SAINS TANAH – Journal of Soil Science and Agroclimatology

Journal homepage: http://jurnal.uns.ac.id/tanah

Biochar-assisted nitrogen reduction improves resource efficiency at the expense of rice yield

Nowrose Jahan Lipi[1], Md. Harun-Or-Rashid[1], Swadesh Chandra Samanta[1], Muhammad Maniruzzaman[2], Md. Abdul Kader[3], Shamim Mia[1]*

[1] Department of Agronomy, Patuakhali Science and Technology University, Dumki, Patuakhali, Bangladesh
[2] Department of Agricultural Chemistry, Patuakhali Science and Technology University, Dumki, Patuakhali, Bangladesh
[3] Discipline of Agriculture and Food Technology, School of Agriculture, Geography, Environment and Natural Science, The University of the South Pacific, Samoa Campus, Samoa

ARTICLE INFO

Keywords:
Apparent Nitrogen recovery
Biochar properties
Inorganic fertilizer
Organic amendments
Physiological Nitrogen Use Efficiency

Article history
Submitted: 2025-05-18
Revised: 2025-08-11
Accepted: 2025-10-30
Available online: 2025-12-23
Published regularly: December 2025

Corresponding Author
Email address:
** smia_agr@pstu.ac.bd*

ABSTRACT

Nitrogen (N) is the most essential nutrient element for improving crop yield. However, urea, its most common form, is highly prone to losses, especially in flooded rice fields. Urea application often reduces N use efficiency (NUE) and contributes to environmental degradation. Here, a field experiment was conducted to examine the yield and growth performance of *Aman* rice, as well as to estimate NUE using different organic amendments and inorganic N application rates. The treatments consisted of two factors: a) organic amendments- waste biochar, sawdust biochar, cow dung, and control, and b) N application rate- control (0), 50%, and 100% of the recommended rate. Overall, waste biochar performed better than sawdust and cow dung. Waste biochar with 100% of the recommended rate of urea application provided the highest grain (4.65 t ha^{-1}) and straw yield (6.72 t ha^{-1}). However, waste biochar with 50% recommended urea application provided the best NUE, i.e., agronomic N use efficiency (46 kg rice grain kg^{-1} N applied), physiological N use efficiency (28 kg rice grain kg^{-1} N uptake), and apparent N recovery (61%). The relatively higher NUE in treatments with organic amendments and half the recommended N rate suggests a trade-off between improved NUE and rice grain yield. The enhanced NUE was possibly manifested by retaining more N in the reactive sites of soil organic matter and its uptake in the plant. Altogether, our results provide insights into NUE in rice cultivation systems after application of diverse organic matters with inorganic N application from urea.

How to Cite: Lipi, N. J., Harun-Or-Rashid, M., Samanta, S. C., Maniruzzaman, M., Kader, M. A., & Mia, S. (2025). Biochar-assisted nitrogen reduction improves resource efficiency at the expense of rice yield. Sains Tanah Journal of Soil Science and Agroclimatology, 22(2), 457-466. https://doi.org/10.20961/stjssa.v22i2.102413

1. INTRODUCTION

Soil is the largest terrestrial reservoir of organic carbon, storing approximately 2,400 Pg of carbon, which is more than the combined carbon in the atmosphere and vegetation (Sadatshojaei et al., 2021). Therefore, increasing soil organic carbon (SOC) and stabilizing it in the soil is considered one of the sustainable means for climate change mitigation. One of the possibilities of increasing the SOC is the application of pyrogenic carbon-rich organic matter (e.g., biochar), while the modern perspective is that carbon sequestration is the protection of SOC from microbial decomposition through organo-mineral complexation or physical protection (Cotrufo et al., 2019). Understanding the relative benefits of these organic amendments is required for informed decision-making or policy formation.

Soil organic matter (SOM) consists of a diverse mixture of plant and microbial residues at various stages of decomposition. Apart from its carbon sequestration role, it is essential for both agricultural productivity and ecosystem health (Kopittke et al., 2019). It improves soil health through multiple ways (Powlson et al., 2011). First, organic matter serves as a reservoir of essential nutrients. It improves the soil's water-holding capacity, soil aggregation, creating a network of pores that facilitates root penetration and provides food and habitat for beneficial microorganisms (Jangir et al., 2019). Like many other countries, where

STJSSA, p-ISSN 1412-3606 e-ISSN 2356-1424
http://dx.doi.org/10.20961/stjssa.v22i2.102413

intensive agriculture is practiced, the average organic matter content in Bangladesh soils is less than 1% ranging between 0.05 to 0.9% (Huq & Shoaib, 2013). Therefore, increasing organic matter in croplands of Bangladesh is a high priority.

Organic matter is usually applied as compost made from farmyard, animal manure, and green manure, or as crop residue retention. In Bangladesh, using organic matter from agricultural residues as organic fertilizer is limited because much of it is used as fuel for cooking. As an alternative, municipal organic waste can be a good option for recycling as a source of organic matter since the waste generation is quite large, estimated at 15500 t day^{-1} (Mia et al., 2018). The majority fraction of the municipal waste (>75%) is organic in nature (Mia et al., 2018). Municipal organic waste can potentially be recycled for agriculture by pyrolysis and composting to replenish the SOM. The biochar obtained from municipal waste is used as an organic amendment for its physicochemical properties (Rehrah et al., 2016). The sawdust biochar, an organic amendment widely used in agriculture for its N and other nutrient content (De Bhowmick et al., 2018).

Biochar typically has a high specific surface area, which is beneficial for nutrient retention and microbial activity (Leng et al., 2021). It carries a significant amount of surface functional groups, which can influence its interactions with soil nutrients and other environmental components. These characteristics make biochar a valuable amendment for agriculture and environmental management, offering benefits in soil fertility, nutrient retention, and overall sustainability. However, the physicochemical properties of biochar vary significantly based on production conditions and the feedstock used in its production (Baquy et al., 2022; Septiana et al., 2018; Tomczyk et al., 2020). The wood-based biochar tends to have a higher proportion of carbon, specifically aromatic carbon, due to its cellulose-rich nature. They generally contain fewer plant-available nutrients, making them more beneficial for long-term carbon sequestration rather than their immediate role as a nutrient source. Manure-based biochar has a lower carbon content compared to wood-based biochar. They are rich in nutrients, such as nitrogen, phosphorus (P), and potassium, which can be readily available for plant uptake (Piash et al., 2021). This makes manure-based biochar suitable for short-term soil fertility improvement. In contrast to biochar, organic amendments such as compost and cow dung carry relatively more readily available nutrients.

The N use efficiency (NUE) in rice cultivation is a crucial topic, especially concerning sustainable agriculture and environmental impact. Nitrogen applied to rice fields can be lost through leaching into groundwater or volatilization into the atmosphere, reducing its availability to the plants and potentially causing environmental pollution (Chen et al., 2021). Improper timing and uneven distribution of N application can lead to suboptimal uptake by rice plants, resulting in reduced yield and efficiency. Excessive N use can lead to environmental issues such as water pollution (eutrophication) and greenhouse gas emissions (e.g., nitrous oxide) (Chen et al., 2021; Tyagi et al., 2022). The NUE can vary widely depending on factors like soil type, climate, crop variety, and management practices (Govindasamy et al., 2023; Sharma & Bali, 2018). Optimizing these factors is essential for improving efficiency.

The N is one of the most important essential nutrient elements that plays a critical role in plant growth and yield (Iqbal et al., 2021). Therefore, a large amount of N is applied to boost yield. However, long-term effects of chemical N fertilizers on soil health can indeed lead to soil degradation, which hinders plant growth and reduces productivity over time (Guo et al., 2017). The combined application of inorganic fertilizer and organic amendments has been suggested as a strategy to increase nutrient use efficiency through nutrient cycling and changing soil properties with organic amendments (Iqbal et al., 2019; Oyetunji et al., 2022). The biochar application with N fertilizer in the rice field increases yield and NUE (Liu et al., 2022; Yuan et al., 2024). Since the organic amendment varies in biochemical properties, the effects of the combined application of organic and inorganic fertilizers can be variable. However, understanding is limited on how the application of biochar with diverse properties with urea would affect the productivity and N use efficiency in rice cultivation. Here, we examined the combined application of urea and biochar (produced from sawdust and organic waste) on rice culture.

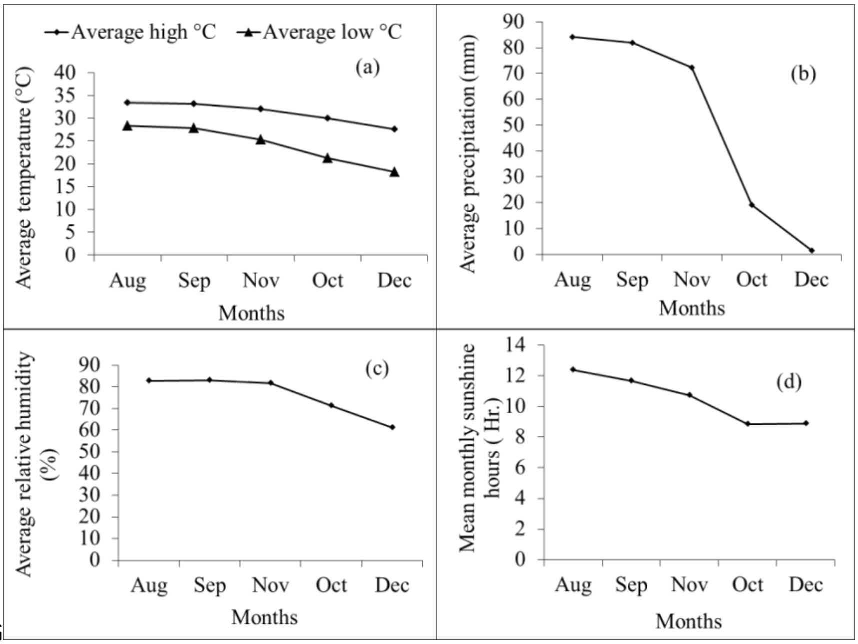
Our aim was to examine the effect of the combined application of diverse organic amendments with inorganic urea-N on the NUE and grain yield in rice. Specifically, the efficacy of diverse biochar (sawdust and waste biochar) was compared with cow dung and absolute controls against two rates of N application using a field trial.

2. MATERIAL AND METHODS

2.1. Field trial

The experiment was conducted from 13th August to 6th December 2020 in the Agronomy Field Laboratory (22° 27.50′N and 90° 23.08′E) at Dumki, Patuakhali, Bangladesh. The experimental area is situated in the subtropical climatic zone, which belongs to the Agro-ecological Zone of the Ganges Tidal Flood Plain (AEZ-13). During the experimental period, the average temperature, precipitation, relative humidity and monthly sunshine hours are declined in Fig. 1. The experiment included two factors. Factor A included organic amendments- (i) waste biochar (ii) sawdust biochar (iii) cow dung (iv) control while factor B included rate of N fertilizer application- (i) 100% recommended N (RN) (ii) 50% RN, and (iii) control. The treatments were replicated three times. Biochar was produced from waste and sawdust in a slow pyrolysis biochar kiln for 10 h at ~ 400 °C (Mia et al., 2015).

Organic fertilizers (biochar and cow dung) were applied to plots at 5.0 t ha^{-1} on a dry biomass basis during final land preparation and incorporated into surface soils (0-20 cm). The inorganic fertilizer was applied as per the recommendation of fertilizer for BRRI Dhan 52 cultivation technology (BRRI, 2016). As per the calculation, the recommended rates of fertilizers were 167, 62, 84, 56, and 8 kg ha^{-1} of urea, triple super phosphate, muriate of potash, gypsum, and zinc sulphate, respectively, for BRRI Dhan 52. The plot size was 10 m^2. One-third of the urea and all other fertilizers were applied to each plot at final land preparation. The second and third instalments of urea were broadcast at 25 DAT and at 55 DA.



G

Figure 1. Weather data during experimental period; (a) average temperature, (b) average precipitation, (c) average relative humidity, and (d) mean monthly sunshine hours

Table 1. Chemical properties of organic amendments and initial soil

treatments	Properties				
	pH	EC (dSm^{-1})	%C	%N	%P
Waste biochar	7.4±0.1	0.36±0.01	68.9±0.4	2.83±0.15	0.23±0.02
Sawdust biochar	6.5±0.6	0.52±0.01	66.3±0.6	0.73±0.13	0.12±0.01
Cow dung	8.2±0.1	1.62±0.03	42.7±1.2	1.80±0.10	0.44±0.02
Soil (initial)	7.5±0.2	6.31±0.24	0.014±0.001	0.07±0.01	0.0008±0.0001

Twenty-five-day-old healthy seedlings of BRRI Dhan 52 were transplanted with a spacing of 25 cm × 20 cm. After transplanting, regular irrigation was maintained during the growing period, if required. Three weddings were done during the growing period. At harvest, five hills (excluding the border one) from each plot were randomly selected, uprooted, and properly tagged for recording necessary data on crop yield contributing characters. The rest of the plot was harvested separately to record the yield for each plot. Soil samples (0-20 cm) were collected before land preparation.

The properties of the initial soil and the organic amendments are presented in Table 1. The initial soil contained a very low amount of N (0.07%). The waste biochar contained relatively higher amount of N (2.83%) than cow dung (1.80%), followed by sawdust biochar (0.73%). Similarly, the waste biochar had a relatively higher amount of carbon (68.9%) than sawdust biochar (66.3%), followed by cow dung (42.7%). The cow dung showed the highest value of EC (6.31 dSm^{-1}) and P (0.44%) compared to waste biochar, followed by sawdust biochar.

2.2. Soil and plant chemical analysis

Soil pH was determined by a glass electrode pH meter (Jackson, 1973). Twenty grams (20 g) of air-dried soil from each sample was taken in 50 ml beakers separately, and 50 ml of distilled water was added to each beaker. The suspensions were shaken by a shaker for about 30 minutes and pH was measured (APHA, 2012). The electrical conductivity of collected soil samples was determined electrometrically (1:5, soil : water ratio) by a conductivity meter (APHA, 2012). Organic carbon was determined wet oxidation method. One gram of soil, along with 10 mL of 0.5 N potassium dichromate solution and 20 mL of H_2SO4, was taken in a 500 mL conical flask. After 30 minutes of rest, 200 mL of distilled water was added, followed by the addition of 10 mL of concentrated H_3PO_4 and 40 drops of diphenylamine indicator. The solution mixture was then titrated against 0.2 N ferrous ammonium sulphate solution until the purplish blue color turned to fresh green color (Walkley & Black, 1934). Total N content in samples was determined by the macro Kjeldahl method. Five grams of soil was taken in an 800 mL Kjeldahl flask, and then 20 mL concentrated H_2SO_4, and 5 g catalyst mixture (100 10 1, K_2SO_4: $CuSO_4$: Se powder) were added to it, and the digestion was started. The flask was placed in the distillation set, so that the end of the condenser remained below the surface of the boric acid solution. When about 150 mL of distillate was collected, distillation was over. Then the distillate was titrated against H_2SO_4. At the endpoint, the green color of the solution changed to blue. A blank titration was conducted following the same procedure stated above (Jackson, 2005). For determining the available P in soil and organic amendments, Olsen's method was applied. Five grams of the sample were taken in a 250 mL conical flask. Then, a little of (P and arsenic-free) carbon black and 100 mL 0.5M $NaHCO_3$ were added to it. The contents were then shaken for 30 minutes on a horizontal mechanical shaker and were filtered through Whatman No. 42 filter paper. For determining the P, 5 mL of extract was taken into a 50 mL volumetric flask, followed by 4 mL of sulphomolybdate solution and distilled water up to the volume of 45 mL. A few drops of stannous chloride solution were added, and finally, the volume was made up to the mark with distilled water and allowed to stand for 10 minutes for complete colour development. The absorption readings were taken with the help of a spectrophotometer at 660 nm wavelength, comparing with a standard series solution running in the same way (Jackson, 2005).

2.3. Nitrogen use efficiency and recovery

The agronomic nitrogen use efficiency (ANUE), physiological nitrogen use efficiency (PNUE), and apparent nitrogen recovery (ANR) were calculated using Equations, 1, 2, and 3, respectively (Oladele et al., 2019).

$$ANUE = \frac{YN_t - YN_0}{NA} \quad [1]$$

$$PNUE = \frac{YN_t - YN_0}{PN_t - PN_0} \quad [2]$$

$$ANR = \frac{PN_t - PN_0}{NA} \times 100 \quad [3]$$

Where, ANUE= Agronomic N use efficiency (Kg grain Kg^{-1} N applied), YN_t= Yield in N treated plots (kg), YN_0= Yield in N untreated plots (kg), PNUE= physiological N use efficiency (Kg grain Kg^{-1} N uptake), PN_t= Plant N uptake in treated plots (kg), PN_0= Plant N uptake in untreated plots (kg), ANR= apparent N recovery (%), NA= N applied (kg).

2.4. Statistical analysis

A two-way analysis of variance was performed to examine the main and interactive effects of biochar amendments and N application rates using JMP 8.0 (SAS, USA). The means were separated using Tukey's HSD at 5%. Model assumptions, including normality and equal variance, were checked, and data were transformed when assumptions were not met. Regression and principal component analyses were also performed.

3. RESULTS

3.1. Plant performance

Average across fertilizer treatments, the rice performance and yield was higher in waste biochar (4.65 t ha^{-1}) treatment than both control (3.23 t ha^{-1}) and sawdust biochar (4.11 t ha^{-1}) treatment (Table 2). Among the N application rates, 100%RN produced the maximum grain (4.65 t ha^{-1}) and straw (6.72 t ha^{-1}) yield. The interaction effect of different biochars and inorganic N treatment had significant effects on the plant height, effective tillers $hill^{-1}$, filled grains $panicle^{-1}$, unfilled grains $panicle^{-1}$, panicle length, thousand-grain weight, straw yield of rice and grain yield of rice ($P<0.05$, Table 2). Waste biochar with 100% of the recommended N addition produced significantly the longest plant (116.27 cm), the highest number of effective tillers $hill^{-1}$ (14.13), the highest no of filled grains $panicle^{-1}$ (110), the maximum thousand-grain weight(28.84 g), the maximum straw yield (6.72 t ha^{-1}) and the maximum grain yield (4.65 t ha^{-1}) (Table 2). The lowest values for all parameters were found in control treatments except unfilled grains $panicle^{-1}$.

3.2. Nitrogen content in plants and soils

There is a significant difference in grain and straw N concentration among the treatments (Table 3). Higher grain and straw N concentration was recorded in organic amended plots, including cow dung and biochar, compared to no fertilizer (i.e., control) application treatment. The highest concentration of N in straw (0.56%) was found in cow dung with 100% recommended N fertilizer, while the lowest amount (0.33%) was found from the control treatment, i.e., no organic and inorganic N application (Table 3). Similarly, grain N concentration was relatively higher in cow dung treatment with 100% recommended N fertilizer application (1.13%), while the lowest concentration (0.70%) was found in the control treatment (Table 3).

Table 2. Effect of biochars of different sources and N fertilizers on yield and yield contributing character of rice (mean ± SD)

Treatment Combination		Plant Height at Harvest (cm)	Number of Effective Tiller per hill	Number of filled grain per panicle	Number of unfilled grain per panicle	Panicle length (cm)	1000- grain weight (g)	Straw yield (t ha^{-1})	Yield (t ha^{-1})
Organic Amendments	Nitrogen								
Control	0% RN	95.1±0.8f	6.9±0.1f	64.6±1.4e	52.2±4.65ab	19.62±0.15g	23.25±0.15f	1.88±0.02f	1.82±0.03h
Control	50% RN	101.0±0.4d	9.3±0.2d	70.5±0.6d	44.47±2.44bc	21.57±0.15f	24.58±0.34e	3.3±0.45d	2.53±0.12f
Control	100% RN	106.0±0.8c	10.6±0.2c	85.3±2.3c	60.33±2.1a	23.29±0.38de	25.27±0.21de	5.16±0.26c	3.23±0.22e
Cow dung	0% RN	99.4±0.4de	8.0±0.5de	69.5±1.3d	44.87±1.17bc	22.69±0.16ef	24.42±0.17e	3.27±0.17de	2.27±0.06g
Cow dung	50% RN	105.7±0.2c	10.7±0.8c	87.5±1.3c	48.53±5.72abc	24.14±0.06cd	26.25±0.04cd	4.91±0.4c	3.51±0.03d
Cow dung	100% RN	113.2±0.8b	12.5±0.4b	95.7±0.5b	36.6±3.86cd	25.25±0.29bc	27.38±0.09b	6.13±0.72b	4.29±0.5bc
Sawdust biochar	0% RN	98.7±1.2e	8.3±0.5e	69.1±1.51d	44.87±1.17bc	22.69±1.16ef	24.42±0.17e	2.91±0.05e	2.08±0.05g
Sawdust biochar	50% RN	105.0±0.6c	10.7±0.26c	87.53±1.29c	48.53±5.72abc	24.32±0.34bcd	25.25±0.04de	5.03±0.11c	3.54±0.1d
Sawdust biochar	100% RN	112.6±1.0b	12.6±0.2b	96.67±2.04b	36.6±3.86cd	25.25±0.29bc	27.58±0.27b	6.06±0.55b	4.11±0.7c
Waste biochar	0% RN	100.7±1.1de	8.6±0.2e	71.4±1.51d	53±11.36ab	23.8±0.24de	24.89±0.07e	3.49±0.24d	2.57±0.04f
Waste biochar	50% RN	111.6±0.8b	12.33±0.1b	94.87±1.42b	55.6±4.01ab	25.35±0.18b	26.91±0.93bc	5.83±0.2b	4.34±0.05b
Waste biochar	100% RN	116.3±0.4a	14.13±0.31a	109.6±1a	26.87±5.69d	26.55±0.2a	28.64±0.49a	6.72±0.19a	4.65±0.13a
CV%		6.2	20.6	16.5	21.8	7.9	6.6	31.3	30.0
P value		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Level of significance		**	**	**	**	**	**	**	**

Notes: **= Significant at 1% level of probability; Means that do not share same letters are significantly different at 5% level (Tukey HSD), 100% RN=76.84 kg N ha^{-1}

Table 3. Effect of organic amendments and N fertilizers on nitrogen concentration in rice grain and straw (mean ± SD)

Treatment Combination		Straw %N	Grain %N
Organic Amendments	Nitrogen		
Control	0% RN	0.34±0.06d	0.70±0.13d
Control	50% RN	0.45±0.09bc	0.95±0.19bc
Control	100% RN	0.48±0.02bc	0.96±0.04bc
Cow dung	0% RN	0.44±0.06bc	0.92±0.13bc
Cow dung	50% RN	0.51±0.17ab	1.08±0.35ab
Cow dung	100% RN	0.56±0.08a	1.13±0.04a
Sawdust biochar	0% RN	0.41±0.02cd	0.86±0.04c
Sawdust biochar	50% RN	0.46±0.03bc	0.97±0.05bc
Sawdust biochar	100% RN	0.50±0.02ab	1.03±0.07ab
Waste biochar	0% RN	0.41±0.02cd	0.86±0.03c
Waste biochar	50% RN	0.46±0.03bc	0.97±0.07abc
Waste biochar	100% RN	0.51±0.02ab	1.06±0.07ab
CV%		13.2	28.2
P value		<0.01	<0.01
Level of significance		**	**

Table 4. Soil chemical properties after harvest of rice (mean±SE)

Treatment Combination		Total N (%)	Available P (mg/Kg soil)	pH	EC (dSm^{-1})
Organic Amendments	Nitrogen				
Control	0% RN	0.07±0.00	57±9	8.26±0.02	0.12±0.00e
Control	50% RN	0.08±0.00	67±12	7.49±0.10	0.18±0.00d
Control	100% RN	0.09±0.00	73±17	7.26±0.02	0.23±0.00bc
Cow dung	0% RN	0.07±0.01	57±13	8.15±0.04	0.18±0.01d
Cow dung	50% RN	0.09±0.00	67±7	7.72±0.15	0.21±0.00 bd
Cow dung	100% RN	0.10±0.00	50±12	7.40±0.10	0.25±0.01b
Sawdust biochar	0% RN	0.07±0.00	50±0	8.14±0.01	0.18±0.01d
Sawdust biochar	50% RN	0.09±0.00	63±24	7.68±0.23	0.20±0.02cd
Sawdust biochar	100% RN	0.09±0.00	67±27	7.30±0.10	0.25±0.00b
Waste biochar	0% RN	0.07±0.00	93±23	8.42±0.05	0.19±0.01cd
Waste biochar	50% RN	0.09±0.00	47±3	7.51±0.06	0.25±0.01b
Waste biochar	100% RN	0.09±0.00	40±6	7.75±0.40	0.36±0.02a
P- value		0.43	0.30	0.38	<0.01
Level of significance		NS	NS	NS	**

Although there was no significant difference in soil N content among the treated fields after rice harvest, the highest N content was observed in the plots treated with 100% RN. Similarly, for electrical conductivity (EC), no significant differences were found among the treatments; however, the highest EC value was recorded in the plots treated with waste biochar combined with 100% RN. In addition, there were no significant differences in soil P and pH values among the treated fields after rice harvest (Table 4).

3.3. Effect of organic amendments and N fertilizer on nitrogen use efficiency and recovery

The interaction effect of organic amendments and inorganic fertilizer treatment showed a significant effect on agronomic N use efficiency (ANUE), physiological N efficiency (PNUE) and apparent N recovery (ANR) (P<0.01, Fig. 2, 3, & 4). Better nitrogen use efficiency was recorded in organic-amended treatments compared to no-organic fertilizer treatments. Among all the treatment combinations, maximum ANUE (46 kg rice grain kg^{-1} N applied) was obtained from the application of waste biochar with 50% of the recommended N and the minimum ANUE (18 kg rice grain kg^{-1} N applied) was recorded from the combination control and 50% of the recommended N (Fig. 2). The maximum (28.02 kg rice grain kg^{-1} N uptake) PNUE was obtained from the application of waste biochar with 50% of the recommended - N and the minimum PNUE (19.36 kg rice grain kg^{-1} N uptake) was observed in the combination of control and 50% of the recommended N treated plot (Fig. 3). The highest (61.03%) ANR was found from the application of waste biochar with 50% of the recommended N and the lowest ANRE (7.97%) was observed in the combination of control and 50% of the recommended N treated plot (Fig. 4).

3.4. Variables explaining grain yield and NUE

A positive relation between grain N % and straw N%, yield, and SPAD value, and yield and soil N was found (Fig. 5). Moreover, grain yield had significant positive corrections with total number of tillers, number of grains per panicle and grain weight (Fig. 6). A principal component analysis is used to generalize the variation in different among response variables. Component 1 and 2 explained 67.6% and 6.7% of the variabilities in the data set.

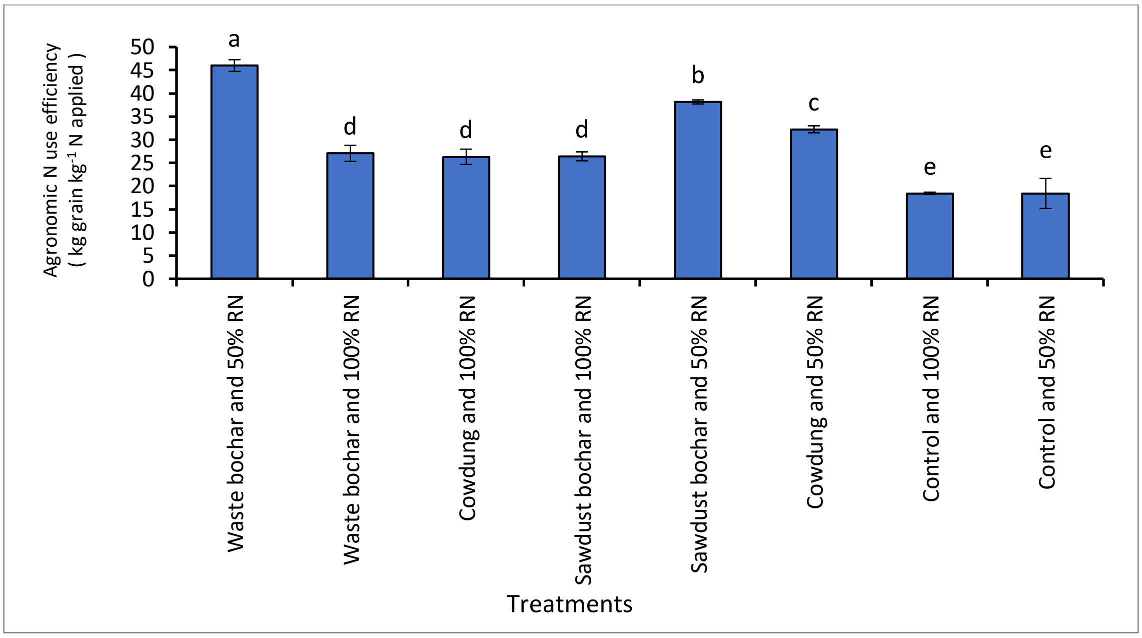


Figure 2. The interaction effect of organic amendments and N fertilizers on agronomic nitrogen use efficiency. Treatments having different lowercase letters are significantly different from each other at *P<0.05*

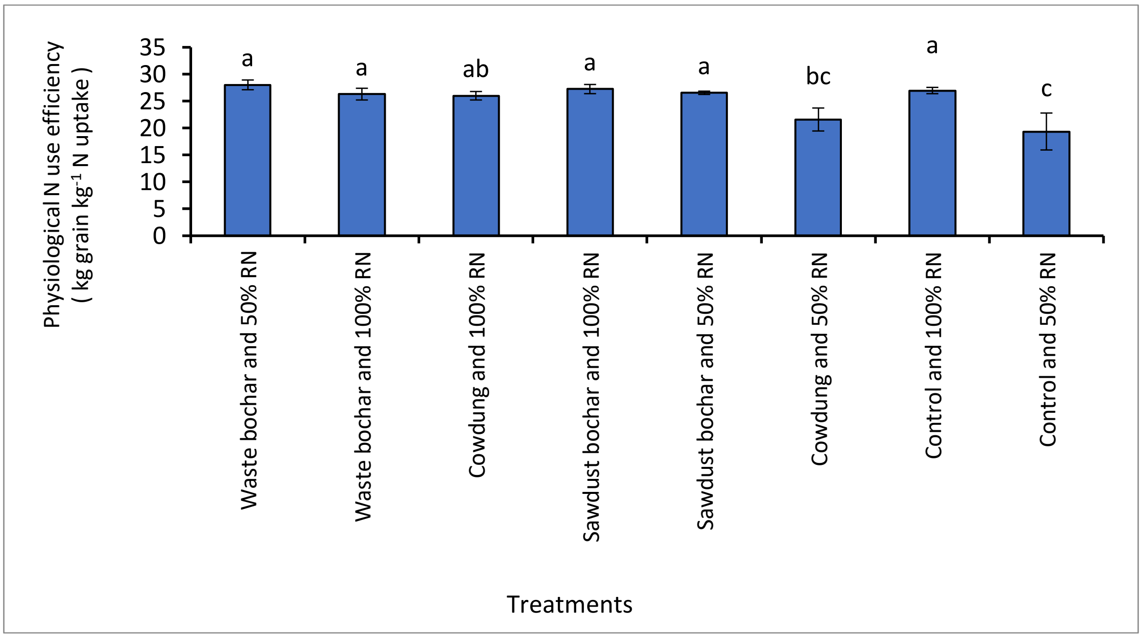


Figure 3. The interaction effect of organic amendments and N fertilizers on physiological nitrogen use efficiency. Treatments having different lowercase letters are significantly different from each other at *P<0.05*

The loading od plant performance (e.g., biomass and grain yield) was closely linked to yield contributing characters, soil N and P while their loading were opposite to soil pH (Fig. 7).

4. DISCUSSION

Biochar application along with inorganic nitrogen can significantly affect crop performance including rice through improving nutrient use efficiency (Ahmed et al., 2025; Awad et al., 2018). In our study, application of organic amendments significantly improved crop yield. Average across fertilizer treatments, the yield advantage was 52%, 27% and 32% in waste biochar, sawdust biochar, and cow dung respectively (Table 2).

Among the N application rates, the highest yield (4.07 t ha^{-1}) was obtained in the 100% RN, which is 86% greater than the control treatment. This increment was 59% when 50% RN was applied (Table 2). When organic amendment and inorganic fertilizers were applied in combination, the increment was dependent on the rate of N application. Without any N addition, the yield improvement was 24.7%, 14.3% and 41.2% with cow dung, sawdust and waste biochar application. At 50% RN, these increments were at 38.7%, 39.9% and 71.5% while N application at 100% RN rates, 32.8%, 27.2% and 44% improvement in yield were recorded in cow dung, sawdust and waste biochar, respectively. This infers that the highest yield (4.65 t ha^{-1}) was obtained from waste biochar with 100% RN compared to the control treatment receiving 100% RN (Table 2).

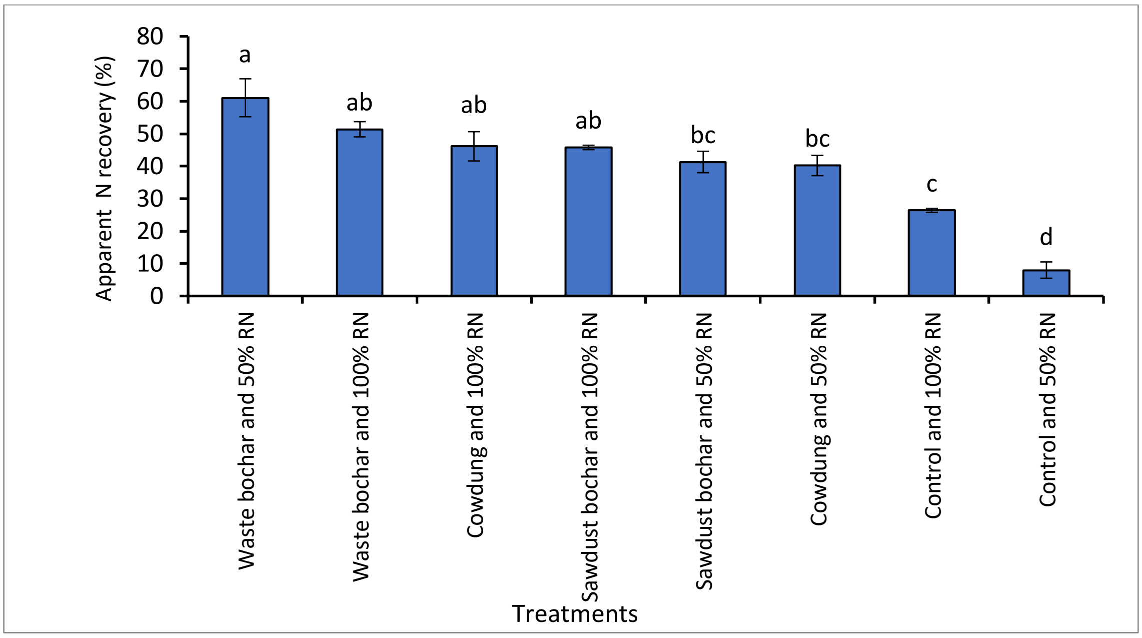


Figure 4. The interaction effect of organic amendments and N fertilizers on apparent nitrogen recovery. Treatments having different lowercase letters are significantly different from each other at *P< 0.05*

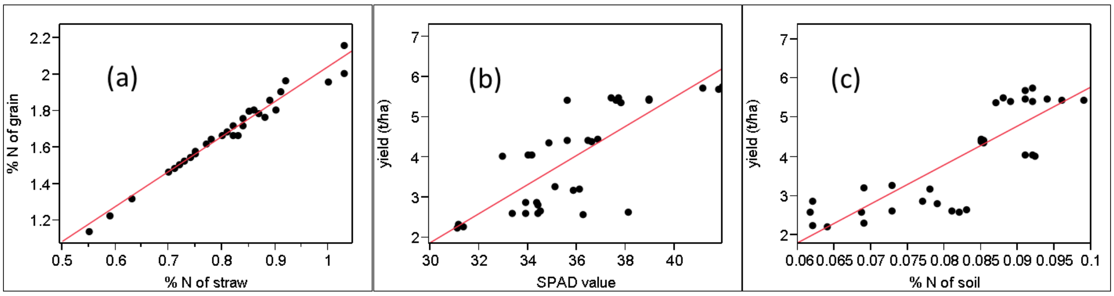


Figure 5. Relation between (a) Grain N % and Straw N% (b) Rice yield and SPAD Value (c) Rice yield and Soil total N content

Similar results were reported in the previous in different crops, such as in *Allium* (Rahayu et al., 2019), rice (Ahmed et al., 2025), and sorghum (Bhatta Kaudal & Weatherley, 2018). In contrast to our study, Liu et al. (2025) reported a reduction in rice yield with biochar-based organic fertilizers due to a reduction in N mineralization. However, a similar reduction in soil available N was not observed in our study.

Organic amendment can significantly improve crop yield as well as NUE (Yuan et al., 2024). We believe the improvement in yield in rice was primarily manifested by an increased retention of applied N on the soil reactive surfaces which was partially contributed by biochar (Ahmed et al., 2025). The nutrient was then taken up by plants and transferred to the grains (Shi et al., 2024). Significant relationship between soil total N, SPAD value, and straw N concentration with grain yield support our attribution (Fig. 5 & 6). Our PCA analysis also showed similar trends with arrows of N concentrations and grain yield in the same directions (Fig. 7). It is plausible because soil reactive surfaces might have increased due to the addition of biochar that carried a relatively a higher cation exchange capacity (Sukartono et al., 2022). Moreover, waste biochar possibly partially contributed to soil nutrition since it carried relatively a larger amount of N and P (Baquy et al., 2022; Singh et al., 2023). In addition, there was a negative relation between soil pH and grain yield suggesting that a higher pH might have caused a significant loss of N through volatilization. Volatilization of N might have been partially suppressed by organic amendments including biochar. However, soil pH in the biochar treatment was not significantly lower than control treatments. A relatively lower yield improvement in sawdust biochar treatment compared to cow dung and waste biochar treatment can be explained by its lower nutritive value (Table 1).Specifically, the N and P contents were much lower 0.73% and 0.12%, respectively, compared waste biochar (N-2.83% and P-0.23%) and cow dung (N-1.8%, P-0.44%). Therefore, the yield improvement in rice with combined application of organic and inorganic fertilizers is possibly increased through nutrient addition from organic amendment and their capacity to retain in the reactive surfaces, and supply of these nutrients to rice plant (Ahmed et al., 2025; Awad et al., 2018; Shi et al., 2024).

Application of N at right amount is critical for having a higher crop yield (Lan et al., 2026). Because a low application rate can compromise the yield while a higher application rate may reduce yield through excessive vegetative growth and lodging. In our study, the average yield improvement with different organic amendments was relatively greater with 50% RN (50.1% over control) than 100% RN (34.7% over control), suggesting that the response to fertilizer was relatively higher with a low application rate than at a higher application rate.

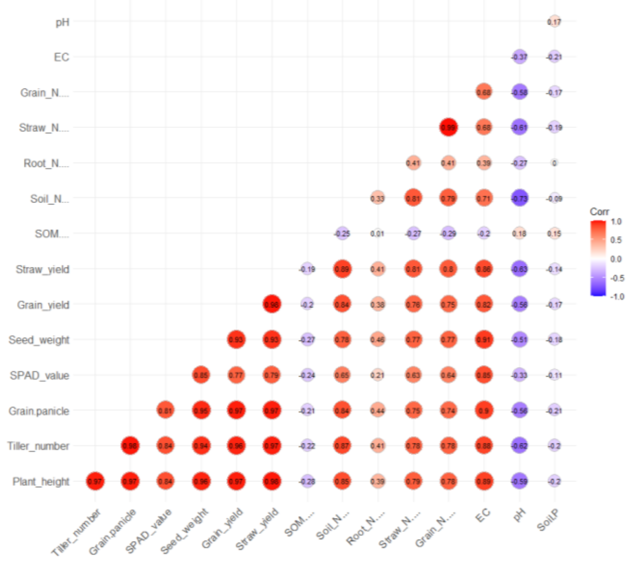


Figure 6. Pearson correlation plot of different variables

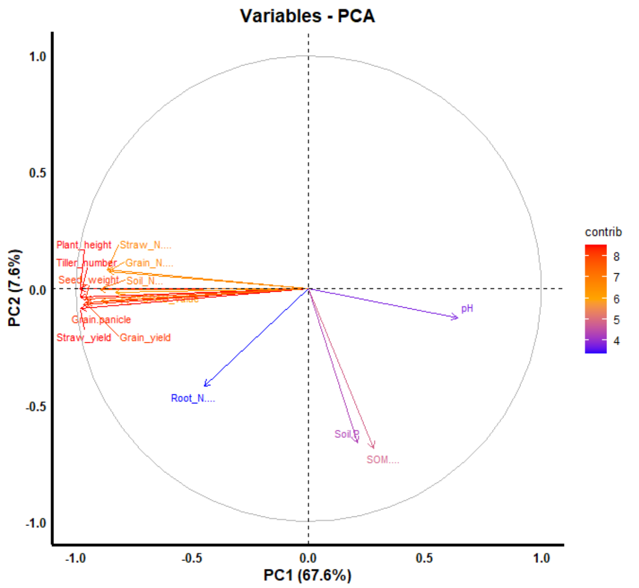


Figure 7. Principal component analysis of different variables

However, there were variations in yield improvement among different organic amendments. The N response was higher in waste biochar and cow dung treatments compared to sawdust biochar application. Although it is not certain why the response was relatively lower in sawdust biochar at 100 RN, some of the mineral N could have immobilized in this treatment.

Increasing NUE is one of the prime global agendas for sustaining agricultural production (Cassman et al., 2002; Liu et al., 2022). Because NUE is relatively low in rice production systems, there are consequences for economic loss and environmental degradation. In our study, the ANUE, PNUE, and ANR were relatively high in plots treated with waste biochar at 50% RN, although the highest yield was achieved with 100% RN (Table 3). This suggests that a reduction of N application to 50% might provide more economic benefits by lowering fertilizer costs while maintaining efficient N utilization. The biochar has been shown to enhance NUE by increasing N retention, and reducing N losses through volatilization and leaching (Ahmed et al., 2021). The application of biochar increased soil N, and enhanced crop N uptake (Jia et al., 2021). These factors suggest that the inclusion of biochar could make it possible to reduce N inputs while still achieving high NUE, which highlights biochar's ability to reduce the need for excessive N fertilization use (Yadav et al., 2019). This indicates that, although higher N rates may lead to greater yields, biochar's role in improving nutrient dynamics still supports efficient N use even at 50%RN application. Therefore, these findings underscore the importance of tailored N management strategies that balance nitrogen input and overall productivity to enhance NUE while providing economic and environmental benefits.

5. CONCLUSION

A field trial was conducted to examine the combined effect of organic amendments and inorganic N fertilizer on the yield and NUE. Among the treatment combinations, waste biochar with 100% of the recommended rate of urea application showed the highest grain yield (4.65 t ha^{-1}) and straw yield (6.72 t ha^{-1}). However, waste biochar with 50% RN showed the highest agronomic use efficiency of N. Thus, our findings show a tradeoff between yield advantage and NUE in rice production with the combined application of biochar and urea.

Declaration of Competing Interest

The authors declare that no competing personal interests may appear to influence the work reported in this paper.

Acknowledgements
The authors acknowledge the financial support from the Ministry of Education, the People's Republic of Bangladesh (LS 2018767).

References

Ahmed, M., Jaffar, M. T., Ahmad, Z., Naveed, M., Javed, S. A., Asad, M. S., . . . Zhang, J. (2025). Potential of Organic Amendments as a Sustainable Strategy to Enhance Rice Yield by Improving Nutrient Use Efficiency and Physiological Performance in Alkaline Soil. *Journal of Plant Growth Regulation*. https://doi.org/10.1007/s00344-025-11900-7

Ahmed, N., Basit, A., Bashir, S., Bashir, S., Bibi, I., Haider, Z., . . . Alotaibi, S. S. (2021). Effect of acidified biochar on soil phosphorus availability and fertilizer use efficiency of maize (*Zea mays* L.). *Journal of King Saud University-Science*, *33*(8), 101635. https://doi.org/10.1016/j.jksus.2021.101635

APHA. (2012). *Standard methods for the examination of water and wastewater* (E. W. Rice, R. B. Baird, A. D. Eaton, & L. S. Clesceri, Eds. 22nd ed.). American Public Health Association, American Water Works Association, Water Environment Federation.

Awad, Y. M., Wang, J., Igalavithana, A. D., Tsang, D. C. W., Kim, K.-H., Lee, S. S., & Ok, Y. S. (2018). Chapter One - Biochar Effects on Rice Paddy: Meta-analysis. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 148, pp. 1-32). Academic Press. https://doi.org/10.1016/bs.agron.2017.11.005

Baquy, M. A.-A., Mamun, M. A. A., Mia, S., Alam, M. M., Khan, M. S. H., & Rahman, S. M. (2022). Biochar research advancement in Bangladesh: challenges and opportunities of biochar in improving soil health. *Sains Tanah Journal of Soil Science and Agroclimatology*, *19*(2), 15. https://doi.org/10.20961/stjssa.v19i2.59758

Bhatta Kaudal, B., & Weatherley, A. J. (2018). Agronomic effectiveness of urban biochar aged through co-composting with food waste. *Waste Management*, *77*, 87-97. https://doi.org/10.1016/j.wasman.2018.04.042

BRRI. (2016). *Bangladesh Rice Knowledge Bank*. Bangladesh Rice Research Institute. https://knowledgebank-brri.org/

Cassman, K. G., Dobermann, A., & Walters, D. T. (2002). Agroecosystems, Nitrogen-use Efficiency, and Nitrogen Management. *AMBIO: A Journal of the Human Environment*, *31*(2), 132-140, 139. https://doi.org/10.1579/0044-7447-31.2.132

Chen, X., Yang, S.-H., Jiang, Z.-W., Ding, J., & Sun, X. (2021). Biochar as a tool to reduce environmental impacts of nitrogen loss in water-saving irrigation paddy field. *Journal of Cleaner Production*, *290*, 125811. https://doi.org/10.1016/j.jclepro.2021.125811

Cotrufo, M. F., Ranalli, M. G., Haddix, M. L., Six, J., & Lugato, E. (2019). Soil carbon storage informed by particulate and mineral-associated organic matter. *Nature Geoscience*, *12*(12), 989-994. https://doi.org/10.1038/s41561-019-0484-6

De Bhowmick, G., Sarmah, A. K., & Sen, R. (2018). Production and characterization of a value added biochar mix using seaweed, rice husk and pine sawdust: A parametric study. *Journal of Cleaner Production*, *200*, 641-656. https://doi.org/10.1016/j.jclepro.2018.08.002

Govindasamy, P., Muthusamy, S. K., Bagavathiannan, M., Mowrer, J., Jagannadham, P. T. K., Maity, A., . . . Tiwari, G. (2023). Nitrogen use efficiency—a key to enhance crop productivity under a changing climate [Review]. *Frontiers in Plant Science*, *Volume 14 - 2023*. https://doi.org/10.3389/fpls.2023.1121073

Guo, J., Hu, X., Gao, L., Xie, K., Ling, N., Shen, Q., . . . Guo, S. (2017). The rice production practices of high yield and high nitrogen use efficiency in Jiangsu, China. *Scientific Reports*, *7*(1), 2101. https://doi.org/10.1038/s41598-017-02338-3

Huq, S. M. I., & Shoaib, J. U. M. (2013). *The Soils of Bangladesh*. Springer Dordrecht. https://doi.org/10.1007/978-94-007-1128-0

Iqbal, A., He, L., Ali, I., Ullah, S., Khan, A., Akhtar, K., . . . Jiang, L. (2021). Co-incorporation of manure and inorganic fertilizer improves leaf physiological traits, rice production and soil functionality in a paddy field. *Scientific Reports*, *11*(1), 10048. https://doi.org/10.1038/s41598-021-89246-9

Iqbal, A., He, L., Khan, A., Wei, S., Akhtar, K., Ali, I., . . . Jiang, L. (2019). Organic Manure Coupled with Inorganic Fertilizer: An Approach for the Sustainable Production of Rice by Improving Soil Properties and Nitrogen Use Efficiency. *Agronomy*, *9*(10), 651. https://doi.org/10.3390/agronomy9100651

Jackson, M. L. (1973). *Soil Chemical Analysis: Advanced Course* (2nd ed.). Prentice- Hall of India Private Limited, New Delhi.

Jackson, M. L. (2005). *Soil Chemical Analysis: Advanced Course : a Manual of Methods Useful for Instruction and Research in Soil Chemistry, Physical Chemistry of Soils, Soil Fertility, and Soil Genesis*. UW-Madison Libraries Parallel Press.

Jangir, C. K., Kumar, S., & Meena, R. S. (2019). Significance of soil organic matter to soil quality and evaluation of sustainability. *Sustainable agriculture*, 357-381. https://www.researchgate.net/publication/332240887_Significance_of_Soil_Organic_Matter_to_Soil_Quality_and_Evaluation_of_Sustainability

Jia, Y., Hu, Z., Ba, Y., & Qi, W. (2021). Application of biochar-coated urea controlled loss of fertilizer nitrogen and increased nitrogen use efficiency. *Chemical and Biological Technologies in Agriculture*, *8*(1), 3. https://doi.org/10.1186/s40538-020-00205-4

Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A., & Lombi, E. (2019). Soil and the intensification of agriculture for global food security. *Environment International*, *132*, 105078. https://doi.org/10.1016/j.envint.2019.105078

Lan, C., Xu, H., Qin, B., Li, J., Zhang, B., Zou, J., . . . Lin, W. (2026). Optimizing water and nitrogen management to balance yield and nitrogen loss in mechanically harvested low-stubble ratoon rice. *Field Crops Research*, *336*, 110216. https://doi.org/10.1016/j.fcr.2025.110216

Leng, L., Xiong, Q., Yang, L., Li, H., Zhou, Y., Zhang, W., . . . Huang, H. (2021). An overview on engineering the surface area and porosity of biochar. *Science of The Total Environment*, *763*, 144204. https://doi.org/10.1016/j.scitotenv.2020.144204

Liu, J., Zhang, M., Pan, M., Yuan, H., Sun, S., Sun, Q., . . . Chen, W. (2025). Pig Manure and Biochar Reduce Nitrogen Availability and Rice Yield Compared to Mineral Fertilization in a Three-Year Field Experiment. *Agronomy*, *15*(9), 2242. https://doi.org/10.3390/agronomy15092242

Liu, Y., Li, H., Hu, T., Mahmoud, A., Li, J., Zhu, R., . . . Jing, P. (2022). A quantitative review of the effects of biochar application on rice yield and nitrogen use efficiency in paddy fields: A meta-analysis. *Science of The Total Environment*, *830*, 154792. https://doi.org/10.1016/j.scitotenv.2022.154792

Mia, S., Uddin, M. E., Kader, M. A., Ahsan, A., Mannan, M. A., Hossain, M. M., & Solaiman, Z. M. (2018). Pyrolysis and co-composting of municipal organic waste in Bangladesh: A quantitative estimate of recyclable nutrients, greenhouse gas emissions, and economic benefits. *Waste Management*, *75*, 503-513. https://doi.org/10.1016/j.wasman.2018.01.038

Mia, S., Uddin, N., Mamun Hossain, S. A. A., Amin, R., Mete, F. Z., & Hiemstra, T. (2015). Production of Biochar for

Soil Application: A Comparative Study of Three Kiln Models. *Pedosphere*, *25*(5), 696-702. https://doi.org/10.1016/S1002-0160(15)30050-3

Oladele, S., Adeyemo, A., Awodun, M., Ajayi, A., & Fasina, A. (2019). Effects of biochar and nitrogen fertilizer on soil physicochemical properties, nitrogen use efficiency and upland rice (*Oryza sativa*) yield grown on an Alfisol in Southwestern Nigeria. *International Journal of Recycling of Organic Waste in Agriculture*, *8*(3), 295-308. https://doi.org/10.1007/s40093-019-0251-0

Oyetunji, O., Bolan, N., & Hancock, G. (2022). A comprehensive review on enhancing nutrient use efficiency and productivity of broadacre (arable) crops with the combined utilization of compost and fertilizers. *Journal of Environmental Management*, *317*, 115395. https://doi.org/10.1016/j.jenvman.2022.115395

Piash, M. I., Iwabuchi, K., Itoh, T., & Uemura, K. (2021). Release of essential plant nutrients from manure- and wood-based biochars. *Geoderma*, *397*, 115100. https://doi.org/10.1016/j.geoderma.2021.115100

Powlson, D. S., Gregory, P. J., Whalley, W. R., Quinton, J. N., Hopkins, D. W., Whitmore, A. P., . . . Goulding, K. W. T. (2011). Soil management in relation to sustainable agriculture and ecosystem services. *Food Policy*, *36*, S72-S87. https://doi.org/10.1016/j.foodpol.2010.11.025

Rahayu, Syamsiyah, J., Cahyani, V. R., & Fauziah, S. K. (2019). The Effects of Biochar and Compost on Different Cultivars of Shallots (*Allium ascalonicum* L.) Growth and Nutrient Uptake in Sandy Soil Under Saline Water. *Sains Tanah Journal of Soil Science and Agroclimatology*, *16*(2), 13. https://doi.org/10.20961/stjssa.v16i2.34209

Rehrah, D., Bansode, R. R., Hassan, O., & Ahmedna, M. (2016). Physico-chemical characterization of biochars from solid municipal waste for use in soil amendment. *Journal of Analytical and Applied Pyrolysis*, *118*, 42-53. https://doi.org/10.1016/j.jaap.2015.12.022

Sadatshojaei, E., Wood, D. A., & Rahimpour, M. R. (2021). Potential and Challenges of Carbon Sequestration in Soils. In *Applied Soil Chemistry* (pp. 1-21). https://doi.org/10.1002/9781119711520.ch1

Septiana, L. M., Djajakirana, G., & Darmawan. (2018). Characteristics of Biochars from Plant Biomass Wastes at Low-Temperature Pyrolysis. *Sains Tanah Journal of Soil Science and Agroclimatology*, *15*(1), 14. https://doi.org/10.15608/stjssa.v15i1.21618

Sharma, L. K., & Bali, S. K. (2018). A Review of Methods to Improve Nitrogen Use Efficiency in Agriculture. *Sustainability*, *10*(1), 51. https://doi.org/10.3390/su10010051

Shi, G., Hou, R., Li, T., Fu, Q., Chen, Q., Xue, P., & Yang, X. (2024). Effects of biochar on the transformation and utilization of nitrogen fertilizer in the black soil region of Northeast China. *Science of The Total Environment*, *953*, 176218. https://doi.org/10.1016/j.scitotenv.2024.176218

Singh, D., Mishra, A. K., Patra, S., Mariappan, S., Singh, N., & Kar, S. K. (2023). Spatial variability of soil hydraulic and physical properties in erosive sloping agricultural fields. *Water Science and Engineering*, *16*(1), 57-66. https://doi.org/10.1016/j.wse.2022.10.001

Sukartono, Kusumo, B. H., Suwardji, S., Bakti, A. A., Mahrup, Susilowati, L. E., & Fahrudin. (2022). Influence of biochar amendments on the soil quality indicators of sandy loam soils under cassava–peanut cropping sequence in the semi-arid tropics of Northern Lombok, Indonesia. *Sains Tanah Journal of Soil Science and Agroclimatology*, *19*(2), 6. https://doi.org/10.20961/stjssa.v19i2.65452

Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology*, *19*(1), 191-215. https://doi.org/10.1007/s11157-020-09523-3

Tyagi, J., Ahmad, S., & Malik, M. (2022). Nitrogenous fertilizers: impact on environment sustainability, mitigation strategies, and challenges. *International Journal of Environmental Science and Technology*, *19*(11), 11649-11672. https://doi.org/10.1007/s13762-022-04027-9

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, *37*(1), 29-38. https://journals.lww.com/soilsci/fulltext/1934/01000/an_examination_of_the_degtjareff_method_for.3.aspx

Yadav, V., Karak, T., Singh, S., Singh, A. K., & Khare, P. (2019). Benefits of biochar over other organic amendments: Responses for plant productivity (*Pelargonium graveolens* L.) and nitrogen and phosphorus losses. *Industrial Crops and Products*, *131*, 96-105. https://doi.org/10.1016/j.indcrop.2019.01.045

Yuan, X., Gu, X., Liang, R., Ban, G., Ma, L., He, T., & Wang, Z. (2024). Comparing combined application of biochar and nitrogen fertilizer in paddy and upland soils: Processes, enhancement strategies, and agricultural implications. *Science of The Total Environment*, *933*, 173160. https://doi.org/10.1016/j.scitotenv.2024.173160