this variety has demonstrated a grain yield of around 8 t $ha^{-1}$is considered well-adapted to local pedo-climatic conditions.

BC: BC, prepared from rice straw, was collected from commercial farm. BC contains a wide range of materials generally used as soil physical conditioner for improving air flow or dropping the bulk-density of heavy soils. The physio-chemical properties of BC were determined and are existed in (Table 3).

Table 1. Weather data of the experimental location from January to May, 2017.

Months	** Temperature (°C)			*Precipitation (mm)	**Relative humidity (%)
	Minimum	Maximum	Average		
January	8.0	27.6	17.80	5	69.0
February	11.2	30.0	20.60	0	71.0
March	14.0	31.4	22.70	102	72.0
April	20.4	32.2	26.30	192	77.0
May	22.3	34.3	28.30	175	79.0

* = Monthly total, ** = Monthly average, Source: Meteorological Station, HSTU, Dinajpur-5200

Table 2. Physico-chemical properties of pre-sown soil of the experimental field.

Physical attributes		
Properties	**Value (%)**	**Extraction method**
Sand	60.0	-
Silt	27.0	-
Clay	13.0	-
Textural class	Sandy loam	Hydrometer method was employed and textural class was determined by following Marshall's Triangular coordinates as described in the USDA system

Chemical traits			
Properties	**Analytical value**	**Critical value**	**Extraction methods**
pH (1:1.25, Soil: H_2O)	5.87	-	Glass electrode type pH meter method. (soil-water ratio = 1:1.25)
Organic matter (%)	0.91	-	The method of wet oxidation was used and there after Van Bemmelen factor of 1.73 was employed for final calculations.
Total N (%)	0.09	0.08	By employing Micro-Kjeldahl apparatus
Available P (ppm)	14.60	10.00	Olsen method
Exchangeable K (me/100g soil)	0.15	0.12	By using Flame photometer
Available S (ppm)	8.60	10.00	Turbidity method involving the use of $BaCl_2$

Table 3. Composition of employing BC as a research tool.

Properties	Value	Extraction method
pH (1:1.25, Soil: H_2O)	9.87 (1:20)	4500-H^+. B
Organic carbon (%)	22.5	Wet oxidation method.
Total nitrogen (%)	0.028	Micro-Kjeldahl method
Available phosphorous (ppm)	32.48	Olsen method
Exchangeable potassium (meq/100g soil)	11.85	Determined by Flame photometer
Available sulfur (ppm)	168.89	Turbidity method using $BaCl_2$
Ash content (%)	15.2	In-house
Water holding capacity (%)	277	Percolation Method

Experimental treatments and design: The experiment encompassed five distinct treatments, namely i) T_1= Recommended doses of fertilizers (RDF) (N, P, K and S), ii) T_2 = BC 10 t ha^{-1}, iii) T_3 = BC 10 t ha^{-1} + 50% RDF, iv) T_4= BC 7.5 t ha^{-1} + 50% RDF, and v) T_5 = BC 5 t ha^{-1} + 50% RDF. The Randomized Complete Block Design (RCBD) was used in the experimental setup, with four replications. Each plot had a unit size of 2.5m x 2.0m, totaling 5 m^2, and an irrigation channel, 50 cm in width, was constructed around each individual plot.

Experimentation: The BRRI dhan29 seeds were acquired from the Bangladesh Agricultural Development Corporation (BADC) located in Dinajpur, Bangladesh. The selection of viable seeds was meticulously carried out using the specific gravity method, involving immersion in water for 24 hrs. Subsequently, the seeds were extracted and densely packed in a gunny bag. After soaking in water and maintaining a moist condition for 48 hrs to stimulate sprouting. The soil puddling was performed for ensuring the removal of weeds and stubble, and proper leveling of the land. The sprouted seeds were woven using the broadcast method on the wet bed on December 2, 2016. Considerable concern was seized to foster healthy seedlings in the seedbed, involving consistent weeding and irrigation maintenance. The main field plots within each block underwent thorough preparation through plowing, cross plowing with a power tiller, and spading, followed by leveling just before the scheduled transplanting on January 10, 2017. For land preparation, fertilizers such as urea, triple super phosphate (TSP), muriate of potash (MOP), and gypsum were employed at rates of 250, 100, 200, and 50 kg ha^{-1}, respectively. The full doses of TSP, MOP, gypsum, and finely ground BC were incorporated during final land preparation. Urea application was divided into three equal splits, with the first portion was administered at 7 days after transplantation (DAT), the second as top dressing at 30 DAT, and the last doses at 60 DAT during the panicle initiation stage. Carefully uprooted 40-days-old seedlings were then transplanted on January 10, 2017 in such a way that there were three seedlings per hill. Stringent measures were implemented for weeding, water management, and insect and pest control throughout the growth period to ensure optimal crop development. The fully ripened rice was harvested on May 26, 2017.

Data collection

Plant parameters: The data was recorded during the growing period and after harvesting i.e., plant height (cm), number of tillers hill^{-1}, panicle length (cm), number of grains panicle^{-1}, number of filled grains panicle^{-1}, number of unfilled grains panicle^{-1}, weight of 1000 grains (g), grain yield (t ha^{-1}), straw yield (t ha^{-1}) and biological yield (t ha^{-1}), and harvest index (%) (Fageria *et al*., 2009).

Sterility (%): Separate counting of both sterile and filled spikelets was done by using 10 randomly selected panicles, whereas spikelet sterility was acknowledged by following the equation stated by Islam *et al*., (2021).

$$\text{Spikelet sterility (\%)} = \frac{\text{Sterile spikelets panicle}^{-1}}{\text{Total spikelets panicle}^{-1}} \times 100$$

Agronomic Efficiency (AE) of fertilizers: The AE was determined by following the equation suggested by Shah *et al*., (2001).

AE of N = GYNA GYN0/NR

Where,
GYNA = Grain yield (kg ha^{-1}) after fertilizer addition,
GYN0 = Grain yield (kg ha^{-1}) without fertilizer,
NR = Rate of fertilizer addition (kg ha^{-1}).

Soil parameters: At the Department of Soil Science, HSTU, Dinajpur, an in-depth analysis of soil samples extracted from the field both before harvesting and after transplanting was conducted. Various methods were employed to investigate the chemical characteristics of the soil, encompassing the use of the glass electrode pH meter, wet oxidation, Semi micro-kjeldahl, Olsen, ammonium acetate extraction, and $CaCl_2$ extraction. These methods enabled the examination of crucial soil chemical properties, such as pH, organic matter, total nitrogen, available phosphorus, exchangeable potassium, and available sulfur.

Statistical analysis

The data collected underwent analysis of variance (ANOVA) utilizing the RCBD with the assistance of the computer package programs MSTAT-C and SPSS. To assess the differences among the treatment means, the Fisher's Test (FT) was applied (Fisher, 2012), following the methodology outlined by Gomez & Gomez (1984).

Results and Discussion

Plant characteristic

Plant height (cm): The plant height of BRRI dhan29 exhibited variations because of the various treatments applied in the study. The maximum plant height, recorded at 103.0 cm, was noted in treatment T_1. This height was statistically comparable to the plant height in treatment T_3, which exhibited a value of 99.93 cm (Table 4) and the most dwarf (90.80 cm) plants were distinctly observed in treatment T_5. Plant heights was similar with application of BC and half RDF in the treatment T_3 because BC helped to uptake higher amount of nutrients from fertilizers by favoring higher organic matter content in soil (Table 6) which might have prevented leaching losses of N resulting increased vegetative growth and increased plant height. The incorporation of BC into the soil, coupled with a reduction in inorganic fertilizers, resulted in increased levels of soil contains N, P, K, and S (refer to Table 6) that enhanced plant growth and increased plant height. The outcomes correspond with Kim *et al*., (2013), Khan *et al*., (2013, 2018) who reported that BC significantly increased the plant height.

Yield contributing characteristics

Number of tillers hill^{-1}: In terms of number of tillers per hill (NT), treatment T_1 exhibited the highest TN (26.10) that was statistically equivalent to treatment T_3 (25.17) (Table 4). Additionally, T_2 resulted in the lowest NT, (18.43). The studies demonstrated that adding BC to soil reduced the fertilizer requirement by 50% while achieving the same number of tillers (NT) as the control treatment using the full recommended dosage (100% RDF) without BC. Specifically, treatment T_3, which combined 10 tha^{-1} of BC with 50% RDF, resulted in an 18.17% increase in NT compared to T_5, which used 100% RDF and 5 tha^{-1} of BC. The BC applied had notable physio-chemical properties and a high pH, enhancing soil organic matter and nutrient availability, thus likely increasing NT. The effect of BC on NT varied with different BC and fertilizer doses, impacting plant growth and tiller numbers. Consistent findings in various field assessments (Zheng *et al*., 2012; Khan *et al*., 2013; Paiman & Effendy, 2020; Chen *et al*., 2021) indicated that BC conserved more water and reduced nutrient leaching, significantly increasing NT in rice.

Panicle length (cm): The BC greatly lengthened the panicle both with and without inorganic fertilizers of BRRI dhan29. However, the longest PL (24.89 cm) was recorded for T_3 involving BC (10 t ha^{-1}) and 50% RDF which was comparable to 100% RDF while only BC (10 tha^{-1}) without inorganic fertilizers showed the shortest PL (19.46 cm). Liang *et al*., (2016) invent that BC ameliorate PL and increased the number of grains. BC's ability to reduce soil nitrate-nitrogen leaching (Cao *et al*., 2019), boost soil nutrient levels (Amin, 2018; Cong *et al*., 2023), and promote higher plant biomass production (Liu *et al*., 2021) suggests that using BC with RDF improves PL in rice. Liu *et al*., (2016) showed a 10.53% increase in PL with BC application compared to no BC (Kamara *et al*., 2015).

Number of total grains panicle^{-1}: The use of both organic and inorganic fertilizers had a substantial impact on the total number of grains panicle^{-1} (TG) (Table 4). The BC and RDF applied jointly showed higher TG compared to sole BC. The maximum TG (195.40) was found when plants grown with BC (10 t ha^{-1}) along with half of the RDF (T_3), which was statistically equivalent while using the only 100% RDF (T_1). On the other hand, the lowest TG (160.00) was found in the treatment of T_2. The results indicated that addition of BC without chemical fertilizers do not perform better, while BC with chemical fertilizers not only perform better but also reduced the requirement of RDF. Liang *et al*., (2016) additionally documented that BC led to higher TG-induced PL.

Number of filled grains panicle^{-1}: When BC and inorganic fertilizers were applied together, there was a noticeable difference in the quantity of filled grains per panicle (FG) (Table 4). However, the treatment T_3 recorded the highest count of FG (191.1), and this was statistically comparable to the count observed in the treatment T_1 (183.30). Adding BC with 50% conventional fertilization increased FG by 4.26% compared to conventional fertilization alone. The grain setting rate significantly improved with the coupled use of BC and chemical fertilizers (CF1), compared to using only CF or BC alone. The high carbon content in BC enhanced the number of grains and grain yield (Liu *et al*., 2016; Gu *et al*., 2022). Organic carbon, crucial for nutrient and water retention in soil (Wiesmeier *et al*., 2019), in BC (Table 3) likely boosted the grain filling rate by ensuring nutrient and water availability during this stage.

3.2.5 1000-grain weight (g): The 1000-grain weight (TGW) of rice treated with BC and RDF significantly increased compared with the sole BC treated plants. Nevertheless, the treatment T_3, involving BC at 10 t ha^{-1} and 50% RDF, demonstrated the maximum TGW (25.53 g). This TGW was statistically similar (24.17 g) to the conventional fertilization treatment T_1. Conversely, the minimum TGW (21.17 g) was observed in treatment T_2, which incorporated BC at 10 t ha^{-1}. The order of TGW for rice followed the sequence $T_3 > T_1 > T_4 > T_5 > T_2$ among the treatments. Soil organic carbon content affects the soil's capacity to hold on to water and nutrients (Wiesmeier *et al*., 2019), and the availability of water and nutrients during the rice grain filling stage increased the rice grain size, which in turn raised the weight of the 1000 grains. Unlike BC, the combination of organic matter (OM) and inorganic fertilizers remarkably enhanced the weight of 1000-grain of rice (Khatun *et al*., 2018; Islam *et al*., 2021).

Sterility (%): The combination of BC-treated blocks with inorganic fertilizers resulted in a noticeable alteration in the number of sterile grains per panicle. The FG of rice increased when BC was used in conjunction with a lesser amount of inorganic fertilizers. The emptiest grains per panicle were found in Treatment T_2 (19.15), whereas treatment T_3 exhibited the lowest value (3.57). Our results are consistent with Bahera *et al*., (2020), who observed a 42.86% reduction in non-filled grains in rice with the addition of BC. Similarly, Islam *et al*., (2021) reported a significant decrease in rice sterility percentage when cow dung was used as an amendment. Combining organic manure with inorganic fertilizer increased nutrient accumulation (Table 6), leading to improved plant growth and higher numbers of filled grains, consequently reducing sterility percentage.

Crop harvests

Grain yield (t ha^{-1}): A substantial variance in grain yield is highlighted in Table 5. The maximum yield of grain was achieved by treatment T_3, reaching 7.82 t ha^{-1}, which, in terms of statistics, was analogous to the results from treatment T_1 at 7.46 t ha^{-1}. But in contrast, T_2 yielded the minimum grain yield at 4.22 t ha^{-1}, a statistic similarity with T_4 and T_5, which had yields of 6.31 and 5.97 t ha^{-1}, respectively. Zhang & Zaitun (2012) observed a 57% increase in rice yield when utilizing BC at a rate of 10 tha^{-1}. Using BC to enhance low-quality soil has significantly increased rice yield, typically by 16% to 35% (Haefele *et al*., 2011). BC application improves soil physical and chemical properties, fostering an optimal growth environment for rice (Shafie *et al*., 2012). This improvement includes enhancing soil pH, cation exchange capacity (CEC), and organic carbon levels (Lehman *et al*., 2003; Liang *et al*., 2006), thereby ensuring better nutrient availability (Table 6) and leading to improved growth characteristics and higher grain yields (Table 3).

Straw yield (t ha^{-1}): The maximum straw production was achieved in treatment T_2, which consisted of 10 t ha^{-1} of BC mixed with 50% of the authorized amount of fertilizer at 8.76 t ha^{-1}, a statistically similar result to treatment T_1 at 8.72 t ha^{-1}. The lowest straw yield of 6.21 t ha^{-1} was observed in treatment T_2 (Table 5). Adding BC to rice significantly impacted the harvest index, particularly increasing straw yield, as shown by yield component analysis (Liu *et al*., 2016). Augmenting biomass production is suggested as a viable approach to understand compensatory interactions among grain yield components, especially in rice (Huang *et al*., 2013). BC use increased straw yield by 14% (Koyama & Hayashi, 2017) and 13% (Mac Carthy *et al*., 2020).

Biological yield (t ha^{-1}): The biological yield (BY) was greatly affected by the application of BC, whether it was combined with inorganic fertilizers or applied alone. Statistically, treatments T_1 and T_3 were found to be identical, with T_3 having the highest BY at 16.58 t ha^{-1}. Treatment T_2, as per Table 5, exhibited the least BY, measuring 10.43 t ha^{-1}. The use of BC in rice was shown to have the greatest effect on BY, according to yield component analysis (Liu *et al*., 2016). The accession of BC to the soil resulted in the rise in soil permeability, soil water availability, organic carbon, soil pH, available phosphorus, exchangeable potassium, and calcium cation exchange capacity (CEC) ensuring a favorable environment for rice growth and may contribute to increased biomass weight (Masulili *et al*., 2014).

Table 4. Effects of BC and inorganic fertilizers on the yield and yield contributing traits of BRRI dhan29. Values are means of three independent replicates ± standard error.

Treatments	Plant height (cm)	Tillers hill^{-1} (no)	Panicle length (cm)	Number of grains panicle^{-1}	Filled grains panicle^{-1}	1000-grain weight (g)
T_1	103.00a ± 0.03	26.10a ± 0.60	24.75a ± 0.19	192.50a ± 0.60	183.30a ± 0.52	24.17a ± 0.23
T_2	92.33b ± 0.84	18.43c ± 0.30	19.46c ± 0.49	160.00c ± 0.35	141.50c ± 0.35	21.17c ± 0.47
T_3	99.93a ± 0.57	25.17a ± 0.72	24.89a ± 0.26	195.40a ± 0.41	191.10a ± 0.38	25.53a ± 0.49
T_4	92.63b ± 0.67	22.07b ± 0.60	22.22b ± 0.40	167.90b ± 0.97	153.20b ± 0.53	23.83ab ± 0.50
T_5	90.80b ± 0.42	21.30b ± 0.26	23.43ab ± 0.34	162.10b ± 0.49	157.50b ± 0.29	22.00bc ± 0.08
CV (%)	3.13	3.10	4.02	7.72	2.67	3.10

Different letters indicate significant differences among treatments ($P < 0.05$ Fisher's test); T_1= RD of N, P, K and S, T_2 = BC 10 t ha^{-1}, T_3 = BC 10 t ha^{-1} + 50% RD of N, P, K and S, T_4 = BC 7.5 t ha^{-1} + 50% RD of N, P, K and S and T_5 = BC 5 t ha^{-1} + 50% RD of N, P, K and S; CV= Co-efficient of variance; Values are means of three independent replicates ± standard error

Table 5. Effects of BC and inorganic fertilizers about the output of BRRI dhan29.

Treatments	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Biological yield (t ha^{-1})	Harvest index (%)
T1	7.46a ± 0.02	8.72a ± 0.02	16.18ab ± 0.03	46.11a ± 0.03
T2	4.22c ± 0.02	6.21d ± 0.02	10.43e ± 0.02	40.46c ± 0.03
T3	7.82a ± 0.02	8.76a ± 0.03	16.58a ± 0.02	47.17a ± 0.02
T4	6.31b ± 0.02	7.93b ± 0.02	14.24c ± 0.02	44.31b ± 0.02
T5	5.97b ± 0.03	7.61c ± 0.08	13.58d ± 0.02	43.96b ± 0.03
CV (%)	6.47	0.68	1.18	0.11

Different letters indicate significant differences among treatments ($P < 0.05$ Fisher's test); T_1= RD of N, P, K and S, T_2 = BC 10 t ha^{-1}, T_3 = BC 10 t ha^{-1} + 50% RD of N, P, K and S, T_4 = BC 7.5 t ha^{-1} + 50% RD of N, P, K and S and T_5 = BC 5 t ha^{-1} + 50% RD of N, P, K and S; CV= Co-efficient of variance; Values are means of three independent replicates ± standard error

Harvest index (%): The impact of BC and inorganic fertilizers recorded statistically pronounced harvest index (HI). Nevertheless, the treatment T_3 recorded the highest percentage of HI at 47.17%, and the second-highest HI (46.11%) was observed in treatment T_2, with their difference being negligible. Treatment T_2 had the lowest HI of 40.46%. Biochar (BC) application alone has been observed to decrease the HI of rice, as documented by Asai *et al*., (2009) and Karer *et al*., (2013). Combining BC with inorganic fertilizers in rice cultivation significantly impacted the HI, correlating with BY, as evidenced by yield component analysis (Liu *et al*., 2016).

Effects of BC and fertilizers on soil properties

Organic matter (%): Soil characteristics were examined after harvest to determine the effect of BC and inorganic fertilizers (Table 6). The organic matter content in the control treatment T_1 was at its minimum (0.79%), while treatment T_3 exhibited the highest organic matter level (1.69%), representing a substantial 2.14-fold increase. Conversely, treatments T_4 and T_5 showed a lowering in organic matter percentage due to the decreased doses of BC. The utilization of BC can lead to an increase in soil organic matter levels, that's mostly made up of insoluble C compounds (Reed *et al*., 2017). Initially, introducing BC in low organic matter soils may increase native carbon losses, but over time, the priming effect of BC's labile carbon diminishes which stabilize through organo-mineral interactions with BC (Singh & Cowie, 2014). Pandian *et al*., (2016) also reported that the addition of BC resulted in an increase in soil organic matter because of the carbon components that BC delivered, organic matter degradation by microorganisms and root exudates.

Total nitrogen (%): The results of the tests showed significant swings in percent total nitrogen (N). However, the highest percentage of total N 0.19 was found on treatment T_3 which was 1.9-fold higher than the control treatment T_1 (0.10%) and treatment T_2 exhibited the lowest value of 0.05%. The incorporation of BC improves the availability of mineralizable N, namely ammonium (NH_4^+) (Gao *et al*., 2016). According to numerous studies (Jeffery *et al*., 2011; Jones *et al*., 2012; Abbruzzini *et al*., 2019), soil N availability is improved by adding BC, N intake, and crop nitrogen use efficiency. Furthermore, Edwards *et al*., (2018) found that higher quantities of BC promoted nitrification to avail N content.

Available phosphorus (ppm): The variation in soil phosphorus (P) availability was notably distinct among rice fields fertilized with organic and inorganic fertilizers, both individually and in combination. Treatment T_3 exhibited the highest P availability at 18.39 ppm, whereas treatment T_2 recorded the lowest at 11.71 ppm. Baquy *et al*., (2020) observed that an increase in the density of negatively charged surfaces with the incorporation of BC contributed to greater P availability, facilitated by the electrostatic repulsion between soil colloids and various P species ($H_2PO_4^-$, HPO_4^{2-}, and PO_4^{3-}). Additionally, BC increases P availability by preventing its leaching (Madiba *et al*., 2016) and by mineralizing organic P via improved microbial growth (Dume *et al*., 2017). The appliance of BC at a rate of 10 t ha^{-1} resulted in improved soil P availability and absorption, especially in acidic and heavily textured soils characterized by low P content (Tesfaye *et al*., 2021).

Exchangeable potassium (me 100^{-1} g soil): Table 6 indicates a significant influence of integrated organic and inorganic fertilizer treatments on soil exchangeable potassium (K) concentration compared to their individual applications. Among the treatments, T_3, which was implemented with reduced inorganic fertilizer application, exhibited the highest exchangeable K concentration at 0.42 me 100^{-1} g of soil, while T_2, which did not include inorganic fertilizer, showed the lowest K at 0.21 me 100^{-1} g of soil. Interestingly, the control group displayed no alteration in outcomes for T_4 or T_5 treatments, despite the use of less BC. Biochar stimulates soil microbes and plant life, influencing soil K availability for exchange (Limwikran *et al.*, 2018). Oram *et al*., (2014) and Singh *et al*., (2019) exhibited that BC added to inorganic K fertilizers increases soil K availability and stimulates bacterial growth in alfisols and entisols.

Available sulphur (ppm): Soil organic and inorganic amendments were shown to significantly alter the available sulfur (S) content. However, the most notable amount of available S was seen in treatment T_3 at 13.61 ppm, whereas the lowest concentration was found in treatment T_2 at 10.02 ppm. Soil containing BC increases the concentration of multiple trace elements, which are at relatively low amounts in BC (Rondon *et al*., 2007), but are especially important for these autotrophic species which enhances photosynthesis efficiency and leads to a rise in yield (Suman *et al*., 2018). Based on the findings of Liang *et al*., (2016), who cited previous research by Glaser *et al*., (2002), Lehmann & Rondon (2006), Yamato *et al*., (2006), and Khan *et al*., (2014), it was found that BC with finer particle sizes had an increased S content, which improved soil enzyme activity, chemical properties of soil (including the presence and holding of nutrients), soil physical properties, and biological properties (such as S reducing bacteria).

Agronomic efficiency: Agronomic efficiency (AE) is an important metric that evaluates the impact of each input relative to the output produced. The increase in yield relative to the control group for each unit of input, in this case fertilizers, is used to determine this yield-dependent metric. The maximum amount of grain yield was found on treatment T_3 (28.80 kg, 72.00 kg, 36.00 kg and 72.00 kg, respectively (Table 7) with the application of per kg urea, TSP, MOP and gypsum which is 2.2, and 1.1-fold superior than the control treatment T_1 (12.96 kg, 32.40 kg, 16.20 kg and 64.80 kg grain per kg urea TSP, MOP and gypsum, respectively). The BC application effectively increased the N use efficiency by rising the nitrate carrying capacity of the soil, whereas it suppressed the nitrate reductase activity along with denitrification fluxes and leaching (Cao *et al*., 2019; Liu *et al*., 2021; Cong *et al*., 2023).

Correlation analysis among the studied traits: Positive strong and weak association was found among the studies traits (Fig. 2). However, the PH showed significant positive (p=0.05) correlation only with NGPP, and rest of the characters exhibited positive non-significant relationship from each other's. The NGPP showed significant positive relationship with the FGPP, TPH, TGW, GY, BY, and non-significant relationship with the SY, HI and PL. The FGPP characteristic was positively correlated with almost all of the measures (p=0.05), with the exception of the TGW. Except PH, the TPH showed significantly positive association with rest of the parameters. There was a like pattern seen with GY and BY. The SY found significant positive association with majority of the traits except PH and NGPP. Same result was also recorded for HI. All of the analyzed features, with the exception of PH, NGPP, and TGW, showed a strong positive association with the PL. Positive association of two traits indicated that there was no threat to decreasing certain level of one trait when increased another trait, and elimination for one trait will automatically be well enough for the other (Islam *et al*., 2019; Islam *et al*., 2021; Islam *et al*., 2021b; Islam *et al*., 2023; Sayed *et al*., 2024).

Table 6. **Effects of BC and inorganic fertilizers on soil properties.**

Treatments	Organic matter content (%)	Total nitrogen (%)	Available phosphorous (ppm)	Exchangeable potassium (me 100^{-1} g soil)	Available Sulfer (ppm)
T_1	0.79e ± 0.02	0.10b ± 0.02	14.48c ± 0.09	0.31c ± 0.02	13.35b ± 0.002
T_2	0.93d ± 0.02	0.05c ± 0.01	11.71e ± 0.01	0.21d ± 0.00	10.02e ± 0.001
T_3	1.69a ± 0.01	0.19a ± 0.02	18.39a ± 0.01	0.42a ± 0.01	13.61a ± 0.002
T_4	1.23b ± 0.03	0.10b ± 0.02	14.8b ± 0.02	0.33bc ± 0.01	12.88c ± 0.002
T_5	1.05c ± 0.02	0.10b ± 0.02	13.71d ± 0.02	0.33bc ± 0.02	12.33d ± 0.001
CV (%)	3.36	23.65	0.43	5.29	0.03

Different letters indicate significant differences among treatments (P < 0.05 Fisher's test); T_1= RD of N, P, K and S, T_2 = BC 10 t ha^{-1}, T_3 = BC 10 t ha^{-1} + 50% RD of N, P, K and S, T_4 = BC 7.5 t ha^{-1} + 50% RD of N, P, K and S and T_5 = BC 5 t ha^{-1} + 50% RD of N, P, K and S; CV= Co-efficient of variance; Values are means of three independent replicates ± standard error

Table 7. Agronomic efficiency/nutrient use efficiency of NPKS fertilizers under BC amendent rice.

Treatments	GYNA (Kg ha^{-1})	GYNO (Kg ha^{-1})	NR (Kg ha^{-1})				AE of fertilizer (Kg grain per kg applied fertilizers)			
			Urea	TSP	MOP	Gypsum	Urea	TSP	MOP	Gypsum
T1	7460		250	100	200	50	12.96d	32.40d	16.20d	64.80 b
T2	4220	4220	0	0	0	0	0.0e	0.0e	0.0e	0.0e
T3	7820		125	50	100	50	28.80a	72.00a	36.00a	72.00 a
T4	6310		125	50	100	50	16.72b	41.80b	20.90b	41.80 c
T5	5970		125	50	100	50	14.00c	35.00c	17.50c	35.00 d
CV%							**1.47**	**1.52**	**1.56**	**0.85**

GYNA= Grain yield with the addition of fertilizer, GYN0= Grain yield without fertilizer, NR= rate of fertilizer addition (kg ha^{-1})

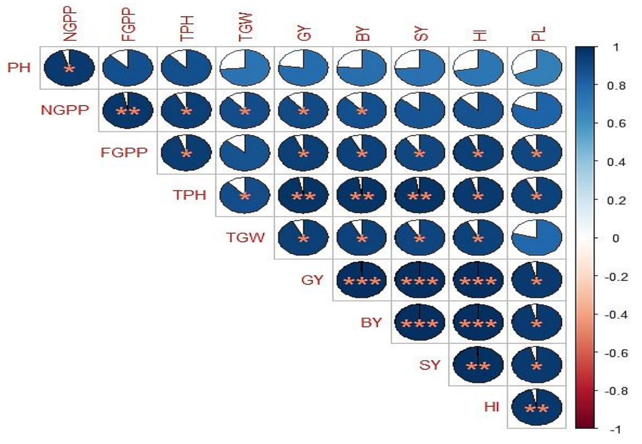

Fig. 2. Correlation co-efficient of yield components traits with grain yield of rice induced BC (PH= Plant height; TPH= Tillers hill^{-1}; PL= Panicle length; NGPP= Number of grains panicle^{-1}; FGPP= Filled grains panicle^{-1}; TGW=1000-grain weight; SY= Straw yield; BY= Biological yield ; HI= Harvest index; GY= Grain yield; *= Significant at p=0.05; **= Significant at p=0.01; ***= Significant at p=0.001).

Conclusion

The findings of trial remained in line with the research hypothesis as different doses of biochar applied solely and in conjunction with reduced doses of fertilizers had varying effects on yield characteristics and yield of rice. These findings confirm that addition of biochar could be developed as a biologically viable strategy to diminish the use of chemical fertilizers and that too with reduction in the grain outcome of rice. From the recorded findings, we can recommend that rice growers in the region could utilize 10 tha^{-1} biochar + half of recommended doses of N, P, K and S to attain the similar yield as that of conventional system. Moreover, this strategy had not only the efficiency to minimize the use of synthetic fertilizers but also can be developed as a potent farming practice to restrict the use of greenhouse gases emission from paddy fields.

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