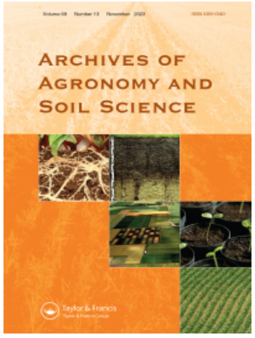

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Biochar and nitrogen fertilizer application increased yield and economic benefits in no-till lowland rice production system

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ABSTRACT

Biochar and nitrogen (N) fertilizer application have been shown to increase rice yield in conventional rice production system. However, studies evaluating the responses of rice yield and farmers' incomes to biochar and N fertilizer application under no-tillage are rare. A two-year field study was conducted to assess the agronomic and economic effects of integrating biochar and N fertilizer to no-till rainfed lowland rice production system in Cote d'Ivoire. The treatments were factorial combination of two biochar rates (3 and 6 t ha^{-1}) and three N fertilizer rates (0, 60 and 120 kg N ha^{-1}) under no-tillage (T0), and a control (i.e. the farmers' practice of manual tillage with hoe and N fertilizer at 120 kg N ha^{-1}). The results indicated that biochar and N fertilizer application under no-tillage significantly ($p < 0.05$) increased rice yield and labour productivity by 6 – 9% and 2 – 45%, respectively, over the control. The highest partial productivity of N (113%) was observed under no-tillage with biochar at 6 t ha^{-1} and N at 60 kg N ha^{-1}, which reduced the production cost by 22% and increased the benefit by 224% relative to the control. Additionally, the soil properties improved significantly ($p < 0.05$) under biochar and N fertilizer application without tillage.

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Biochar; nitrogen fertilizer; rainfed lowland; rice yield; benefit–cost analysis

Introduction

Rice is an important food crop for many people around the world (Prasad et al. 2017; Rodenburg and Saito 2022). In Africa, it is the third-largest food source for the population (Gorfer et al. 2022) and serves as a source of income for about 35 million farmers (Ndjiondjop et al. 2023). West Africa, which accounts for over 40% of the total rice output in Africa, is the continent's leading rice producer (Niang et al. 2017). However, rice production in the region is concentrated in lowland ecosystems (Rakotoson et al. 2022) and dominated by smallholder farmers with low access to machinery (Katic et al. 2013).

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This challenge together with poor soil fertility (Rakotoson et al. 2022), and sub-optimal nitrogen (N) fertilizer application by farmers due to the high cost of chemical fertilizers (Tsujimoto et al. 2019) have resulted in low rice yield. The average paddy yield in Côte d'Ivoire is about 2.4 t ha^{-1} and below the global average, which was estimated at 4.7 t ha^{-1} in 2020 (Dossou-Yovo et al. 2020).

Consequently, the resource poor farmers in most African countries including Côte d'Ivoire often relied on organic manure and limited inorganic fertilizer application to meet crop nutrient requirement and enhance yield (Oladele et al. 2019; Phares and Akaba 2022). However, due to high temperature and rainfall in the tropics, the applied organic materials often fail to achieve any significant increase in crop yield as they readily undergo rapid decomposition, while N is easily volatilized or leached out of the root zone (Oladele et al. 2019a). In addition, organic materials are inherently low in nutrient contents and thus are required to be applied in large quantities to enhance crop yield (FAO and International Fertilizer Industry Association [IFIA], 2000; Phares and Akaba 2022). But, the application of organic materials in large quantities increases the farmers' cost of production (Phares and Akaba 2022) as well as leads to N immobilization and accumulation of heavy metals in the soil (Chen 2006). Therefore, alternative nutrient management strategies are urgently needed to enhance both farmers' income and improve rice yield to meet the growing rice demand in West Africa.

The conversion of organic materials to biochar and its application to the soil have been suggested as a good strategy to improve crop yield in the tropics (Jeffery et al. 2011; Adekiya et al. 2019; MacCarthy et al. 2020). Biochar is characterized by recalcitrant carbon and large surface area (Lehmann et al. 2011) and possesses the key advantage of decelerating organic carbon decomposition (Mukome and Parikh 2016). In addition, soil amendment with biochar is credited with other multiple benefits including N retention and increase in N use efficiency (Kang et al. 2021). Biochar has equally been shown to reduce farmers' N demand and its associated cost and as such increased return on investment (MacCarthy et al. 2020). Previous studies in Nigeria (Oladele et al. 2019b), Ghana (Danso et al. 2023) and other parts of the world (Xu et al. 2021) have all demonstrated that biochar application with N enhanced rice yield. Albeit, contrasting results such as no effects (Xie et al. 2013; Liu et al. 2019b) or decrease in rice morphological parameters have also been found (Yin et al. 2020). These contradictions merit further investigation to properly document the overall impact of biochar and N application on rice yield, particularly in Africa.

Moreover, most of the previous studies (Isimikalu et al. 2023; Oladele et al. 2019a, 2019b; Remigius et al. 2022) on biochar and N have been conducted under tilled system and focused on agronomic benefits, with little or no consideration for cost analysis. In instances where costs were considered, the recommended biochar rates to achieve profitability were usually high and unattainable (MacCarthy et al. 2020; Sun et al. 2020; Danso et al. 2023). This point has been emphasized by Baveye (2023) who noted that biochar use for crop production may be economically unviable if the rate of application is high. Therefore, a lower biochar application rate under climate smart technique such as no-tillage may be more suitable to smallholder farmers.

No-tillage system has been reported to reduce labour and water requirements, improve crop yield (Huang et al. 2018), mitigate greenhouse gases emissions (Dossou-Yovo et al. 2016a, 2016b; Maucieri et al. 2021) and increase carbon sequestration (Rahman et al. 2021; Smith and Chalk 2020), which are essential to sustainable rice cultivation.

Nonetheless, contrasting effects of no-tillage on rice yield across various studies have been reported (Zhang et al. 2016; Chen et al. 2021). On the one hand, no-tillage was reported to enhance soil structure, moisture retention and organic matter content, leading to improved yields (Huang et al. 2018; Nath et al. 2024). But on the other hand, studies have found yield reductions under no-tillage due to issues such as increased weed pressure (Singh et al. 2011), slower nutrient cycling, reduced soil aeration (Chakraborty et al. 2017) and mechanical impedance to root development (Iijima et al. 2007). These mixed outcomes suggest that the effectiveness of no-tillage on rice yield is influenced by site-specific factors such as soil type, climate and management practices, highlighting the need for tailored approaches to optimize its benefits. Therefore, the present study aimed to assess the agronomic and economic benefits of integrating biochar at low rate with nitrogen (N) fertilizer and no-tillage into the rainfed lowland rice production system.

Materials and methods

Study location

The study was conducted at the Africa Rice Centre (AfricaRice) research field at M'bé, Bouaké (7°52′10.69″ N, 5°6′57.51″ W and 298 m above sea level), Côte d'Ivoire during the 2021 and 2022 rainy seasons (August – December). The area has a tropical climate and bi-modal rainfall with a long dry period in between (Dossou-Yovo and Saito 2021). The average temperature and cumulative rainfall during the study period and for the period 2015–2022 were presented in Table 1.

The soil is derived from the weathered granite and metamorphic rocks (Hakkeling et al. 1989) and is classified as sandy clay loam Inceptisol (Saito et al. 2019). Prior to the start of the experiment, the soil was under a one-year fallow. At the start of the experiment, the soil was cleared, sampled (0–20 cm) and analysed at the AfricaRice soil science laboratory. The general properties of the soil are shown in Table 2.

The biochar used for the experiment was sourced from the rice millers in Bouake, Cote d'Ivoire, and was produced from rice husk at a temperature of 350°C to 400°C. The rice millers use the AfricaRice's modified Paul Olivier's gasifier for rice parboiling with rice husk and biochar as feedstock and by-product, respectively (Ndindeng et al. 2019). The basic properties of the biochar are presented in Table 2.

Table 1. Means of the daily values of temperatures, solar radiation and cumulative daily rainfall during the study in 2021 and 2022, compared to 2015–2022 averages at mbe, Bouake, Côte d'Ivoire.

Year/Month	August	September	October	November	December
Minimum temperature 2021 (°C)	21.01	21.23	21.21	20.26	16.13
Maximum temperature 2021 (°C)	28.43	29.54	30.91	32.31	32.61
Solar radiation 2021 (kJ m^{-2})	9787.81	10869.42	12168.92	12667.18	11799.08
Minimum temperature 2022 (°C)	20.46	20.81	20.93	17.23	15.83
Maximum temperature 2022 (°C)	27.90	28.88	29.84	31.53	31.15
Solar radiation 2022 (kJ m^{-2})	8436.03	9447. 74	11183.11	11714.19	10852.46
Minimum temperature 2014–2022 (°C)	19.91	19.83	19.94	19.94	19.83
Maximum temperature 2014–2022 (°C)	31.36	31.46	31.45	31.42	31.41
Solar radiation 2014–2022 (kJ m^{-2})	13730.92	13713.44	13976.36	13942.86	13910.64
Rainfall 2021 (mm)	152.83	135.2	76.05	40.21	21.03
Rainfall 2022 (mm)	279.66	184.01	264.84	49.46	53.47
Average rainfall 2014–2022 (mm)	168.97	173.74	160.13	47.85	11.74

Table 2. Biochar and initial soil properties (0–20 cm) at the onset of the study in 2021.

Properties	Biochar	Soil
pH-H_2O (1/2.5)	9.64	5.98
P. Bray1 (mg kg^{-1})	35.08	3.58
OC (%)	37.80	2.80
Total N (g kg^{-1})	3.17	2.73
CEC ($cmol^{+}$ kg^{-1})	0.03	0.02
K-Total (g kg^{-1})	7.07	0.23
Bulk density (g cm^{-3})	–	1.52
Mg-Total (g kg^{-1})	3.16	1.05

Note: OC: organic carbon, CEC: cation exchange capacity.

Table 3. Treatments evaluated in the study during the 2021 and 2022 rice growing seasons at M'bé Bouake, Côte d'Ivoire.

No	Treatments	Treatment components
1	T1N2	Farmers' practice of manual tillage with hoe (T1) and 120 kg N ha^{-1} (N2)
2	T0B1N0	No-tillage (T0) without nitrogen fertilizer (N0) + B1 (3 t ha^{-1} biochar)
3	T0B1N1	No-tillage (T0) + B1 (3 t ha^{-1} biochar) + 60 kg N ha^{-1} (N1)
4	T0B1N2	No-tillage (T0) + 3 t ha^{-1} biochar (B1) + 120 kg N ha^{-1} (N2)
5	T0B2N0	No-tillage (T0) without nitrogen fertilizer (N0) + B2 (6 t ha^{-1} biochar)
6	T0B2N1	No-tillage (T0) + B2 (6 t ha^{-1} biochar) + 60 kg N ha^{-1} (N1)
7	T0B2N2	No-tillage (T0) + 6 t ha^{-1} biochar (B2) + 120 kg N ha^{-1} (N2)

Experimental design and treatment application

The experimental design for the study was a Randomized Complete Block Design (RCBD) with three replications (Table 3). Each replicates plot measured 5 m × 5 m and was separated by earthen buffer bunds to prevent the exchange of materials between plots. The treatments were the conventional farmers' practices in Cote d' Ivoire (manual tillage with hoe and N fertilizer application at 120 kg N ha^{-1}; T1N2) as the control, and six other treatments consisting of factorial combination of two biochar rates (3 and 6 t ha^{-1} referred to as B1 and B2, respectively), and three nitrogen (N) fertilizer rates (0, 60 and 120 kg N ha^{-1} referred to as N0, N1 and N2, respectively) under no-tillage (T0) (Table 3).

Crop management

For the plots receiving biochar as treatment, the biochar was applied uniformly to the surface and gently tapped using a light-weighted locally fabricated wooden material to ensure a good contact between the biochar and the soil surface. A day after biochar application (i.e. 27 August 2021 and 19 September 2022 representing the start of the 2021 and 2022 trials respectively), the pre-germinated popular rice variety in Côte d'Ivoire, WITA9 was sown manually with dibbling sticks at a planting distance of 20 cm × 20 cm, and a plant density of three seeds per hill. Ten Days After Seeding (DAS), the seedlings were thinned to two seedlings per hill.

Nitrogen (N) fertilizer was applied in three splits (50%: 25% and 25%) for plots receiving N fertilizer. The basal N was applied 13 DAS, while the first and second top-dressing fertilizers were, respectively, applied 33 and 63 DAS, using urea. All treatments received equal amounts of phosphorus (P) and potassium (K) at 60 kg K ha^{-1} and 60 kg P ha^{-1} 13 DAS in the forms of triple super phosphate (40% P_2O_5) and muriate of potash (60% K_2O), respectively.

Weeding was done by hand at the early stage of rice growth (30 DAS), while at the later stage when rice roots were well established (55 DAS), a mixture of two selective herbicides; garil power (fluroxylpyr-methyl 230.73 g l^{-1} + cyhalofop-butyl 184.3 g l^{-1}) and herbextra (2, 4-dichlorophenoxyacetic acid-50.53 % w w^{-1}) (1 l ha^{-1}) were used for weed management. Similarly, handpicking and 'vrai lambda 50 EC' (cyhalothrine (50 g l^{-1})) (50 ml mixed with 12 l of water) insecticide were used for insect control at 24 DAS in both years.

Rice morphological and yield data collection

Data on rice morphological traits (plant height, number of tillers and straw biomass), and yields at harvest were collected in 2021 and 2022. A destructive sampling technique was used, and a total of three sampling events at 30 (tillering stage), 60 (heading stage) and 90 (maturity stage) DAS were conducted. At each sampling event, 25 rice hills were marked in an area of 1 m^2 (1 m × 1 m) per plot after leaving out the first two rows to avoid biased results due to border effect. The number of tillers in each of the marked hills was counted, and the height was taken by placing a 100-cm meter rule vertically beside the base of the hill and reading off the value. Thereafter, the hills were uprooted, washed in flowing water and separated into aboveground and below ground parts. The aboveground biomass was oven-dried at 65°C for 48 h to a constant weight and used to determine straw biomass weight.

The rice plants were harvested in late December 2021 and early January 2023 for the first- and second-year trials, respectively, to determine yield. Yield was determined in two replicates per plot from an area measuring 2 m × 2 m (4 m^2) and adjusted to 14% moisture content.

Determination of soil properties

At the end of the 2 years of the experiment, the soil samples were collected (0–20 cm) using soil auger. The collected samples were air-dried and sieved with a 2 mm sieve for further chemical analysis. The standard laboratory procedures were used to determine the soil pH, soil organic carbon (SOC) and soil total nitrogen as well as soil phosphorus and potassium. Additionally, in each year, the soil moisture and temperature for the 5 cm soil depth were measured using a hand-held moisture probe (ML2×-KIT, Delta-T Devices Ltd., Cambridge).

Partial productivity of nitrogen and economic analysis

The partial productivity of nitrogen was calculated as the ratio of yield to the quantity of nitrogen (N) fertilizer applied. The cost of production was estimated for all the treatments by assigning monetary costs to farm operations including field clearance, tillage, rice seeds, seeding, weeding, harvesting, packing and threshing as well as the costs of the applications of biochar, N fertilizer, herbicide and insecticide. Additionally, the costs of herbicide, insecticide, N fertilizers and biochar used for the experiment were also added to the production cost. On the other hand, labour input was calculated as the total number of labours required (labour ha^{-1}) for field clearance, tillage, rice seeding, weeding, treatments and chemical applications, harvesting, packing and threshing, while labour productivity was calculated as the ratio of yield to the labour input (kg of yield labour^{-1}). The local current man-hour rate 4.55 United States Dollar (USD) ($) was used for the estimation of cost of labour for each of the field activities. The sum of all the costs incurred under a given treatment constituted the total cost of production for that treatment.

For both years, the gross revenue was estimated as the product of the price of WITA 9 rice (~0.263 and 0.280 kg^{-1} in 2021 and 2023, respectively) and yield, while benefit was calculated by subtracting the treatment's total cost of production from its gross revenue. All costs and benefits were converted to their dollar equivalents using the OANDA exchange (www.oanda.com/currency-converter) rate of 607.8 West African France CFA/ 1 USD ($). The benefit–cost ratio was estimated as the ratio between the treatment benefit and its cost of production. Detailed information relating to the cost of individual production activity, benefits and benefit cost ratio have been provided in the supplementary Excel sheet (Table S1).

Statistical analyses

All data analyses were performed using R statistical software 4.2.1 (R Core Team, 2023). The rice plant height, number of tillers, straw biomass, yield, partial N use efficiency, labour input, labour productivity, total cost of production, benefits and benefit–cost ratio were analysed using a two-way analysis of variance (ANOVA) with treatments and year as the two factors. Where $p < 0.05$ was significant, the means were separated with Tukey Honest Significant Difference (HSD) ($p < 0.05$).

Results

Rice growth, yield and partial productivity of nitrogen

Biochar and nitrogen (N) fertilizer application under no-tillage significantly ($p < 0.05$) promoted plant height across the three growth stages (tillering, heading and maturity), with no significant interaction between treatment and year (Table 4). Biochar application at 6 t ha^{-1} with N fertilizer at 120 kg N ha^{-1} under no-tillage (T0B2N2) consistently produced the tallest rice plants among the treatments regardless of the rice growth stage (Table 5). In contrast, biochar at 3 t ha^{-1} applied with N fertilizer at 120 kg N ha^{-1} under no-tillage (T0B1N2) produced the shortest plant at the tillering stage. While at the heading and maturity stages, the shortest rice plants were found in sole biochar application of 3 t ha^{-1} without tillage (T0B1N0) (Table 5). Compared to T1N2, T0B2N2 increased the rice plant heights by approximately 1%, 3% and 2% at the tillering, heading and maturity stages, respectively (Table 5). Increasing N fertilizer rate at constant biochar rate or vice versa did not result in a linear increase or decrease in the mean plant height at any of the rice growth stages.

Similarly, the number of rice tillers measured across the three growth stages varied significantly ($p < 0.05$) among treatments, but not the interaction between treatment and year (Table 4). At the tillering stage, the highest mean number of rice tillers (310.8 tillers m^{-2}) was observed in the treatment combining biochar at 3 t ha^{-1} and N fertilizer at 120 kg N ha^{-1} without tillage (T0B1N2), while the lowest mean number of rice tillers

Table 4. F and p-values from the analysis of variance for rice plant height (cm), number of tillers (tiller m^{-2}) and straw biomass (g m^{-2}) at the tillering, heading and maturity stages during the 2021 and 2022 rice growing seasons at mbe, Bouake, Côte d'Ivoire.

Variables	Df	Plant height (c)						Number of tillers (tiller m^{-2})						Straw biomass (g m^{-2})					
		Tillering		Heading		Maturity		Tillering		Heading		Maturity		Tillering		Heading		Maturity	
Yr (Y)	1.00	2.20	ns	2.30	ns	13.54	**	6.86	*	3.49	ns	8.90	**	80.20	***	9.80	**	37.46	***
Trts (T)	6.00	2.97	*	15.44	***	10.01	***	2.96	*	5.92	***	12.82	***	1.312	ns	7.57	***	6.22	***
Y × T	6.00	0.00	ns	0.94	ns	0.67	ns	1.12	ns	0.71	ns	1.57	ns	1.32	ns	1.95	ns	1.19	ns

Note: Yr: Year, Trt: Treatments and Df: Degree of freedom. F and P: are the F-statistic value and probability level respectively. '*', '**', '***', and 'ns' indicate significant difference at $p < 0.05$, $p < 0.01$, $p < 0.001$ and no significance, respectively.

Table 5. F and p-values from the analysis of variance for rice grain yield (t ha^{-1}), partial productivity of nitrogen (PPN) (kg kg^{-1}), labour input (labour ha^{-1}), labour productivity (kg grain labour^{-1}), production cost (USD ha^{-1}), benefit (USD ha^{-1}), benefit–cost ratio during the 2021 and 2022 rice growing seasons at mbe, Bouake, Côte d'Ivoire.

		Yield		PPN		Labour input		Labour productivity		Production cost		Benefit		Benefit–cost ratio	
Variables	Df	F	P	F	P	F	P	F	P	F	P	F	P	F	P
Yr (Y)	1.00	3.53	ns	1.37	ns	3.60	ns	2.79	ns	301.94	***	2.48	ns	0.08	ns
Trts (T)	6.00	17.28	***	60.77	***	98.39	***	26.52	***	265.50	***	8.80	***	8.09	***
Y × T	6.00	1.19	ns	0.98	ns	1.09	ns	0.87	ns	14.95	***	0.75	ns	1.04	ns

Note: Yr: Year, Trt: Treatments and Df: Degree of freedom. F and P: are the F-statistic value and probability level respectively. '*', '**', '***', and 'ns' indicate significant difference at $p < 0.05$, $p < 0.01$, $p < 0.001$ and no significance, respectively.

(185.2 tillers m^{-2}) was found under sole biochar application at 6 t ha^{-1} with no-tillage (T0B2N0). The general trend indicated that the mean number of rice tillers were broadly similar among treatments that received the same rates of N fertilizer regardless of the tillage condition. Also, treatments with N fertilizer promoted tillering compared to the treatments without N irrespective of the tillage condition (Table 5). Apart from T0B1N2, which increased the average number of rice tillers by 6%, all other treatments decreased the mean number of rice tillers at the tillering stage relative to T1N2. Furthermore, at the heading stage, only T0B1N2 promoted (12%) rice tillers more than T1N2 while at the maturity stage, T1N2 produced the highest mean number of tillers (536.2 tillers m^{-2}) among treatments. Also, significantly ($p < 0.05$) higher mean number of rice tillers were found in 2022 than in 2021 at the tillering and maturity stages (Table 5).

Rice straw biomass varied significantly ($p < 0.05$) across treatments at the heading and maturity stages but not at the tillering stage (Table 4). At the heading stage, the highest and lowest straw biomasses were found in T0B1N2 and T0B2N0, respectively. While at the maturity stage, T0B1N2 and T0B2N2 produced the largest straw biomass, which were, respectively, 24% and 11% higher than T1N2 (Table 6). Meanwhile, no significant interactions between treatment and year were found across the rice growth stages, but consistently higher rice straw biomasses were observed in 2022 compared to 2021, regardless of the growth stage (Table 5).

Average of the 2-years data showed that treatment significantly ($p < 0.05$) affected both rice yield and partial productivity of N (PPN), but no interactive effects of treatment and year on either yield or PPN were found (Table 8). Co-applying biochar and N fertilizer generally enhanced rice yield and PPN over the sole biochar application, with T0B2N1 recording the highest yield and PPN across treatments (Table 5). Compared to T1N2, rice yield and PPN increased by 6 – 9% and 5 – 113% under biochar and N fertilizer application with no-tillage T1N2 (Table 5).

Effects of biochar and N fertilizer application on selected soil properties

The soil moisture contents for the 5 cm soil depth in each treatment were collected during the rice growing season in 2021 and 2022. The result of the analysis showed significant ($p < 0.05$) treatment and year effects, but the interaction between treatment and year was not significant (Table 6). Overall, the mean soil moisture content ranged from 57% in T0B1N1 to 61% under T0B2N2. Under no-tillage, and the same N fertilizer rate, biochar application at 6 t ha^{-1} enhanced the soil moisture content than biochar at 3 t ha^{-1} (Table 7).

Furthermore, the analysis of the mean soil temperature revealed significant ($p < 0.05$) interactive effects of treatment and year (Table 6). In 2021, the soil temperature ranged from 26°C to 27°C with the co-application of biochar and N fertilizer under no-tillage generally enhancing soil temperature compared to T1N2 (Figure 1). However, no particular order in the mean soil temperature was observed as either biochar or N fertilizer rate was increased. The highest increases of 3% and 4% in the mean soil temperature relative to T1N2 were found in 2021 under T0B2N1 and T0B1N2, respectively. Similarly, in 2022, T0B2N1 and T0B1N2 increased the mean soil temperature by 2% and 1%, respectively, compared to T1N2 (Figure 1).

Table 6. F and p-values from the analysis of variance for soil moisture, soil temperature, pH, soil organic carbon (SOC), soil total nitrogen (TN), soil phosphorus and soil potassium during the 2021 and 2022 rice growing seasons at mbe, Bouake, Côte d'Ivoire.

		Soil moisture		Soil temperature		Ph		SOC		TN		P		K	
Variables	Df	F	P	F	P	F	P	F	P	F	P	F	P	F	P
Yr (Y)	1.00	159.29	***	166.13	***	—	—	—	—	—	—	—	—	—	—
Trts (T)	6.00	3.88	**	3.82	**	3.96	*	3.06	*	5.73	**	0.29	ns	0.75	ns
Y × T	6.00	0.70	ns	3.03	*	—	—	—	—	—	—	—	—	—	—

Note: Yr: Year, Trt: Treatments and Df: Degree of freedom. F and P: are the F-statistic value and probability level respectively. '*', '**', '***' and 'ns' indicate significant difference at $p < 0.05$, $p < 0.01$, $p < 0.001$ and no significance, respectively.

Table 7. Treatments and year effects on rice morphological traits (plant height, number of tillers and straw biomass at the rice tillering, heading and maturity stages), yield and partial productivity of nitrogen (PPN) during the 2021 and 2022 rice growing seasons at mbe, Bouake, Côte d'Ivoire.

	Plant height (cm)			Number of tillers (tiller m^{-2})			Straw biomass (g m^{-2})			Yield (t ha^{-1})	PPN (kg kg^{-1})
Variables	Tillering	Heading	Maturity	Tillering	Heading	Maturity	Tillering	Heading	Maturity		
Years											
2021	34.26a	73.15a	94.61b	209.11b	304.63b	395.26b	1.38b	284.91b	549.46b	4.86a	61.48a
2022	35.78a	71.19a	99.03a	269.49a	331.05a	450.78a	3.27a	343.62a	833.18a	5.17a	64.53a
Treatments											
T0B1N0	33.92ab	60.74d	89.76b	194.81c	274.04 cd	277.75d	1.92a	214.95b	553.58c	3.63c	—
T0B1N1	35.83a	68.62c	96.91a	214.35bc	323.81bc	422.36c	1.93a	303.76a	616.81bc	4.97ab	81.11b
T0B1N2	31.05b	73.06ab	99.71a	310.80a	385.54a	499.83ab	2.56a	374.28a	908.56a	5.61a	46.74c
T0B2N0	33.82ab	61.63d	89.94b	185.26c	246.81d	347.04d	2.53a	225.07b	470.52c	4.01bc	—
T0B2N1	33.8ab	70.41bc	97.72a	201.57c	327.34bc	453.81bc	1.88a	361.03a	736.92ab	5.70a	94.51a
T0B2N2	37.63a	74.97a	100.61a	271.05abc	323.53bc	423.76c	2.54a	359.43a	817.76a	5.82a	48.37c
T1N2	37.26a	71.93abc	98.36a	297.24ab	343.59ab	536.20a	2.53a	361.76a	734.92ab	5.30a	44.31c

Note: N0: no N fertilizer, N1: N fertilizer at 60 kg N ha^{-1} and N2: N fertilizer at 120 kg N ha^{-1}, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T1: manual tillage with hoe. Means with different letters under the same column are significantly different ($p < 0.05$, Tukey HSD test).

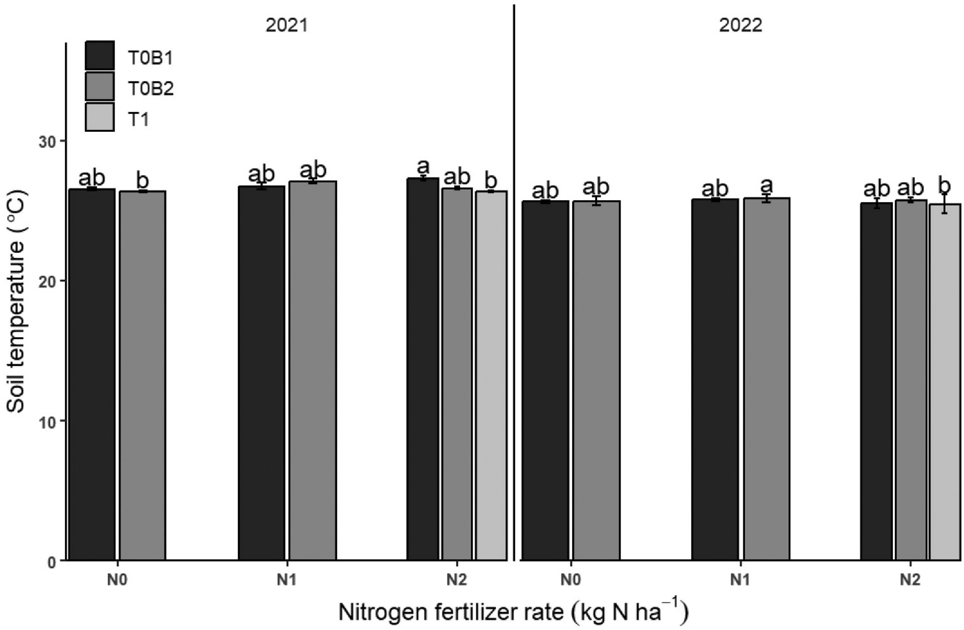

Figure 1. Variation of the mean soil temperature under different treatment application. N0: no N fertilizer, N1: N fertilizer at 60 kg N ha^{-1} and N2: N fertilizer at 120 kg N ha^{-1}, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T1: manual tillage with hoe. Bars with different letters are significantly different ($p < 0.05$, TukeyHSD test).

Table 6 indicated that at the end of the experiment, biochar and N application under no-tillage significantly affected soil pH, soil organic carbon (SOC) and soil total nitrogen. Compared to T1N2, biochar and N fertilizer application increased soil pH, soil organic carbon (SOC) and soil total nitrogen by 10%–64%, 12%–53% and 50%–89%, respectively (Table 7). Albeit, it is important to note that T0B1N1 decreased SOC and soil total N relative to T1N2 (Table 7). In addition, no significant treatment effects on soil phosphorus and potassium were found across the treatments, while, sole biochar application under no-tillage tended to enhance soil pH more than the co-application of biochar and N fertilizer (Table 5).

Regression of rice yield and soil properties

The regression of rice yield and some selected soil properties at the end of the 2 years experiment indicated that yield was positively and linearly related to all the investigated soil properties (Figure 2). However, the magnitude of the relationship differed. Soil total N content showed the strongest relationship with rice yield and had a significant *p* value of 0.001 and R^2 of 57%. In contrast, the relationships of SOC, soil phosphorus, potassium, pH, soil temperature as well as soil moisture with rice yield were low and non-significant (Figure 2).

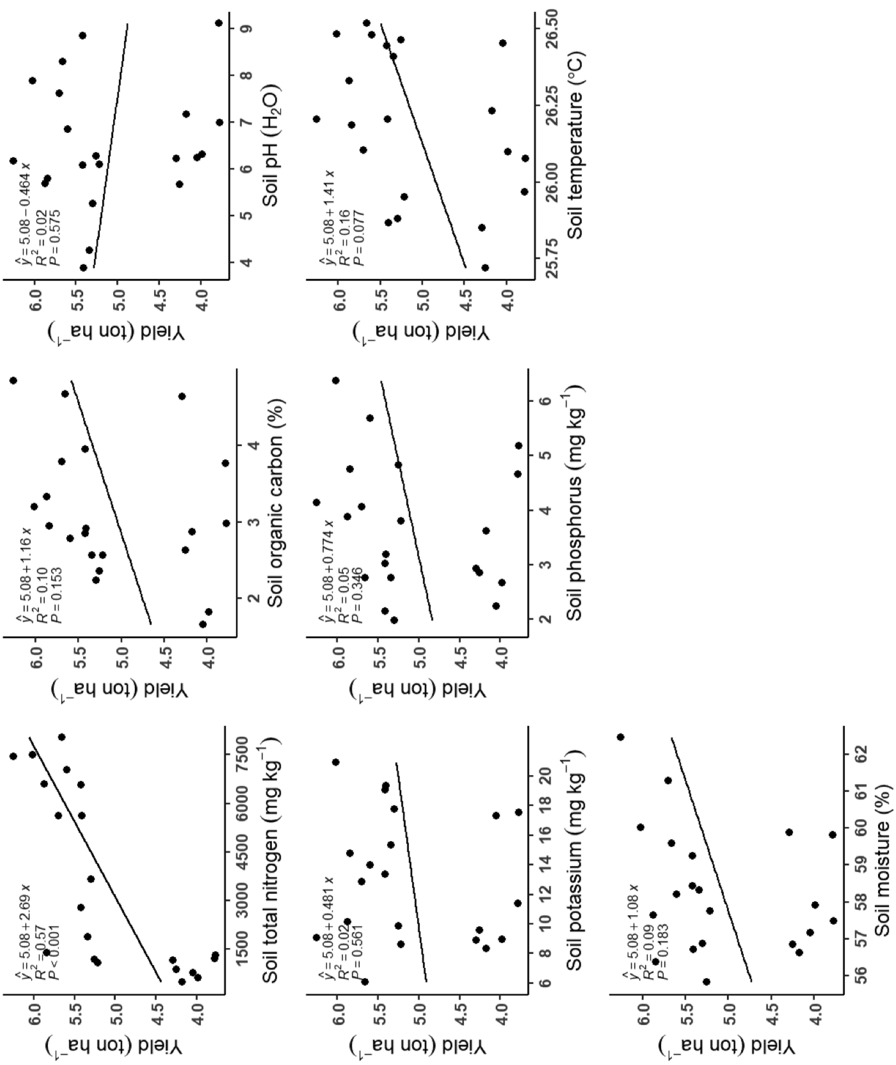

Figure 2. Regression of rice yield and some selected soil properties.

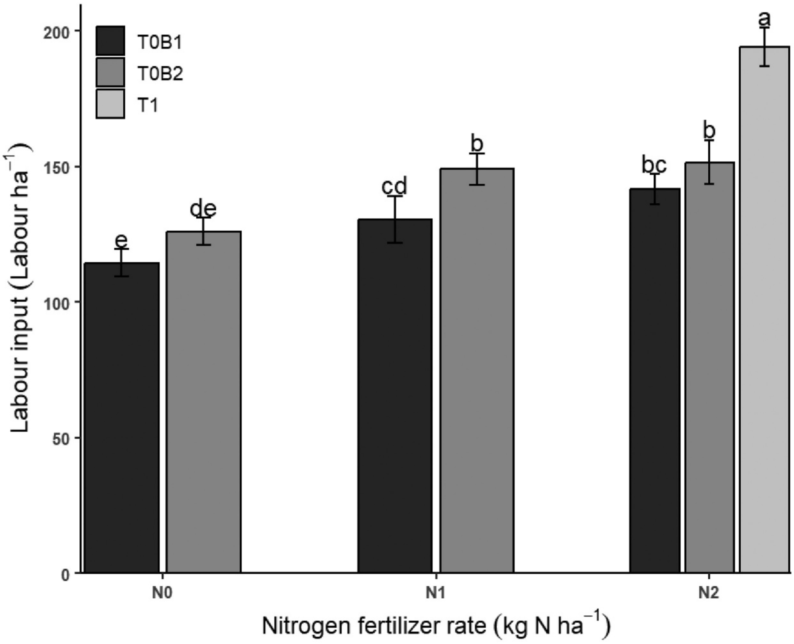

Figure 3. Labour requirement for rice production under different treatments. N0: no N fertilizer, N1: N fertilizer at 60 kg N ha^{-1} and N2: N fertilizer at 120 kg N ha^{-1}, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T1: manual tillage with hoe. Bars with different letters are significantly different ($p < 0.05$, TukeyHSD test).

Labour input, labour productivity and economic indicators

Labour input, and labour productivity varied significantly ($p < 0.05$) among treatments but no significant effect of year or the interaction of treatment and year was found (Table 8). The highest labour input (194 labour ha^{-1}) was found in T1N2, while the least labour input (114 labour ha^{-1}) was recorded in T0B1N0 (Figure 3). The result indicated that the inclusion of N fertilizer to biochar under no-tillage tended to increase labour input, although not linearly. Compared to T1N2, biochar application with or without N fertilizer under no-tillage decreased labour input by 22–41% (Figure 3).

Conversely, biochar and N fertilizer application under no-tillage significantly enhanced labour productivity (Figure 4). The highest increase in labour productivity was found under T0B1N2 which was 45% higher than the labour productivity under T1N2 (Figure 4). The high labour requirement and moderate rice yield recorded under T1N2 resulted in low labour productivity, in contrast to the high labour productivity achieved under biochar and N fertilizer application without tillage (Figure 4).

Table 8 showed the total cost of production was significantly ($p < 0.05$) affected by treatments, year and the interaction between year and treatment. Higher production cost was incurred in 2022 compared to 2021 (Figure 5). Among the treatments, the highest and lowest costs of production were recorded in T1N2 and T0B1N0, respectively (Figure 5). In both years, the inclusion of N fertilizer with biochar under no-tillage generally enhanced production cost over sole biochar application. Yet, the

Table 8. Biochar and N fertilizer effects on soil pH, soil organic carbon (SOC), soil total nitrogen (TN), soil phosphorus (P) and soil potassium (K).

Variables	Soil moisture	pH (H_2O)	SOC (%)	TN (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})
Yr						
2021	54.71b	—	—	—	—	—
2022	61.87a	—	—	—	—	—
Trts						
T0B1N0	57.15b	6.28bc	2.42c	966.46b	3.42a	14.80a
T0B1N1	56.70b	6.11bc	2.37c	1042.72b	4.08a	11.15a
T0B1N2	58.04ab	5.59c	2.89abc	5149.8a	4.10a	13.12a
T0B2N0	58.76ab	7.49ab	3.75ab	933.78b	3.73a	9.51a
T0B2N1	59.60ab	8.336a	3.93a	6082.61a	4.05a	15.34a
T0B2N2	60.71a	6.61bc	3.82a	6521.07a	3.44a	11.72a
T1B0N2	57.10b	5.07c	2.57bc	3442.41ab	2.99a	15.22a

Note: Yr: Year, and Trts: Treatments, N0: no N fertilizer, N1: N fertilizer at 60 kg N ha^{-1}, and N2: N fertilizer at 120 kg N ha^{-1}, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T1: manual tillage with hoe. Means with different letters under the same column are significantly different ($p < 0.05$, Tukey HSD test).

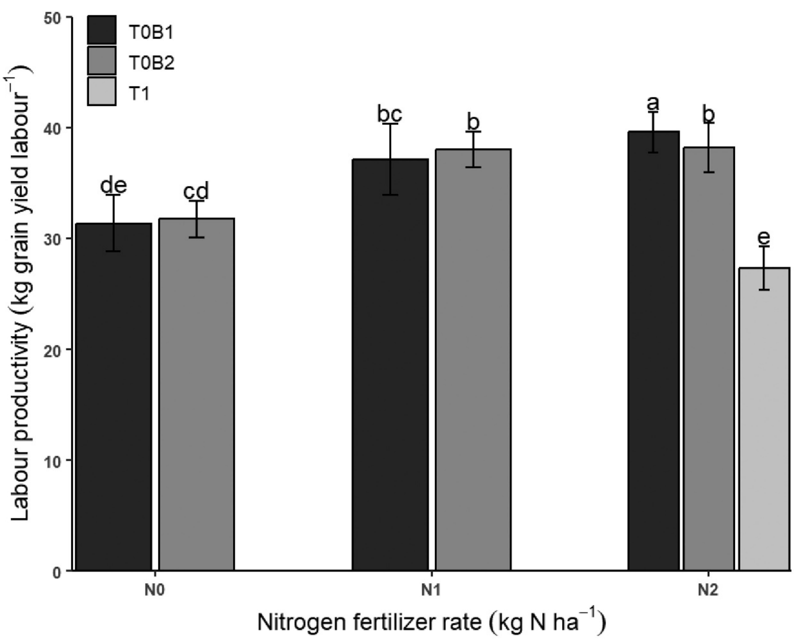

Figure 4. Labour productivity as affected by treatment application. N0: no N fertilizer, N1: N fertilizer at 60 kg N ha^{-1} and N2: N fertilizer at 120 kg N ha^{-1}, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T1: manual tillage with hoe. Bars with different letters are significantly different ($p < 0.05$, TukeyHSD test).

costs of production under biochar and N fertilizer application without tillage were still generally lower than the production cost under T1N2 (Figure 5). Additionally, the cost of applying biochar constituted the major component of the total production cost in biochar-receiving treatments, while the cost of N fertilizer was the main determinant of the production cost in N fertilizer receiving treatments especially in

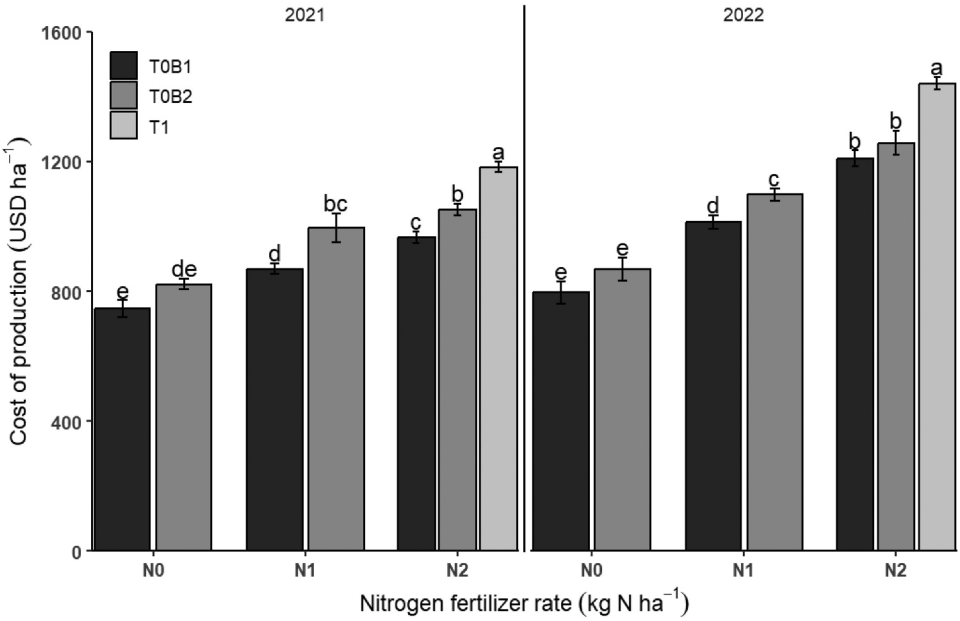

Figure 5. Mean cost of rice production under different treatments. N0: no N fertilizer, N1: N fertilizer at 60 kg N ha^{-1} and N2: N fertilizer at 120 kg N ha^{-1}, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T1: manual tillage with hoe. Bars with different letters under the same year are significantly different ($p < 0.05$, TukeyHSD test).

2022 (Table S1). Compared to T1N2, the average total cost of production decreased by 42%, 37% and 29% in T0B1N0, T0B2N0 and T0B1N1, respectively, in 2022 (Figure 5).

The benefits obtained under the various treatments showed statistically significant ($p < 0.05$) differences with no significant interactive effects of treatment and year (Table 8). Across treatments, the lowest benefit was found under T1N2, while T0B2N1 produced the largest benefit (Figure 6). Interestingly, despite increasing the total cost of production, biochar and N fertilizer application under no-tillage significantly ($p < 0.05$) increased benefit over sole biochar or N application irrespective of the tillage method (Figure 6).

Furthermore, Table 8 indicated that benefit–cost ratio varied significantly ($p < 0.05$) among treatments, with no significant year or interactive effect between treatment and year. Highest benefit-cost ratios were found in biochar and N fertilizer treatments and lowest under sole biochar or N fertilizer treatments (Figure 7). Regardless of N fertilizer rate, biochar application in no-tillage enhanced benefit–cost ratio by 145% –324% compared to T1N2 (Figure 7).

Correlation of rice morphological traits, labour input, productivity, yield and economic indicators

The correlation analysis between rice morphological traits, yield and economic indicators is presented in Table 7. Rice yield significantly ($p < 0.05$) correlated with the number of rice

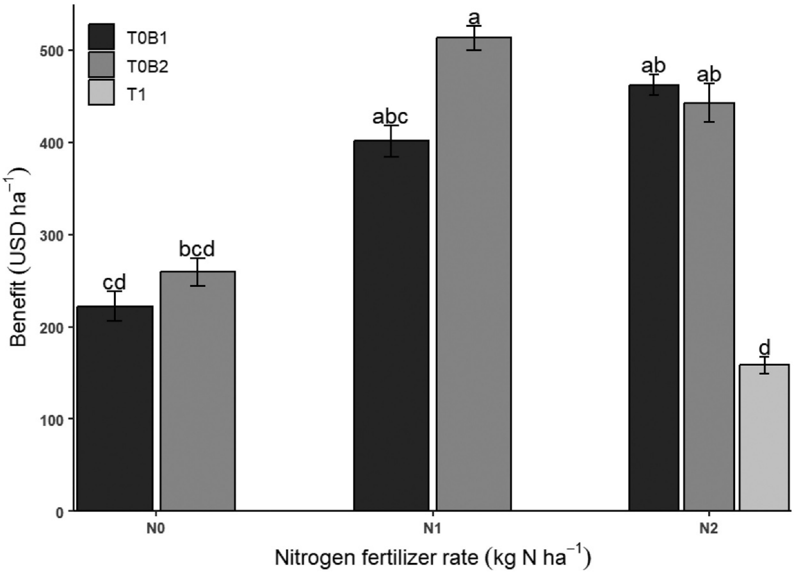

Figure 6. Mean benefit of rice production under different treatments. N0: no N fertilizer, N1: N fertilizer at 60 kg N ha^{-1} and N2: N fertilizer at 120 kg N ha^{-1}, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T1: manual tillage with hoe. Bars with different letters are significantly different ($p < 0.05$, TukeyHSD test).

tillers, straw biomass, labour productivity, benefit and benefit–cost ratio with R^2 values of 0.78, 0.70, 0.71, 0.70 and 0.45, respectively (Table 7). The linear relationship between yield and benefits implied that treatments that enhanced yield also tended to increase benefits and benefit-ratio (Table 9). However, in 2022, due to the high N fertilizer cost, the benefit and yield relationship was only observed among treatments with low N fertilizer rates.

Discussion

Responses of rice growth, yield, partial productivity of nitrogen and soil properties to biochar and nitrogen fertilizer

The findings of this study indicated that biochar application combined with nitrogen (N) fertilizer under no-tillage significantly ($p < 0.05$) enhanced rice height, number of tillers, straw biomass and yield and the partial productivity of nitrogen (PPN) (Table 5). The positive responses of rice growth and yield to biochar and N fertilizer application under no-tillage over the farmers' practices were predominantly attributed to biochar-induced increase in soil properties (Table 7) (Sánchez-García et al. 2020; Yin et al. 2021). Biochar and N application increased soil pH, soil organic carbon (SOC) and soil total N by 10%–64%, 12%–53% and 50%–89%, respectively, compared to farmers practices of sole chemical fertilizer application. Such enhancement in soil properties favoured rice growth and yield by promoting the activities of microorganisms and enhancing the uptake of nutrients such as nitrogen and phosphorus (Van Zwieten et al. 2015; Li et al. 2016; Ghorbani et al. 2019) and was confirmed by the significantly positive relationship observed between soil properties

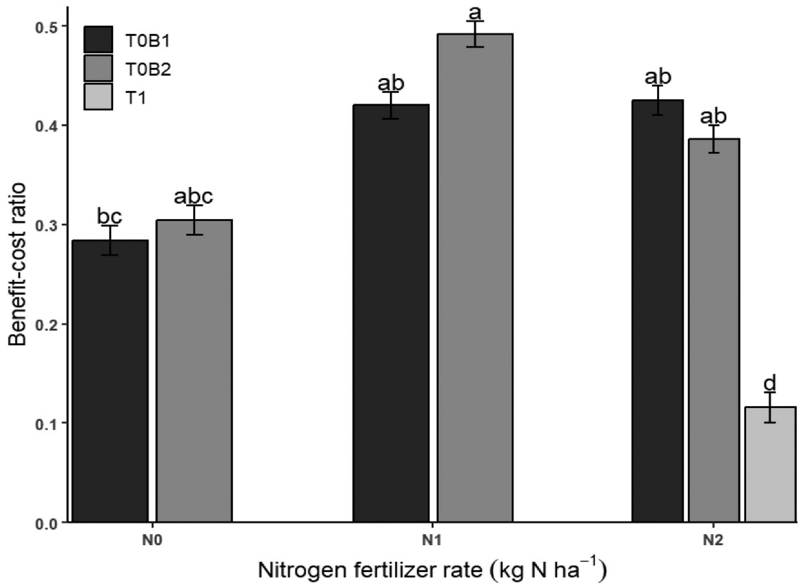

Figure 7. Mean benefit–cost ratio under different treatments. N0: no N fertilizer, N1: N fertilizer at 60 kg N ha^{-1} and N2: N fertilizer at 120 kg N ha^{-1}, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B1: no-tillage +3 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T0B2: no-tillage +6 t ha^{-1} biochar, T1: manual tillage with hoe. Bars with different letters are significantly different ($p < 0.05$, TukeyHSD test).

and rice yield in this study (Table 7 and Figure 2). Similarly, Oladele et al. (2019a), Fernanda et al. (2019), Phares and Akaba (2022) and Danso et al. (2023) reported significant increase in rice growth and yield of rain-fed rice under biochar and N fertilizer application in Nigeria, Brazil and Ghana due to the positive effects of biochar on soil properties, which enhanced the uptake of fertilizer application by rice plants.

Contrarily, biochar application without N fertilizer under no-tillage significantly decreased rice plant height, tillering, straw biomass and yield (Table 6), probably due to biochar-induced *N*-immobilization (Gao et al. 2019), negative priming (Qin et al. 2016) or the inhibition of the activities of soil micro-organisms (Cayuela et al. 2014) responsible for nutrient transformation for plant utilization by biochar. Our results agree with the findings made in previous studies by Sun et al. (2020) and Danso et al. (2023). In addition, Shaukat et al. (2019) have reported 6–14% reduction in rice biomass accumulation in sole biochar treatment compared to treatments receiving N fertilizer with or without biochar. The effect was attributed to biochar-induced delay in rice plant to initiate tillering and the production of fewer tillers. Therefore, to achieve optimum crop performance, biochar should be applied with N fertilizer.

Overall, improved rice growth and yield were observed in 2022 compared to 2021 (Table 6) which may be attributed to the heavy rainfall in 2021 after rice seeding, which flooded the plots and retarded early plant development. The higher rice growth and yield in 2022 may also be linked to the residual effects of biochar and higher and better rainfall distribution in 2022 (Table 1). Over time, the high cation exchange capacity of biochar may promote the gradual release of retained nutrients, such as phosphorus, potassium and magnesium, supporting sustained crop productivity with reduced fertilizer

Table 9. Correlation between plant height (cm), number of tillers (tillers m^{-2}), straw biomass (g m^{-2}), grain yield (t ha^{-1}), benefits ($), benefit cost ratio, labour input (labour ha^{-1}) and labour productivity (kg grain yield $labour^{-1}$ ha^{-1}).

	Plant height	Tillers	Straw biomass	Yield	Benefits	Benefit cost ratio	Labour input	Labour productivity
Plant height	1							
Tillers	0. 80***	1						
straw biomass	0.64**	0.83***	1					
Yield	0.88^{ns}	0.78***	0.70***	1				
Benefits	0.50*	0.49*	0.42^{ns}	0.70***	1			
Benefit cost ratio	0.24^{ns}	0.28^{ns}	0.22^{ns}	0.45*	0.94***	1		
Labour input	-0.17^{ns}	0.01^{ns}	0.07^{ns}	-0.18^{ns}	-0.04^{ns}	0.10^{ns}	1	
Labour productivity	0.70***	0.60**	0.57**	0.71***	0.70***	0.57**	-0.23^{ns}	1

Note: '*', '**', '***' and 'ns' indicate significant difference at $p < 0.05$, $p < 0.01$, $p < 0.001$ and no significance, respectively.

dependence (Qin et al. 2016; Liu et al. 2018; Hou et al. 2022; Nath et al. 2024). Biochar ability to improve soil structure, water retention and microbial activity can be particularly beneficial in rainfed lowlands of West Africa, where erratic rainfall and nutrient leaching pose challenges to rice cultivation. These long-term benefits may contribute to higher and more stable yields, improved nutrient-use efficiency and enhanced soil fertility, making biochar a promising tool for sustainable intensification in lowland rice systems. Also, the long-term application of biochar can sequester carbon in the soil, which would contribute to climate change mitigation (Carvalho et al. 2016; Lorenz and Lal 2018; Soinne et al. 2020). In this study, biochar benefited rice crops by enhancing water retention, and soil pH, which may have increased nutrient availability and crop growth (van Zwieten et al. 2010; Lehmann et al. 2011). The addition of biochar to rice fields increase soil mositure and reduce soil temperature in this study (Figure 1 and Table 5), creating a more favorable microclimate for microbial activity. Biochar porous structure enhances the soil water-holding capacity, reducing evaporation and maintaining adequate moisture levels during dry periods, while its insulating properties moderate soil temperature fluctuations. These improved soil physical conditions stimulate microbial populations and enzymatic activities, which in turn enhance nutrient mineralization and availability to rice plants. This synergistic effect likely contributes to the observed increases in rice yield, as more nutrients become accessible during key growth stages under improved soil moisture and thermal regimes (Carvalho et al. 2016; Raboin et al. 2016).

It is important to note that this study did not include the Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) analyses of biochar, which may limit a deeper understanding of the underlying mechanisms through which biochar influences soil properties and enhances rice growth. SEM could reveal biochar surface morphology and porosity, which affect its capacity to retain nutrients and water, while FTIR would provide insight into the functional groups responsible for cation exchange and nutrient interactions. Despite those limitations, the observed improvements in soil chemical properties remain valid and are supported by the robust field measurements. These substantial gains in key soil fertility indicators demonstrate the practical benefits of biochar use, even in the absence of detailed spectroscopic and morphological data. Previous meta-analyses also revealed a significant positive correlation between crop yield and biochar organic carbon, N content, CEC and pH (Dai et al. 2020; Xie et al. 2013), which is similar to the results obtained in this study.

Labour input, labour productivity and economic indicators

The labour input, labour productivity, cost of production, benefits and benefit–cost ratio varied significantly among treatments (Table 8). The variation was caused mainly by the costs of biochar application, N fertilizer and tillage (Table S1). Among treatments, significantly higher labour input was found under T1N2 which was related to the high labour requirement for tillage (Figure 3). Similarly, biochar application, especially at 6 t ha^{-1} in combination with N fertilizer, was the main contributor to high labour requirement among treatments receiving biochar under no-tillage. Nevertheless, the labour inputs in the current study were within the range reported in a previous study in Côte d'Ivoire (Dossou-Yovo et al., 2024). Moreover, despite their relatively high labour use, T0B2N2 and T0B2N1 significantly promoted yield, and thus led to increased labour productivity and profitability in their use. In contrast, sole biochar application under no-tillage decreased labour productivity (Figure 4) mainly due to decreased yield (Table 5). Therefore, our result suggests that focusing on practices that enhance yield rather than on input reduction may be a better strategy to improve labour productivity. However, where feasible, simultaneously reducing labour input and enhancing yield should be pursued to optimize rice productivity and enhance profitability.

Regarding production cost, the tillage operation required in T1N2 significantly increased production cost relative to biochar application without or with N fertilizer and no-tillage (Table 8). Treatments that received N fertilizer had higher production costs in 2022 than in 2021 due to higher cost of N in 2022 (Figure 5). The Russia–Ukraine conflict of 2022 disrupted the global N fertilizer supplies and drove up N fertilizer prices. Whereas in 2021, it cost about \$21 per 50 kg of urea, in 2022, the cost rose to approximately \$53 for the same quantity of N fertilizer (Prices et al. 2022). Contrarily, across the 2 years, the cost of biochar remained relatively low at approximately <\$1 per 50 kg (Table S1). The cost of biochar application was the main cost component for biochar receiving treatments. For instance, while it cost approximately \$9 to apply 120 kg N ha^{-1}, it cost about \$105 to apply 6 t ha^{-1} (Table S1).

In general, the production cost under biochar and N fertilizer treatments without tillage were largely higher than the production cost under sole biochar application (Figure 5). This finding agrees with the result of Danso et al. (2023) who reported a significant increase in the cost of rice production in Ghana following the co-application of biochar and N. Although the authors reported a higher production cost than in our study, the difference is due to the lower biochar rate used in our study. Previous study in Poland revealed the cost of biochar application as the most expensive components of biochar use in agriculture and could deter wide biochar adoption (Latawiec et al. 2021).

Moreover, the inability of sole biochar to overcompensate the cost of production through high yield makes the sole use of biochar unattractive. Except for the treatments receiving N fertilizer in combination with biochar, most of the biochar treated plots produced low rice yield compared to T1N2. This disproportionality between the cost of production and yield under sole biochar application led to low benefits (Figure 6) and benefit–cost ratio (Figure 7). Thus, the finding of this study showed that the benefit derived by applying only biochar was unable to economically justify its use for rice production, indicating that in the absence of other incentives, adoption of sole biochar use under no-tillage may not be feasible. However, when combined with N fertilizer, the benefits and benefit–cost ratio as well as N use efficiency derivable from biochar use under no-tillage became economically viable and attractive. As such, we can state that the use of biochar with N fertilizer under no-tillage is more beneficial and economically viable over the conventional farmers' practice in Côte d'Ivoire.

Similar to our finding, Dickinson et al. (2015), and Sun et al. (2020) reported a high production cost under biochar use, which was linked to the cost of biochar production and application. According to Chew et al. (2020), the cost of biochar is the main factor limiting biochar application by farmers to less than 5 t ha^{-1}. Nevertheless, in the present study, the benefits obtained in sole biochar treatments were still relatively larger than the benefits from T1N2. Albeit, this maybe because the biochar used in the present study was a by-product of rice parboiling system which was hitherto considered a waste product and had no real price value. Therefore, future studies using biochar purchased at the standard international market price are recommended.

Relationship of morphological traits, rice yield, labour input, labour productivity and economic benefits

Rice morphological traits and economic indicators correlated positively and strongly to yield (Table 9). Rice height, number of tillers and straw biomass are important traits necessary for improving and predicting yield. Linear relationships between yield and morphological traits have been reported (Sharma 1995). Taller plants expose leaves better for photosynthesis by plants, while straw houses the leaves that are responsible for photosynthesis. Inadequacy of tillers and straw can hugely limit rice yield by truncating photosynthetic allocation which has a direct effect on farmer's benefits. It was therefore expected as was observed in our study that as the rice plant height, tiller numbers and straw biomass increased that yield and benefits should increase. Similarly, labour productivity correlated strongly and positively with yield (Table 9). This was because labour productivity was derived from yield, as such increase in yield resulted in increase in labour productivity. Conversely, labour input correlated poorly and negatively with yield which was due to the low yield observed under T1N2 despite recording high labour input. Therefore, to maximize labour productivity, practices that enhance yield and reduce labour input should be promoted (Paresys et al. 2018).

Conclusion

This study evaluated the agronomic and economic benefits of integrating nitrogen (N) fertilizer, biochar and no-tillage into the rainfed lowland rice production system. The results indicated that compared to the conventional farmers' practice in Côte d'Ivoire, biochar and N fertilizer application under no-tillage significantly ($p < 0.05$) enhanced soil properties and N partial productivity of nitrogen (PPN), which led to increase in rice growth and yield, and by extension benefit and benefit–cost ratio. Contrarily, sole biochar application under no-tillage significantly decreased rice growth, and yield. The largest increase in PPN and benefit–cost ratio (324%) were found in the combined application of biochar at 6 t ha^{-1} and N fertilizer at 60 kg N ha^{-1} with no-tillage (T0B2N1). Therefore, we recommend the application of T0B2N1 by the smallholder rice farmers in Côte d'Ivoire to increase rice yield, PPN and profitability. We also recommend further studies on the long-term impact of T0B2N1 on yield, carbon sequestration and greenhouse gas emissions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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