



RESEARCH ARTICLE

# Effect of residue management and biochar based slow-release nitrogen fertilizers on growth, yield and economics of wheat under Tarai region of India

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## Abstract

Efficient residue and nitrogen management are critical for sustaining wheat productivity in the Tarai region of India, where rice-wheat cropping systems are constrained by residue disposal and low nitrogen use efficiency. A two-year field experiment (2019-20 and 2020-21) was conducted to evaluate the combined effects of residue management and biochar-based slow-release nitrogenous fertilizers (SRNFs) on growth, yield and economics of wheat. The experiment comprised residue removal, residue incorporation and rice straw biochar application, each combined with nitrogen supplied through conventional urea, biochar-coated urea (BCU) and rice straw biochar-based urea (RSBU) at 75 % and 100 % of the recommended N dose. Results revealed that both residue and nitrogen management practices significantly ( $p < 0.05$ ) affected growth and productivity of wheat. Biochar incorporation enhanced plant height, tiller density and dry matter accumulation compared to residue removal. Among nitrogen treatments, 100 % recommended N rate applied via SRNFs (BCU and RSBU) produced 7-11 % higher dry matter and 6-9 % greater grain yield than conventional urea, while 75 % N through SRNFs achieved yields comparable to N applied via 100 % urea, indicating improved nitrogen use efficiency. Enhanced SPAD, NDVI and Fv/Fm values under SRNFs reflected greater chlorophyll content and sustained photosynthetic activity. Economically, the highest net return and benefit-cost ratio were obtained from the combination of biochar incorporation with 100 % N applied through RSBU, followed by 100 % N via BCU. Despite slightly higher production costs, biochar-based fertilizers substantially improved profitability. Overall, integrating rice straw biochar with biochar-based slow-release urea offers a sustainable and resource-efficient strategy for enhancing wheat productivity and profitability under the Tarai agro-ecological conditions.

**Keywords:** biochar; nitrogen management; nitrogen use efficiency; residue management; slow-release N fertilizers; Tarai region

## Introduction

The rice-wheat cropping system (RWCS) is the most dominant cereal rotation in the Indo-Gangetic Plains (IGP), occupying nearly 13.5 million hectares and contributing about half of India's total food grain consumption (1). Despite its pivotal role in ensuring national food security, the long-term sustainability of this system is threatened by multiple biophysical and environmental constraints, including over-extraction of groundwater, declining soil organic matter, nutrient imbalances, low nitrogen use efficiency (NUE) and inefficient crop residue management (2). The alternate anaerobic-aerobic soil conditions under rice and wheat alter soil structure and biogeochemistry, leading to hardpan formation that restricts root growth in the succeeding wheat crop. Residue burning, particularly of rice straw, has emerged as a major challenge in northwestern India. Rice alone contributes nearly one-third of the total crop

residue biomass and about 100 Mt of rice straw are burnt annually to expedite field preparation for wheat (3). In-situ burning results in substantial nutrient loss, soil degradation and greenhouse gas emissions. Hence, developing sustainable residue management strategies is essential to maintain soil fertility and reduce environmental impacts. Converting rice residues into biochar through pyrolysis offers a viable alternative, as it transforms unstable biomass into a stable carbon-rich material with high surface area, porosity, cation exchange capacity and long-term stability (4, 5). Biochar application has been shown to improve soil aeration, moisture retention, nutrient availability and microbial activity, thereby enhancing soil productivity and carbon sequestration (6, 7). Nitrogen remains the most limiting macro-nutrient for wheat production in the IGP, with urea serving as the predominant N source. However, conventional urea suffers from high N losses

ranging from 20 to 70 % through leaching, volatilization and gaseous emissions (8). These losses not only reduce NUE but also contribute to environmental pollution. Slow or controlled-release nitrogen fertilizers have been developed to synchronize N release with crop demand, thereby improving uptake efficiency and reducing losses (9). The effectiveness of SRNFs largely depends on the coating material, which regulates nutrient diffusion. Although synthetic polymers are commonly used as coatings, they are costly, environmentally persistent and often lack biodegradability (10, 11). Biochar, with its high cation exchange capacity and microporous structure, offers a sustainable alternative substrate for coating urea granules. Biochar absorbs and retains nutrients primarily through physical adsorption on its surface and chemical interaction via functional groups preventing nutrient being lost to environment (12). Biochar-based SRNFs not only enhance nitrogen use efficiency and crop productivity but also provide a productive use for agricultural waste, thus supporting circular nutrient management. However, research on the combined effects of residue-derived biochar and biochar-based SRNFs on wheat performance under the Tarai agro-ecological conditions of India remains limited. Therefore, the present study was conducted to address the research gap and inefficient residue management strategies via biochar and biochar based SRNFs in the Tarai region of India.

## Materials and Methods

### Experimental site, climate and soil characteristics

A field experiment was conducted during 2019-20 and 2020-21 at the Norman E. Borlaug Crop Research Centre, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India (28.97°N, 79.41°E; 243.8 m above mean sea level). The site lies in the Tarai region of the northwestern Indo-Gangetic Plains, approximately 30 km south of the Shivalik foothills of the Himalayas. The climate is subtropical and sub-humid, characterized by hot summers (March-June) and mild winters (November-February), with an average annual rainfall of 1450 mm, mostly received during the monsoon season (June-September). The experimental soil, derived from alluvial deposits of the Bhabar-Tarai system, was sandy loam in texture, moderately fertile and well-drained. Pre-experimental soil analysis conducted using standard procedures (OC: Wakley and Blackmann (1956), Available N: Alkaline potassium permanganate method and P: Olsen-P) indicated a pH of 7.06, organic carbon content of 0.72 % and available N, P and K of 190.6, 22.4 and 238.5 kg ha<sup>-1</sup>, respectively.

### Treatment details and experimental design

The experiment was conducted to evaluate the combined effects of crop residue management and biochar-based SRNFs on wheat productivity and economics. Treatments were arranged in a split-plot design with three replications. Main plots comprised three residue management practices: (i) Residue removal (RR); (ii) Residue incorporation (RI) at 4 t ha<sup>-1</sup>; and (iii) Rice straw biochar incorporation (BCI) at 4 t ha<sup>-1</sup>. The subplots consisted of six nitrogen management treatments: (i) Control (no nitrogen); (ii) 100 % recommended N (RDN) through urea; (iii) 100 % RDN through rice straw biochar-based urea (RSBU); (iv) 100 % RDN through biochar-coated urea (BCU); (v) 75 % RDN through RSBU; (vi) 75 % RDN through BCU. Rice straw biochar was produced at 450 °C using a laboratory-scale pyrolysis reactor. Biochar-based SRNFs (RSBU and BCU) were developed following intercalation and coating processes that enable gradual nitrogen release (13). RSB 450 biochar (60-mesh) was mixed

with a urea solution (200 g urea in 1:2 water) and pre-stirred at 40 °C. The biochar-urea mixture (2:1) was ultrasonicated to enhance urea sorption, then subjected to water bath and dried at 50 °C following a final shade-drying to obtain the bio-urea composite (RSBU). BCU was produced by coating commercial urea prills in a motorized rotary pan with hot air (60 °C). Urea was first heated for 15 min, then coated with 5 % gum acacia, followed by biochar dusting. A thin wax layer (1 %) was sprayed and covered with a second biochar coating (13). Continuous pan rotation and hot air ensured uniform coating and drying.

### Crop management and observations

Wheat (*Triticum aestivum* L., cv. HD 2967) was sown at a seed rate of 100 kg ha<sup>-1</sup> in rows spaced 22.5 cm apart. Residue or biochar was applied and incorporated during final land preparation. The recommended fertilizer dose for wheat was 150:60:40 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O ha<sup>-1</sup>, with corresponding rates for 75 % N treatments. Phosphorus and potassium were supplied through single super phosphate (16 % P<sub>2</sub>O<sub>5</sub>) and muriate of potash (60 % K<sub>2</sub>O), respectively. Nitrogen supplied through urea, biochar coated urea (BCU) and Rice straw bio-urea (RSBU). One-third of N and the full P and K were applied as basal, while the remaining N was top-dressed in three equal splits at basal, 25 and 50 days after sowing (DAS).

Crop was harvested manually at physiological maturity, leaving 5 cm stubble height. Growth parameters- plant height, tiller number and dry matter accumulation were recorded at 90 DAS from representative plants in each plot. Physiological traits including chlorophyll content (SPAD), normalized difference vegetation index (NDVI) and chlorophyll fluorescence (Fv/Fm) were measured at 60 DAS using a SPAD-502-m, Green Seeker handheld sensor and Opti-Sciences OS30P fluorometer, respectively. Yield attributes such as number of spikes m<sup>-2</sup>, grains spike<sup>-1</sup>, test weight (1000-grain weight) and grain weight spike<sup>-1</sup> were determined using standard agronomic procedures. Grain and straw yields were recorded from the net plot area after threshing and expressed in t ha<sup>-1</sup>. The harvest index (HI) was computed as the ratio of grain yield to total biological yield. Economic analysis included computation of cost of cultivation, gross return, net return and benefit-cost (B:C) ratio. Gross returns were calculated using the prevailing minimum support price (MSP) for wheat grain and the local market price of straw. Net return was obtained by subtracting the total cost of cultivation from the gross return and the B:C ratio was derived accordingly. Further, agronomic efficiency (AE) and crop recovery efficiency of applied SRNF were calculated by following the equations (i & ii) proposed by previous researchers (14):

$$AE = (Y_t - Y_c) \div F \dots\dots\dots(i)$$

$$CRE = (U_t - U_c) \div F \dots\dots\dots(ii)$$

Where Y<sub>t</sub> and Y<sub>c</sub> refer to the grain yield (kg ha<sup>-1</sup>) of wheat in SRNFs treated plots and control plots, respectively. Similarly, U<sub>t</sub> and U<sub>c</sub> refer to N uptake by wheat (kg ha<sup>-1</sup>) in SRNFs treated plots and control plots, respectively and F refers to the rate of N fertilizer application (kg ha<sup>-1</sup>). Then the available nitrogen in the post-harvest soil was determined by the alkaline potassium permanganate method (15).

### Statistical analysis

Data on growth, yield and economics from both years were analysed separately using analysis of variance (ANOVA) appropriate for the split-plot design (16). Treatment means were compared using the least significant difference (LSD) test at  $p \leq 0.05$ . Graphical representations were prepared using Microsoft Excel (2013). Both residue management and N sources enhanced growth and yield,

but their effects were independent. The benefit of biochar/residue retention remained consistent across all N sources, resulting in a non-significant interaction. Moreover, uniform experimental conditions (soil properties, irrigation and management) minimized variability, preventing differential responses of N sources under different residue levels.

## Results

### Plant growth

Residue management practices and biochar-based slow-release urea formulations significantly ( $p < 0.05$ ) influenced wheat growth parameters, including plant height, tiller density, dry matter accumulation and physiological attributes (SPAD, NDVI and Fv/Fm) across both experimental years (Table 1).

Under residue management during both years of the trial biochar application and residue incorporation recorded significantly higher plant height at 90 DAS and outperformed residue removal. At harvest during 2019-20, the dry matter accumulation under biochar ( $905.8 \text{ g m}^{-2}$ ) was found to be significantly higher than residue removal ( $877 \text{ g m}^{-2}$ ) but was comparable with residue incorporation ( $814.7 \text{ g m}^{-2}$ ), while in 2020-21 the dry matter recorded under application of biochar ( $939.6 \text{ g m}^{-2}$ ) was significantly higher than both residue incorporation ( $910.7 \text{ g m}^{-2}$ ) and removal of crop residue ( $853.8 \text{ g m}^{-2}$ ), which could be attributed to increased tillering and plant height, as both are responsible for increased dry matter yield. Similarly, a comparable pattern was observed for dry matter accumulation, which was markedly higher under biochar application followed by residue incorporation compared to residue removal. Tiller density at 90 DAS was comparable between biochar application and residue incorporation during the first year but was significantly higher under biochar application in the second year. SPAD, NDVI and Fv/Fm value exhibited no statistically significant differences among residue treatments. Though statistically insignificant but higher SPAD, NDVI and Fv/Fm values were consistently recorded under biochar application, suggesting

improved physiological performance and nitrogen use efficiency.

Nitrogen management through biochar-based slow-release urea formulation exerted a pronounced effect on wheat growth attributes at all growth stages. The application of 100 % N through biochar-based coated urea (BCU at 100 % N) consistently resulted in the greatest plant height, tiller number and dry matter accumulation, comparable to rice straw biochar intercalated urea (RSBU at 100 % N) and conventional urea at the same N rate. At harvest during both the years, the plant with 100 % N supplementation through SRNFs (BCU at 100 % N) was 4 to 5 % higher than height recorded with 100 % N application using commercial urea. The slow-release formulations (BCU at 100 % N and RSBU at 100 % N) produced approximately 7-11 % higher biomass than conventional urea. Tiller density under 100 % N slow-release treatments remained statistically at par with conventional urea but was significantly superior to control treatments. SPAD, NDVI and Fv/Fm values were also maximized under BCU at 100 % N, reflecting higher chlorophyll content and better photosynthetic efficiency. Although differences among the slow-release and conventional urea treatments were generally non-significant, the numerical superiority of biochar-based formulations highlights their potential in sustaining plant vigour under the Tarai conditions.

### Yield attributes

Yield attributes of wheat, including spike density ( $\text{m}^{-2}$ ), grains per spike, test weight and grain weight per spike, were significantly ( $p < 0.05$ ) affected by residue management and biochar-based slow-release nitrogen fertilizer treatments during both experimental years (Table 2). Residue management significantly influenced all yield attributes across both seasons. The incorporation of rice straw biochar consistently produced the highest spike density, which was statistically like residue incorporation but significantly greater than residue removal. Likewise, the number of grains per spike and grain weight per spike were highest under biochar application, comparable to residue incorporation and significantly superior to residue removal.

**Table 1.** Effect of residue management and biochar based slow released nitrogen fertilizer on growth parameters of wheat during 2019-20 & 2020-21

	Plant height at 90 DAS (cm)		Dry matter accumulation ( $\text{g m}^{-2}$ )		Number of tillers ( $\text{m}^{-2}$ )		SPAD value at 60 DAS		NDVI values at 60 DAS		Fv/Fm values at 60 DAS	
	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21
<b>Residue management (R)</b>												
<b>R1:</b> Residue removal	74.5	90.4	814.7	853.8	434	444	37.9	39.13	0.61	0.65	0.71	0.71
<b>R2:</b> Residue incorporation ( $4 \text{ t ha}^{-1}$ )	77.6	93.6	877.0	910.7	457	468	39.71	40.94	0.64	0.68	0.72	0.71
<b>R3:</b> Residue as biochar ( $4 \text{ t ha}^{-1}$ )	80.4	96.9	905.8	939.6	492	498	40.03	40.87	0.67	0.70	0.72	0.72
<b>SEm+</b>	0.71	1.13	15.68	16.52	10	8	0.96	0.77	0.01	0.01	0.01	0.01
<b>CD at 5%</b>	2.8	4.5	61.57	64.84	40	30	NS	NS	NS	NS	NS	NS
<b>Nitrogen management (N)</b>												
<b>N1:</b> Control	38.0	39.5	442.3	535.8	354	370	31.38	32.61	0.45	0.49	0.63	0.61
<b>N2:</b> Urea at 100% N	85.0	82.4	936.7	940.4	476	488	40.95	42.18	0.67	0.71	0.72	0.73
<b>N3:</b> RSBU at 100% N	86.9	88.2	983.7	992.5	493	503	42.41	43.19	0.70	0.73	0.75	0.75
<b>N4:</b> BCU at 100% N	90.5	93.5	993.9	1017	508	518	41.3	42.22	0.69	0.72	0.74	0.74
<b>N5:</b> RSBU at 75% N	80.8	77.4	892.9	953.1	465	460	39.82	41.1	0.67	0.7	0.73	0.73
<b>N6:</b> BCU at 75% N	83.9	84.8	945.6	969.6	470	480	39.4	40.62	0.64	0.68	0.70	0.72
<b>SEm+</b>	2.04	1.87	17.07	17.02	11	11	0.77	1.10	0.02	0.01	0.01	0.02
<b>CD at 5%</b>	5.9	5.4	49.29	49.14	32	31	2.22	3.16	0.05	0.04	0.04	0.05
<b>Interaction R*N</b>	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Where, DAS- days after sowing; RSBU- Rice straw biochar-based urea; BCU- Biochar-coated urea

**Table 2.** Effect of residue management and biochar based slow released nitrogen fertilizer on yield attributes of wheat during 2019-20 & 2020-21

Treatment	No. of spikes m <sup>-2</sup>		No. of grains per spike		Test weight (g)		Grain weight per spike (g)	
	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21
<b>Residue management (R)</b>								
<b>R1:</b> Residue removal	366	370	43	44	38.89	39.13	1.60	1.69
<b>R2:</b> Residue incorporation (4 t ha <sup>-1</sup> )	381	385	46	47	39.08	39.31	1.76	1.78
<b>R3:</b> Residue as biochar (4 t ha <sup>-1</sup> )	390	395	49	50	39.13	39.20	1.86	1.92
<b>SEm±</b>	4	4	1.10	1.09	0.23	0.19	0.05	0.04
<b>CD at 5%</b>	15	17	4	4	NS	NS	0.19	0.15
<b>Nitrogen management (N)</b>								
<b>N1:</b> Control	275	266	35	33	36.35	36.00	1.25	1.21
<b>N2:</b> Urea at 100% N	400	405	47	49	39.81	40.24	1.78	1.84
<b>N3:</b> RSBU at 100% N	405	410	49	51	40.12	40.41	1.96	2.03
<b>N4:</b> BCU at 100% N	418	427	51	53	40.42	40.55	2.02	2.11
<b>N5:</b> RSBU at 75% N	384	388	46	47	38.59	38.99	1.68	1.75
<b>N6:</b> BCU at 75% N	395	400	48	49	38.91	39.16	1.76	1.81
<b>SEm±</b>	6.34	7.84	1.12	1.10	0.52	0.50	0.05	0.04
<b>CD at 5%</b>	17	21	3	3	1.49	1.46	0.13	0.12
<b>Interaction R*N</b>	NS	NS	NS	NS	NS	NS	NS	NS

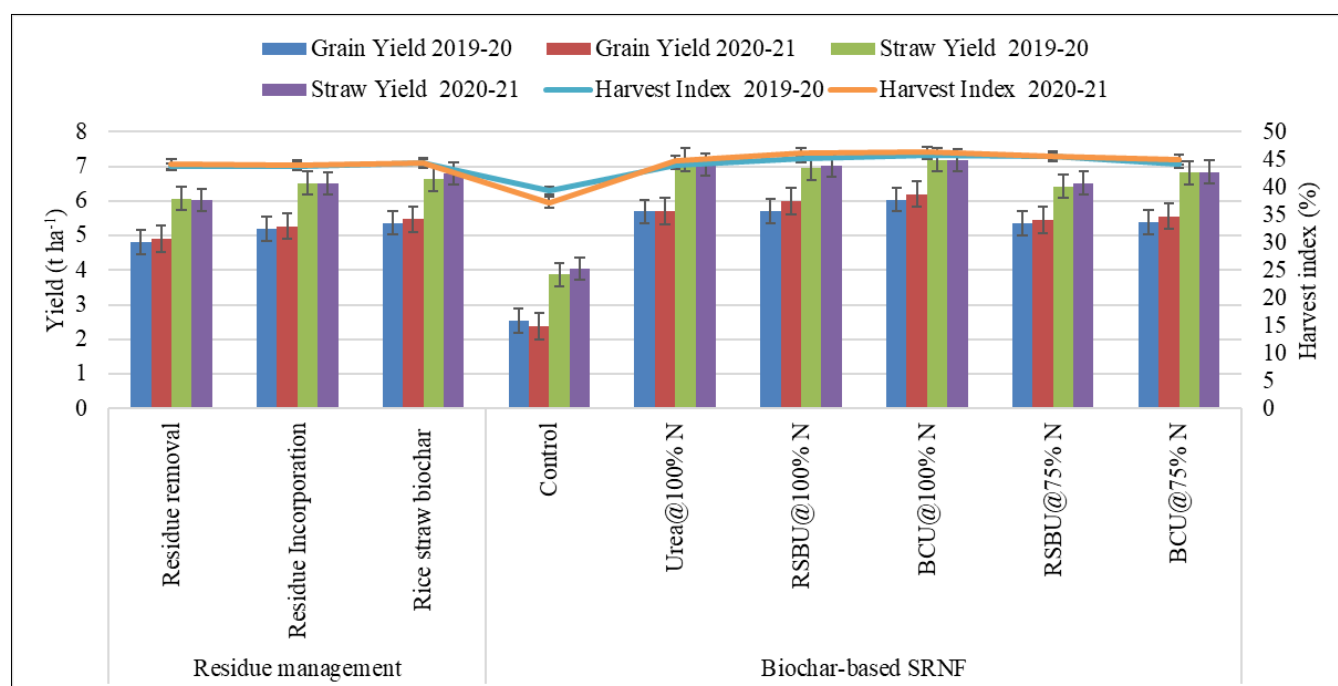
Where, RSBU- Rice straw biochar-based urea; BCU- Biochar-coated urea

Nitrogen management practices exerted a strong influence on yield attributes. Application of 100 % N through biochar-coated urea (BCU at 100 % N) produced the maximum number of spikes per unit area, statistically comparable to rice straw biochar-based urea (RSBU at 100 % N) but significantly higher than other N management treatments in both years. Similarly, the highest number of grains per spike was recorded under BCU at 100 % N, which remained statistically comparable with RSBU at 100 % N and BCU at 75 % N. Differences among these treatments were not significant in the second year, indicating stable performance of slow-release formulations across seasons. Test weight was also maximized under BCU at 100 % N, closely followed by RSBU at 100 % N and conventional urea at equivalent N levels. Grain weight per spike exhibited a similar trend, with BCU at 100 % N producing the highest values, statistically comparable to RSBU at 100 % N but significantly higher than

conventional urea and reduced-N treatments.

### Yield

Grain, straw and the harvest index (HI), were significantly ( $p < 0.05$ ) affected by residue management and biochar-based slow-release nitrogen fertilizer treatments during both years of experimentation (Fig. 1). Residue management practices had a pronounced impact on wheat productivity. Rice straw biochar application consistently produced the highest grain and straw yields across both seasons, followed closely by direct residue incorporation. Residue removal resulted in the lowest yields. On average, grain yield under biochar application exceeded residue removal by approximately 10-11 % and residue incorporation by 2-3% across the two years. Straw yield exhibited a similar pattern, with biochar and residue incorporation treatments producing significantly greater biomass than residue



**Fig. 1.** Effect of residue management and biochar based slow released nitrogen fertilizer on yield and harvest index of wheat during 2019-20 & 2020-21; Where, RSBU- Rice straw biochar-based urea; BCU- Biochar-coated urea.

removal. Although differences in harvest index among residue treatments were not statistically significant, slightly higher HI values were recorded under biochar application.

Among the nitrogen management practices, application of 100 % N through biochar-coated urea (BCU at 100 % N) consistently produced the highest grain yield during both seasons, statistically comparable to rice straw biochar-based urea (RSBU at 100 % N) and conventional urea at equivalent N levels in the first year and to RSBU at 100 % N alone in the second year. On average, the slow-release BCU at 100 % N treatment achieved 6-9 % higher grain yield compared with conventional urea. Straw yield followed a similar trend, with BCU at 100 % N producing the greatest biomass, statistically comparable to RSBU at 100 % N and conventional urea treatments, but significantly superior to reduced N and control treatments. Harvest index varied modestly among nitrogen treatments but tended to be highest under BCU at 100 % N. Additionally, the grain yield demonstrated a strong correlation ( $R^2=0.90-0.99$ ) with yield attributes, SPAD and NDVI value (Fig. 2). However, the interaction effect between the main-plot and subplot was not significant.

### Economics

Economic parameters, including cost of cultivation, gross return, net return and benefit-cost (B:C) ratio, were significantly ( $p < 0.05$ ) affected by residue management and biochar-based slow-release urea application during both cropping years (Table 3). The cost of cultivation was relatively higher under treatments involving rice straw biochar and biochar-based slow-release fertilizers, likely due to the additional expenses associated with biochar production and coating processes. Despite the higher initial investment, these treatments yielded substantially greater economic returns owing to improved grain and straw yields.

Among the evaluated treatments, the combination of biochar incorporation with rice straw biochar-based slow-release urea at 100 % N (BCI + RSBU at 100 % N) consistently produced the highest net return and B:C ratio across both years, followed closely by BCI + BCU at 100 % N and residue incorporation with conventional urea at 100 % N. Treatments receiving 75 % N through biochar-based slow-release formulations (BCI + RSBU at 75 % N and BCI + BCU at 75 % N) also achieved favourable returns, demonstrating the potential for partial N substitution without significant economic loss.

### Nitrogen use efficiency and post-harvest soil N

Residue and nitrogen management practices significantly influenced nitrogen use efficiency (NUE) across both years of experimentation (Fig. 3). Agronomic efficiency (AE) and recovery efficiency (RE) were consistently highest under rice straw biochar, which remained statistically at par with residue incorporation but significantly superior to residue removal. Slow-release nitrogen fertilizers also demonstrated enhanced NUE, with BCU at 75 % N and RSBU at 75 % N recording the greatest AE (27.7-31.0 kg GY kg<sup>-1</sup> N) and RE, outperforming 100 % commercial urea by 19-28 % across both years. Biochar-based slow-release fertilizers, even at reduced nitrogen rates (75 % N), recorded higher efficiencies than conventional urea applied at full dose, indicating improved N utilization and reduced losses.

Post-harvest soil N was significantly improved by residue retention either through incorporation or biochar conversion, resulting in 3.4 % to 10.3 % higher available N than residue removal

by the second year (Fig. 4). Nitrogen management practices also enhanced soil available N, with the maximum values observed under RSBU at 100 % N (227.9-236.9 kg ha<sup>-1</sup>), which was significantly superior to 100 % urea. Treatments with RSBU at 75 % N and BCU at 75 % N were statistically comparable with urea at 100 % N, indicating the potential to reduce fertilizer N inputs without compromising soil N status. Overall, slow-release nitrogen fertilizers and residue retention strategies contributed to improved nitrogen use efficiency and enhanced post-harvest soil N reserves.

## Discussion

The present study demonstrated that residue management and biochar-based SRNFs significantly influenced wheat growth, yield and economic performance under the Tarai region of India. The improved growth and yield observed with biochar application can be attributed to multiple beneficial effects of biochar on soil physico-chemical and biological properties.

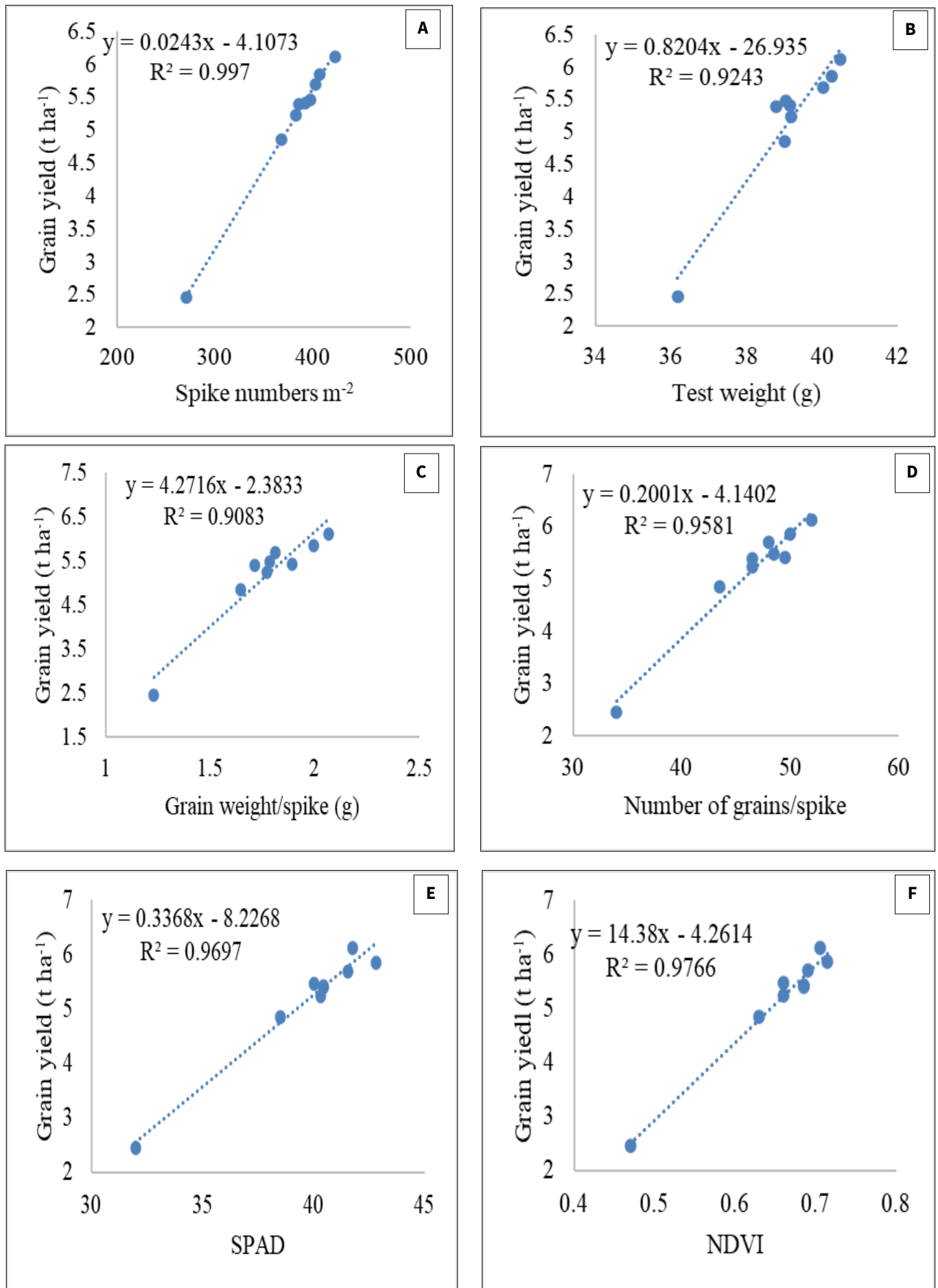
### Effect of biochar and residue management on growth and physiology

The stimulating effect of biochar on plant growth observed in this study is consistent with earlier findings (17, 18). Biochar addition improves soil aeration, water retention and nutrient bioavailability, leading to better root growth and nutrient uptake. Rice straw biochar micro pores are associated with sorptivity against any molecule taken for sorption and this polymeric carbon network regulates water permeation into biochar, thereby controlling nutrient release in soil. Rice straw biochar also serves as a reservoir of essential plant nutrients and interacts with soil minerals to enhance the slow release of N, P, K and S, particularly under slightly alkaline conditions (19). Biochar amendments improve soil organic matter, porosity, cation exchange capacity (CEC) and the retention of polyvalent cations (20), creating a favourable soil environment for sustained plant growth (21). These improvements promote enhanced tillering, greater canopy development and increased dry matter accumulation.

Physiological parameters such as SPAD, NDVI and Fv/Fm were also improved with biochar and SRNFs. These indices are well-recognized indicators of photosynthetic efficiency and nitrogen status and are positively correlated with grain yield (22). Higher SPAD and NDVI values under biochar treatments suggest increased chlorophyll concentration and improved photosynthetic performance, likely due to enhanced nitrogen and moisture availability (23, 24). Biochar-treated plots showed higher leaf chlorophyll content, reflecting greater N uptake efficiency (25). Similarly, slow-release nitrogen formulations synchronized N release with crop demand, maintaining optimal nutrient supply and higher photosynthetic activity throughout the growing season (26).

### Role of biochar-based slow-release nitrogen fertilizers

The superiority of biochar-based SRNFs over conventional urea in promoting plant growth can be attributed to their ability to minimize nitrogen losses and ensure gradual nutrient availability. Conventional urea releases N rapidly, leading to volatilization and leaching losses that reduce uptake efficiency (27). In contrast, biochar-based coated fertilizers maintain a steady supply of nitrogen through controlled dissolution and prolonged release enhancing crop performance. Limited nitrogen release caused by the physical barrier (biochar, acacia and paraffin wax) in BCU, as well as

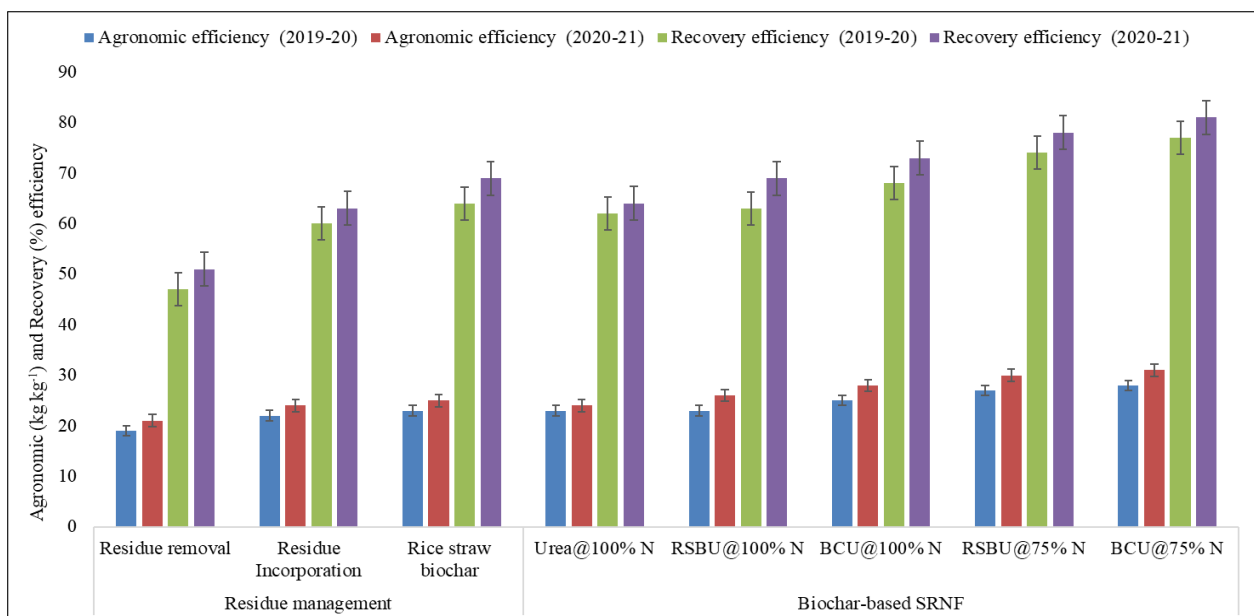
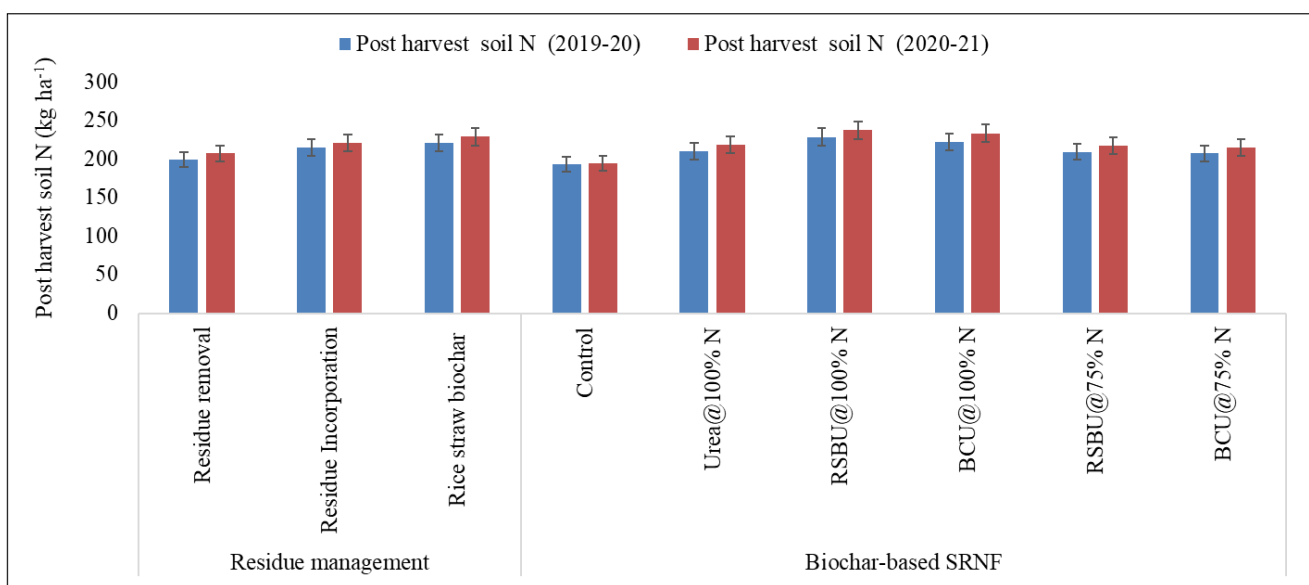


**Fig. 2.** Correlation between (A) Grain yield and number of spikes, (B) Grain yield and Test Weight (C) Grain yield and grain weight/spike (g) (D) Grain yield and number of grains/spike (E) Grain yield and SPAD (F) Grain yield and NDVI as influenced by residue and nitrogen management practices.

**Table 3.** Effect of residue management and biochar based slow released nitrogen fertilizer on economics of wheat during 2019-20 & 2020-21

Treatment	Cost of Cultivation (Wheat)							
	Cost of cultivation (Rs ha <sup>-1</sup> )		Gross returns (Rs ha <sup>-1</sup> )		Net returns (Rs ha <sup>-1</sup> )		B:C ratio	
	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21
<b>Residue management (R)</b>								
<b>R1:</b> Residue removal	35092	37357	88412	94314	53320	59222	2.50	2.67
<b>R2:</b> Residue incorporation (4 t ha <sup>-1</sup> )	33512	35557	95670	101383	62158	67871	2.84	3.00
<b>R3:</b> Residue as biochar (4 t ha <sup>-1</sup> )	38412	40357	98501	105212	60089	66800	2.55	2.72
<b>SEm±</b>	-	-	1812	1849	1812	1849	0.05	0.06
<b>CD at 5%</b>	-	-	7114	7260	NS	NS	0.21	0.22
<b>Nitrogen management (N)</b>								
<b>N1:</b> Control	33132	35217	46777	45580	13645	12448	1.41	1.37
<b>N2:</b> Urea at 100% N	35688	37773	104737	109768	69049	74080	2.94	3.08
<b>N3:</b> RSBU at 100% N	37988	40073	105146	115543	67158	77555	2.77	3.05
<b>N4:</b> BCU at 100% N	36988	39073	111136	119393	74148	82405	3.01	3.23
<b>N5:</b> RSBU at 75% N	35494	37579	98379	104634	62885	69140	2.78	2.96
<b>N6:</b> BCU at 75% N	34743	36828	98992	106902	64249	72159	2.86	3.09
<b>SEm±</b>	-	-	2208	1855	2208	1855	0.06	0.05
<b>CD at 5%</b>	-	-	6376	5357	6376	5357	0.18	0.15

Where, RSBU- Rice straw biochar-based urea; BCU- Biochar-coated urea

**Fig. 3.** Effect of residue management and biochar based slow released nitrogen fertilizer on agronomic efficiency and N recovery efficiency during 2019-20 & 2020-21; Where, RSBU- Rice straw biochar based urea; BCU- Biochar-coated urea.**Fig. 4.** Effect of residue management and biochar based slow released nitrogen fertilizer on available N in post-harvest soil during 2019-20 & 2020-21; Where, RSBU- Rice straw biochar based urea; BCU- Biochar coated urea.

entrapped urea in biochar cavities and pores in RSBU. Improved tillering and plant height under SRNF application reflect sustained nutrient release and better synchronization of nutrient supply with crop demand. The slow and steady release of nitrogen adsorbed on biochar surfaces increases soil N availability and improves soil pH, thereby enhancing the mobility and uptake of P, K and S (28). Moreover, biochar increases soil organic carbon stability and contributes to sustained nutrient release from decomposing organic matter, which further promotes plant growth (29). The synergistic effect of biochar and nitrogen fertilizer in improving soil fertility, nutrient use efficiency and water retention has been documented (30). In this study, such synergism was evident in the improved physiological performance and yield attributes under combined biochar and SRNF treatments.

### Yield response to biochar and SRNFs

The positive yield response under biochar-based treatments is consistent with previous research indicating enhanced nutrient availability, organic matter content and improved CEC (29). It was observed that biochar application resulted in 4-11 % yield increment in wheat. The lower yield under residue incorporation compared with biochar application can be attributed to the slow decomposition of rice straw with a high C:N ratio and temporary N immobilization, which reduces early nutrient availability for wheat (31, 32). Interestingly, in the present study, treatments receiving 75 % N through biochar-based SRNFs achieved yields comparable to those under 100 % N through conventional urea, suggesting a substantial improvement in nitrogen use efficiency (NUE). Biochar microporosity enhances nitrogen adsorption-desorption by providing abundant micro and mesopores that trap urea and ammonium through physical adsorption and surface functional groups. This slows the escape of N into soil solution, creating a gradual desorption pattern rather than an immediate flush of available N. Slow-release N fertilizers (SRNFs) improve N synchronization by controlling diffusion through coatings or biochar matrices. This ensures that N release matches the crop's demand curve with lower release during early stages and sustained release during active tillering and grain filling thereby reducing various N losses through leaching, volatilization and nitrification. Biochar also modifies soil microbial activity, as its porous structure enhances microbial habitat, increases cation exchange capacity and moderates soil pH. This improves microbial immobilization mineralization cycles, stabilizes ammonium and supports nitrifiers and decomposers, collectively improving N turnover and availability throughout the growing period. This observation is supported by release kinetics studies that have demonstrated the capacity of biochar-based coatings and carriers to synchronize N release with crop uptake, thereby minimizing losses and improving NUE.

This observation is supported by release kinetics studies that have demonstrated the capacity of biochar-based coatings to synchronize N release with crop uptake, thereby minimizing losses and improving NUE. The higher NDVI and SPAD values recorded under slow-release N treatments further confirm enhanced chlorophyll content, photosynthetic activity and efficient translocation of assimilates into grain and biomass yield.

## Conclusion

The present study demonstrated that the integration of rice residue management and biochar-based slow-release urea significantly enhanced wheat growth, yield and economic returns under the Tarai region of India. Among the residue management options, rice straw converted into biochar and incorporated into the soil consistently improved plant growth, physiological performance and yield attributes compared with residue removal. Nitrogen management through bBCU and RSBU at 100 % N resulted in the highest grain and straw yields, while 75 % N through SRNFs achieved yields comparable to 100 % N through conventional urea, indicating enhanced nitrogen use efficiency. Although biochar-based treatments incurred slightly higher production costs, the significant gains in yield and economic returns outweighed the additional expense. Combined application of rice straw biochar and biochar-coated urea significantly enhanced crop performance while providing the highest net returns and B:C ratio. This demonstrates that integrating residue-derived biochar with slow-release N technologies can improve both productivity and profitability of wheat-based systems in the Tarai region besides improving the soil health and reducing N losses. Future research should focus on developing more efficient, low-cost coating techniques and materials to further enhance farmers' economic gains and support wider adoption of sustainable nutrient management practices.

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## Authors' contributions

PN contributed to methodology, data curation, formal analysis, validation and writing original draft. SC was responsible for conceptualization, validation, resources, project administration, supervision and writing review and editing. AM contributed to writing - review and editing. TMKN contributed to methodology, data curation, formal analysis, validation and writing original draft. VCD contributed to resources, project administration, supervision and writing review and editing. SN contributed to data analysis and writing review and editing. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT, an AI language model, to polish the language and improve sentence clarity. After using this tool, the authors thoroughly reviewed and edited the content as needed and take full responsibility for the final content of the publication.

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