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Nano Urea-Mediated Partial Substitution of Conventional Urea Strengthens Wheat Productivity, Nitrogen Use Efficiency and Environmental Sustainability

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Abstract

Aims Indiscriminate application of conventional urea (CU) fertilizer in wheat (*Triticum aestivum* L.) production increases production costs, reduces nitrogen use efficiency (NUE), and contributes to elevated greenhouse gas emissions. This study investigated the potential of partial substitution of CU with nano urea (NU) to enhance wheat productivity, nitrogen (N) dynamics, economic returns, and environmental sustainability.

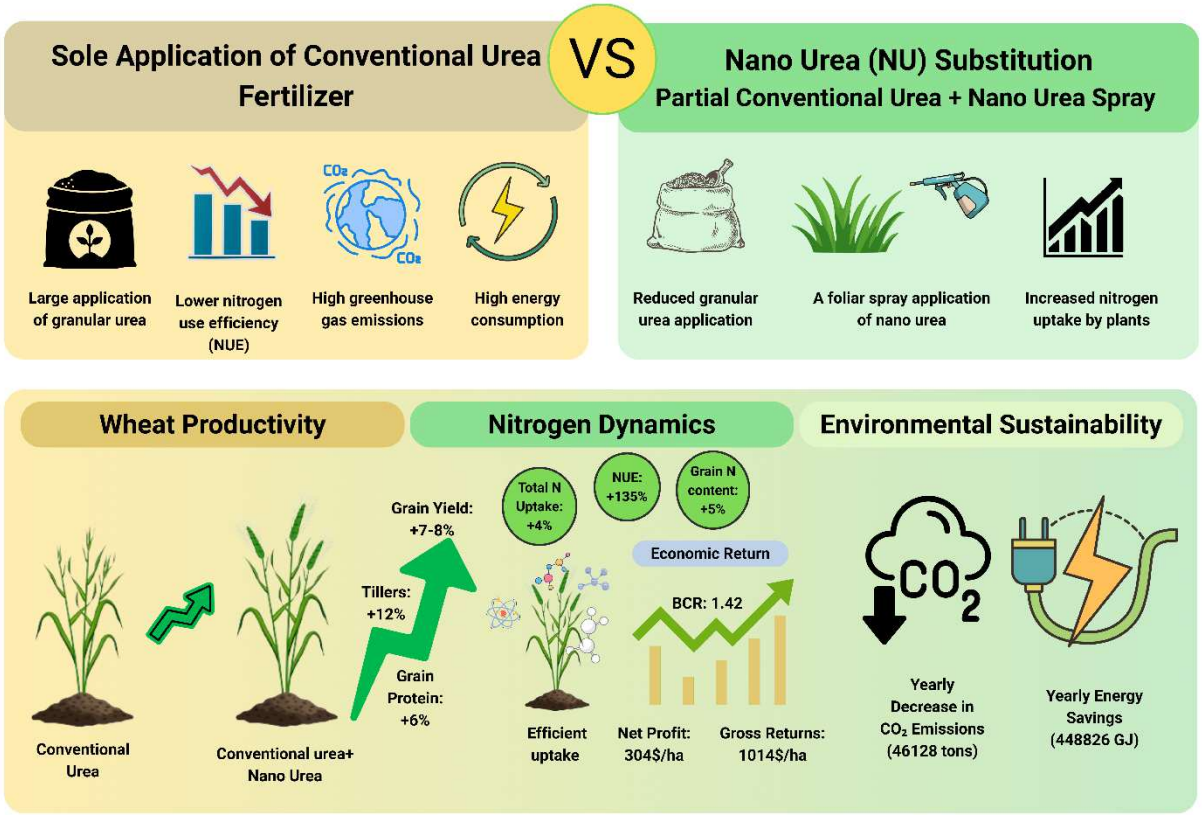
Methods A field experiment was conducted using seven treatment combinations of CU and foliar-applied NU, in a Randomized Complete Block Design with three replications and BARI Gom-32 was used as the test crop.

Results Partial substitution of CU with NU substantially improved agronomic attributes and N uptake relative to sole application of CU. Replacement of 16% CU with one foliar spray of NU (T_3) exhibited a notable increase in the total number of tillers m^{-2}, grain yield, protein content, grain N content, straw N status, NUE, and total N uptake by 12%, 7-8%, 6%, 5%, 2%, 135%, and 4%, respectively, compared with farmers practice (FP). Economic analysis revealed that T_2 performed similarly to T_3, however T_3 generated the highest gross returns (1014 \$ ha^{-1}), net profit (304 \$ ha^{-1}), and benefit-cost ratio (BCR) (1.42). Furthermore, a 16% replacement of N (9,300 tons) could potentially reduce 46,128 tons CO_2 equivalent emissions and 448,826 Gigajoules (GJ) of energy annually relative to FP.

Conclusions Nano urea-mediated partial substitution of CU can strengthen wheat productivity, farm profitability, and environmental sustainability.

Keywords Foliar fertilization, crop nutrient management, soil N dynamics, carbon footprint, sustainable intensification

Graphical Abstract



Introduction

As the global population increases and is projected to reach 9-10 billion by 2050, the demand for food is expected to increase substantially to ensure food security (FAO 2018). Although higher cereal crop production is essential to meet this demand, climate change poses growing risks to global yields. In 2024, wheat production increased by 1% over the previous year to 800.86 mMT (BBS 2024). Wheat (*Triticum aestivum* L.) is an important cereal crop of the family Gramineae (Islam et al. 2025) and is increasingly important in sub-tropical environments such as Bangladesh. In wheat cultivation, chemical fertilizers supply essential nutrients required for their physiological growth, development, and yield (Babu et al. 2021). To maximize returns, wheat growers often apply large amounts of nitrogenous fertilizer (urea), as N application is positively associated with wheat productivity (Li et al. 2022; Saudy 2014; Saudy and Mubarak 2015). However, wheat production in Bangladesh has declined over the years owing to inappropriate fertilizer management, particularly inefficient N management. Nitrogen is an essential plant nutrient required for key physiological processes (protein synthesis, chlorophyll synthesis, and organic compounds) that support plant growth and productivity (Kumari et al. 2022; Liu and Lal 2015). Application of N in soil, either organic or inorganic, causes substantial losses through volatilization, denitrification, immobilization, and leaching, which reduce nitrogen use efficiency (NUE) by 50–60% (Govindasamy et al. 2023; Henryson et al. 2020; Ichami et al. 2019; Singh et al. 2016; Singh 2017; Solanki et al. 2015). Urea, a key fertilizer for crop production, is noted for its rich N composition (46%) and affordability nationwide. However, excessive application of this fertilizer poses serious environmental impacts, such as GHG emissions (N_2O) (Li et al. 2025), water eutrophication (Nyamangara et al. 2003; Peng et al. 2015), and soil acidification (Cheng et al. 2025).

Therefore, there is growing global concern to reduce its detrimental effects by adopting modern technologies like nano-fertilizers (NFs) without affecting agricultural production. Nano-urea (NU) increases NUE, reduces N fertilizer requirements without compromising crop yield, and improves soil and air quality by mitigating pollution (Tripathi et al. 2025).

Nanotechnology is a promising science that deals with the production and application of nanoparticles at molecular and atomic levels with a size range of 1–100 nm (Rajput et al. 2021; Verma et al. 2022). The NFs possess various desirable properties, including remarkable solubility, high efficiency, and stability, as well as controlled nutrient release, targeted action, eco-friendliness, and convenient application and disposal (Astaneh et al. 2021; Jayara et al. 2023; Saudy et al. 2022). The foliar application of NFs is considered highly effective because nutrients can be readily absorbed by plants through leaf plasmodesmata (Iqbal 2020; Kalwani et al. 2022; Rajput et al. 2021). In contrast to conventional urea (CU) fertilizer, NFs release N 12 times slower, which may improve NUE and crop yield (Saurabh et al. 2019; Singh et al. 2025). Foliar application of NFs has been reported to enhance crop nutrient uptake more effectively than soil application (Babu et al. 2022; Grillo et al. 2021). In this context, NU may reduce application and transportation costs relative to CU while improving crop growth, protein content, nutritional quality and overall crop performance, and reducing dependence on conventional fertilizers. The photosynthesis rate, chlorophyll synthesis, and dry matter accumulation were enhanced by the application of NFs, as reported by Al-Juthery et al. (2018), Nasar et al. (2022), Seleiman et al. (2025), and Singh (2017). The crops gain a uniform supply of N as their regulated release nutrients, which promotes vigorous plant growth and results in stronger, healthier plants (Yadav et al. 2024). Several studies have reported that nano-DAP and NU application to crops with proper nutrient management markedly enhances wheat yield compared to conventional fertilizers (Al-Juthery et al. 2018; Jayara et al. 2023; Upadhyay et al. 2023). Due to its effectiveness, NFs are considered more efficient and environmentally friendly than conventional fertilizers (DeRosa et al. 2010; Upadhyay et al. 2023). Despite this potential, field-scale evidence for NU use in wheat remains limited (Gupta et al. 2023). Replacing part of CU with NU may therefore offer a promising strategy to reduce excessive N input, improve cost-effectiveness, and support sustainable wheat production through foliar N application (Ojha et al. 2023; Yadav et al. 2024).

The present study hypothesized that integrating NU with CU fertilizer could enhance wheat growth, yield, and quality while curtailing nitrogenous fertilizer usage and reducing environmental pollution.

Materials and Methods

Experimental Site, Duration, Soil Properties and Meteorological Conditions

The field experiment was conducted at the Sher-e-Bangla Agricultural University (SAU), in Dhaka, Bangladesh, from November 2024 to March 2025. The geographic location of the experimental site, initial physicochemical properties of the experimental site and meteorological conditions prevailing throughout the experimental period are presented in Fig. 1, Table 1 and Table 2, respectively.

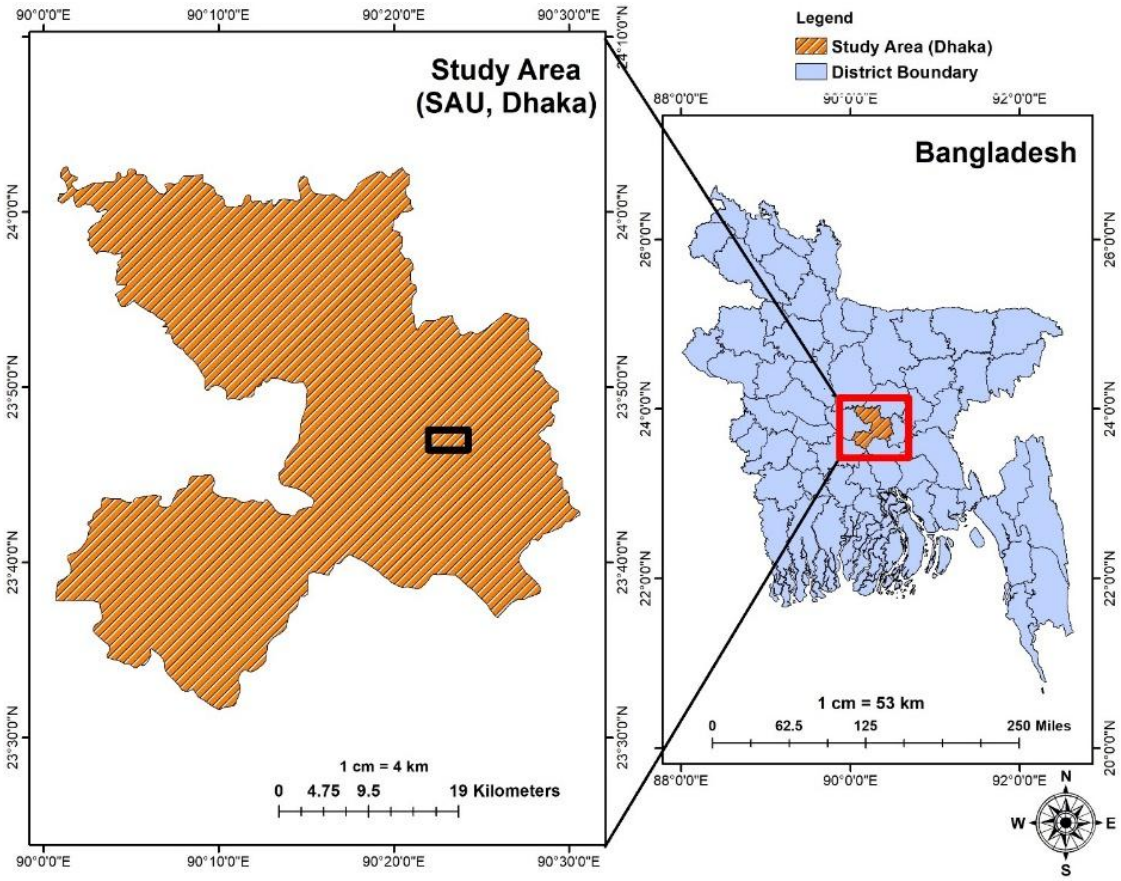


Fig. 1 Geographic location of the experiment site

Table 1 Initial soil physicochemical profile of the study site

Soil properties	Soil Texture	pH	Organic carbon	Organic matter	Total N	Available P	Exchangeable K	Available S
Values	Clay loam	6.30	0.61%	1.06%	0.061%	34.43 ppm	0.121 meq/100g soil	23.13 ppm

Table 2 Monthly meteorological attributes recorded in study site during the experiment.

Month	Air temperature (°C)		Relative Humidity (%)	Total rainfall (mm)
	Maximum	Minimum		
November, 2024	28.2	18.4	72	27
December, 2024	25.8	15.1	64	4
January, 2025	24.4	12.8	68	6
February, 2025	28.9	16.2	70	35
March, 2025	31.8	20.8	74	85

[**Source** Climate Division, Bangladesh Meteorological Department (BMD), Dhaka]

106 **Material Collection**

107 The wheat variety BARI Gom-32 was used as the planting material and was collected from the Bangladesh
108 Agricultural Research Institute (BARI), Gazipur, Bangladesh. The NU used in this experiment was procured from
109 the Nano Biotechnology Research Center, IFFCO, India and commercialized by the Government of India. The
110 fertilizers used in this experiment were collected from the Bangladesh Agricultural Development Corporation
111 (BADC).

112 **Experiments and Treatment Details**

113 Prior to sowing wheat seeds, the field was well prepared with several cross ploughings, and all the fertilizers
114 (RFD) as per treatments were intermixed during the final land preparation. The field investigation was executed
115 using a randomized complete block design (RCBD) with seven treatments and three replicates. The treatments
116 were a combination of CU and NU fertilizers. Each plot received various amounts of N from conventional prilled
117 urea (46% N), as presented in Table 3, where RFD= $N_{180}P_{25}K_{110}S_{16}Zn_{1.5}B_1$ kg ha^{-1} (FRG, 2024).

118 **Table 3** Detailed treatment combinations of CU and NU applied at different growth stages

Treatment	Details of treatment application		
	Basal dose	**At 25 DAS**	**At 55 DAS**
T_0	RFD without N	_	_
T_1 (Farmers practice)	2/3rd of RFD N (soil)	1/3rd of RFD N (top dress before irrigation)	_
T_2	2/3rd of RFD N (soil)	1/3rd of RFD N (top dress before irrigation)	One NU spray @4ml/L
T_3	2/3rd of RFD N (soil)	50% of 1/3rd of RFD N (top dress before irrigation)	One NU spray @4ml/L
T_4	2/3rd of RFD N (soil)	One NU spray @4ml/L	One NU spray @4ml/L
T_5	1/3rd of RFD N (soil)	1/3rd of RFD N (top dress after irrigation)	One NU spray @4ml/L
T_6	1/3rd of RFD N (soil)	One NU spray @4ml/L	One NU spray @4ml/L

119 **Determination of Morphophysiological and Yield Parameters**

120 Different morphological parameters, including plant height and flag leaf length, were recorded at various growth
121 stages (25, 50, 75 DAS, and at harvest) from ten randomly tagged plants in each plot using a 100-cm ruler.
122 Physiological parameters, such as the SPAD value, were measured with the help of a handheld SPAD-502 Plus
123 chlorophyll meter (Konica-Minolta, Tokyo, Japan). Chlorophyll content was measured from ten physiologically
124 mature leaves per plot, ensuring that the midrib was not positioned under the sensor of the instrument, and the
125 average reading was calculated. The leaf area index (LAI) readings were measured with the help of a LI-3100C
126 Area Meter (Li-Cor Biosciences) from ten tagged flag leaves of each treatment. Yield traits, such as the number
127 of tillers m^{-2}, were determined by using the quadrat method. A quadrat was placed randomly in each plot, and the
128 tillers within the quadrat were counted manually four times (25, 50, 75 DAS, and at harvest) during the crop
129 growth period. Spike length (cm), number of spikelets $spike^{-1}$, number of grains $spike^{-1}$, and grain weight $spike^{-1}$
130 (g) were recorded from previously tagged plants at harvest. Moreover, other yield attributes, such as, thousand

grain weight (TWG) (g), grain yield (t ha^{-1}), straw yield (t ha^{-1}), and harvest index (%) were measured at harvest. For each treatment, grain samples were randomly collected, manually counted and weighed to determine the TWG. Grain and straw yield were estimated from the net plot area and then expressed in kg ha^{-1}. The harvest index (HI) was measured as the proportion of grain yield relative to the total biomass of the respective treatments.

Quality Traits

Grain and straw N contents were measured using the Micro-Kjeldahl Method, which involves digestion, distillation, and titration of plant samples. First, the plant samples were oven-dried at 60-70 °C until a constant weight was obtained. The dried samples were finely ground and sieved through a 1 mm mesh. To determine the N concentration, approximately 0.2–1.0 g of powdered plant sample was weighed into Kjeldahl digestion tubes, and the Micro-Kjeldahl method was used. The protein content of wheat was obtained by multiplying the N concentration in the grain by a conversion factor of 6.25 (16% N present in protein molecules) (Mosse 1990). The total nutrient uptake by the crop was measured using the following equation (Dobermann and Fairhurst 2000):

$$Total\ Nutrient\ uptake\ (\ kg\ ha^{-1}) = \frac{Nutrient\ content\ (\%) \times\ Yield\ kg/ha}{100}$$

NUE represents the increase in crop yield obtained per unit of N fertilizer applied and was calculated using the following formula (Novoa and Loomis 1981):

$$NUE(\%) = \frac{Yield\ (fertilized\ plot) -\ Yield\ (control\ plot)}{F\ (applied)} \times 100$$

where Yield (fertilized plot) and Yield (control plot) represent wheat grain yields (kg ha^{-1}) obtained from N-fertilized plots and without N-fertilized plots, respectively, and F (applied) is the amount of N applied in the field.

Soil Properties

Pooled soil samples were procured from each plot using an auger at a depth of 0-15 cm. These samples were air-dried, ground, and sieved through a 2 mm sieve and subjected to the analysis of different physicochemical properties listed in Table 4.

Table 4 Methods used for physicochemical analysis of initial and post-harvest soil samples

Properties	Methods	References
pH	1: 2.5 ratio of soil water suspension	(Jackson 1962)
Total N (%)	Micro-Kjeldahl method	(Page et al.1982)
Available P (ppm)	Olsen method	(Olsen 1954)
Exchangeable K (meq/100 g soil)	Ammonium acetate extractable	(Black 1965)
Available S (ppm)	Calcium chloride extraction method	(Page et al. 1982)
Organic Carbon (%)	Wet-oxidation method	(Walkley and Black 1934)
Organic matter (%)	$OM = OC \times 1.73$ (van Bemmelen Factor)	(Heaton et al. 2016)

Estimation of N, CO_2 Emission, and Energy Savings

The N, CO_2 emission, and energy savings were calculated according to the 17% reduction in N fertilizer recorded with NU compared with farmer practice (FP). The quantity of urea saved was calculated by converting the reduced N into equivalent urea based on a 46% N content. The reduction in CO_2 emissions was determined using an emission factor of 4.96 kg CO_2 per kg of N applied (Yadav et al. 2018). Energy savings associated with reduced urea use were expressed in gigajoules (GJ). Transportation-related fuel costs were excluded from the calculation. The total energy savings were estimated as follows (Baboo 2016):

$$Total\ Energy_{saved} = Urea_{saved} \times 22.2$$

Economic Analysis

An economic analysis was conducted to understand the economic efficiency of wheat cultivation under different treatments. The cost of cultivation, including land preparation, seeds, fertilizers, irrigation, pesticides, herbicides, insecticides, transportation, labor requirements, harvesting, threshing, marketing, and fixed capital costs with interest, was calculated based on the existing local market prices during the cropping season. Gross return ($ ha^{-1}) was measured by summing the individual grain and straw yields according to the market price. The wheat grain market price was \$246 ton^{-1}, whereas the straw price was \$9.48 ton^{-1}. The net return, gross return, and production cost were expressed in US dollars, converted based on the prevailing exchange rate (1 US dollar, \$ =122 BDT). Net return ($ ha^{-1}) was obtained using the following equation:

$$Gross\ returns = (Grain\ yield\ \times Market\ price\ of\ grain) + (Straw\ yield\ \times Market\ price\ of\ straw)$$

$$Net\ returns = Gross\ return - Total\ variable\ production\ cost$$

The benefit cost ratio (BCR) was calculated using the following formula (Heidari and Omid 2011):

$$BCR\ = \frac{Gross\ return}{Total\ variable\ cost} \times 100$$

Statistical Analysis

Data for all measured parameters were expressed as the mean ± standard error (SE) of three replicates. Statistical analyses, including Analysis of Variance (ANOVA) and mean separations using Duncan's Multiple Range Test (DMRT) at a 5% significance level ($p < 0.05$), were conducted using the R programming environment (v4.4.2) via RStudio. Principal Component Analysis (PCA) and its associated visualization were performed in RStudio utilizing the factoextra package. All other data visualizations, including the Pearson correlation matrix and treatment comparison charts, were generated using Python (v3.13) with Matplotlib libraries.

Results

Morphophysiological Traits

Unlike the sole application of urea, its combination with nano urea (NU) significantly influenced the growth and physiological parameters of wheat. Among the growth parameters, plant height varied markedly across the treatments at all growth stages (at 25, 50, 75 DAS, and at harvest) (Fig. 3─a). At harvest, the plant height (PH)

increased by 19% and 21% in the T_2 and T_3 treatments, respectively, compared with that in the control (Fig. 2). However, the difference in PH between T_2 and T_3 was statistically insignificant, indicating that these treatments performed similarly. Furthermore, compared with farmer practices (FP) (T_1), plant height increased by 7% and 8% in the T_2 and T_3 treatments, respectively.

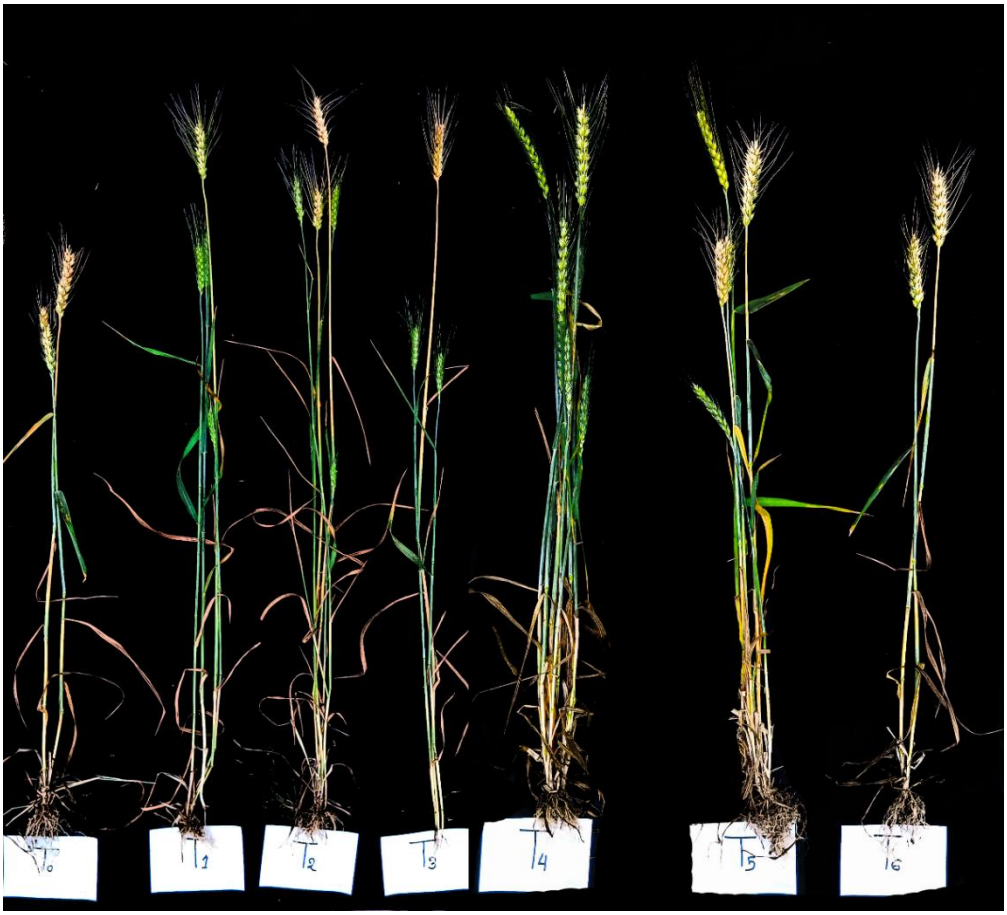


Fig. 2 Phenotypic representations (plant height) of wheat plants exposed to different N management treatments.

The conjoint application of CU and NU markedly affected the flag leaf length of wheat throughout the growing period (Fig. 3─b). At harvest, the T_3 treatment increased flag leaf length by 60%, followed by the T_2 treatment at 55%, which was statistically similar relative to the control. However, flag leaf length increased by 18% and 22% in the T_2 and T_3 treatments, respectively, compared to that in FP (T_1).

The total number of tillers m^{-2} was remarkably influenced by the combined application of conventional and NU fertilizer (Fig. 3─c). The total number of tillers m^{-2} showed an increasing trend at 25, 50, and 75 DAS. At 75 DAS, the total number of tillers m^{-2} was significantly higher in treatment T_2, where 100% of the recommended N was supplied through conventional urea application, along with one foliar spray of NU. Treatment T_2 exhibited a 25% increase in the total number of tillers m^{-2}, which was statistically similar to treatment T_3 (22%). However, at harvest the total number of tillers m^{-2} decreased by 19% and 14% in the T_2 and T_3 treatments, respectively, compared with 75 DAS. In addition, T_2 and T_3 treatments produced 15% and 12% more tillers m^{-2}, respectively, than the FP (T_1).

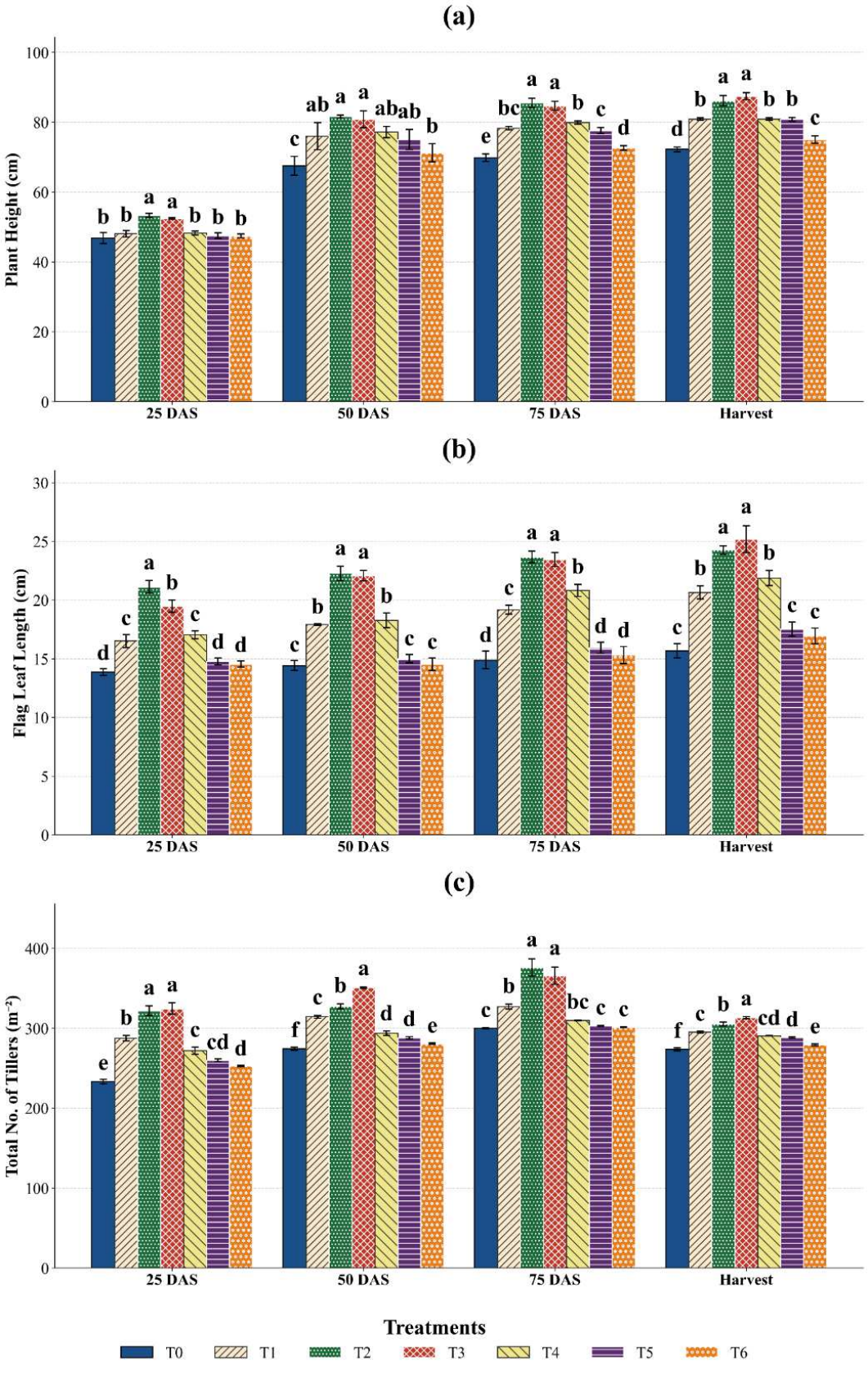


Fig. 3 Plant height (a), flag leaf length (b), and total number of tillers m^{-2} (c) of wheat under combined CU and NU treatments. Details of treatment were presented in Materials and Methods; Values means were calculated of three replicas for each treatment and bars represent mean ± standard error (SE). Dissimilar letters indicate statistically different (DMRT test, $p < 0.05$).

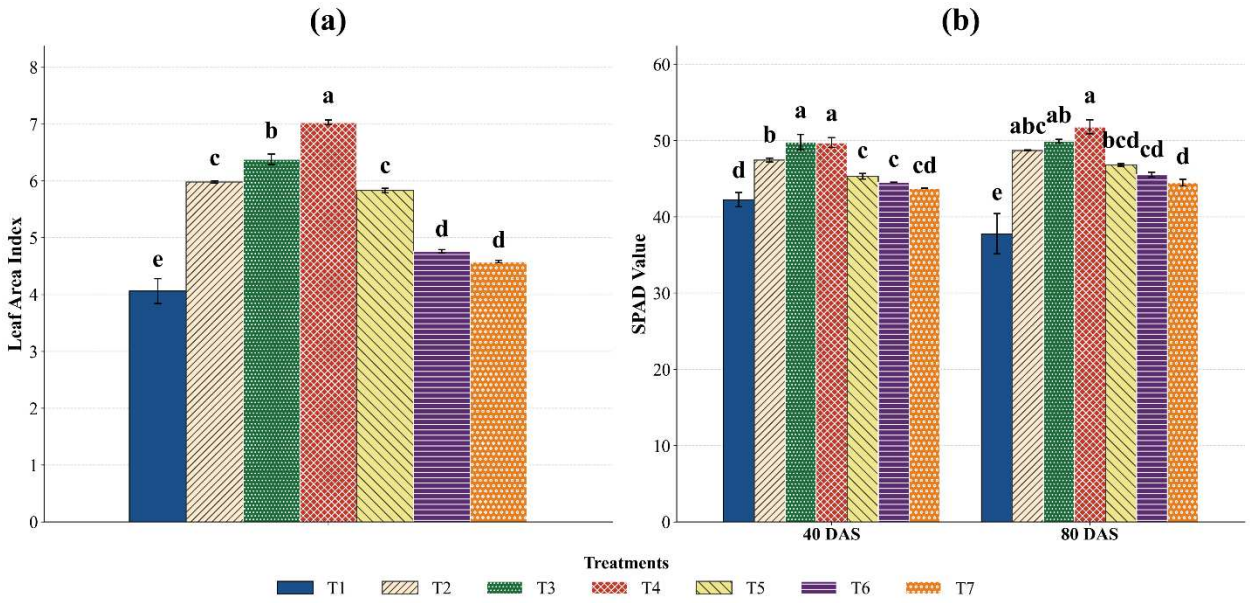


Fig. 4 Photosynthetic performance; (a) LAI, (b) SPAD values of wheat under different N management practices. Details of treatment were presented in Materials and Methods; Values means were calculated of three replicas for each treatment and bars represent mean ± standard error (SE). Dissimilar letters indicate statistically different (DMRT test, $p < 0.05$).

The leaf area index (LAI) and SPAD values differed significantly across the treatments (Fig. 4). At the maximum tillering stage, the LAI in the T_2 and T_3 treatments increased by 57% and 73%, respectively, relative to the control. Moreover, compared with FP (T_1), LAI increased by 7% and 17% in the T_2 and T_3 treatments, respectively. At 40 DAS, SPAD values increased by 18% in both T_2 and T_3 treatments, compared to the control, with no statistically significant difference between the two treatments. By 80 DAS, the SPAD value was enhanced by 32% and 37% in the T_2 and T_3 treatments, respectively, relative to the control. Compared with FP, SPAD values increased by up to 6% under these treatments.

Yield and Yield Contributing Traits

The data analyzed revealed a significant effect of the treatments on the yield and yield-contributing attributes of wheat. Spike length differed significantly among the treatments (Fig. 5—a). The highest spike length was recorded in the T_2 treatment, followed by the T_3 treatment, which was statistically insignificant. The spike length increased by 20% and 18% in T_2 and T_3 treatments, respectively, compared to that in the control. Additionally, relative to FP, the spike length increased by 11-13% in these treatments.

As expected, the number of spikelets spike^{-1} increased by 36% in the T_2 treatment, followed by 28% in the T_3 treatment, compared to the control (Fig. 5—b). Moreover, compared with FP, the number of spikelets spike^{-1} increased by 15% and 8% in the T_2 and T_3 treatments, respectively.

The number of grain spike^{-1} and weight of grain spike^{-1} showed a significant difference and recorded the highest number of grain spike^{-1} and weight of grain spike^{-1} in the T_3 treatment (Fig. 5—c & d). Compared to the control, the number of grain spike^{-1} and weight of grain spike^{-1} increased by 65% and 60%, respectively, in the T_3 treatment, followed by the T_2 treatment. Compared to FP, the number of grain spike^{-1} and weight of grain spike^{-1}

showed an increasing trend, which increased by 22% and 24%, respectively, in the T_2 and T_3 treatments. In contrast, treatments T_0 and T_6 revealed the minimum number of grain spike^{-1} and lower weight of grain spike^{-1}.

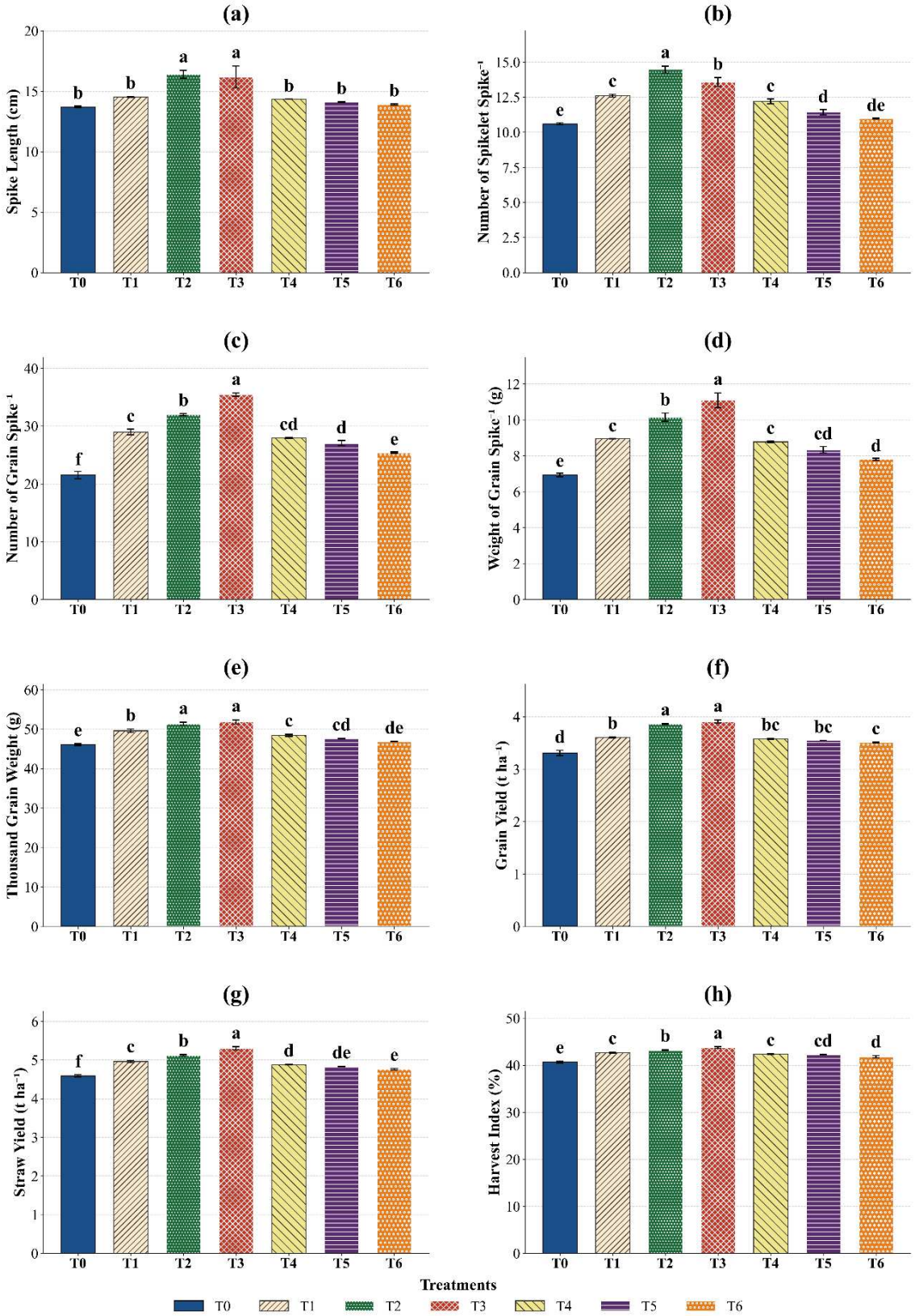


Fig. 5 Yield and yield-contributing attributes of wheat influenced under co-application of CU and NU. Details of treatment were presented in Materials and Methods; Values means were calculated of three replicas for each

treatment and bars represent mean ± standard error (SE). Dissimilar letters indicate statistically different (DMRT test, $p < 0.05$).

The TGW of wheat varied significantly with the application of NU with CU fertilizer across the treatments (Fig. 5—e). The TGW increased by 12% in T_2 and T_3 treatments compared to the control, which showed no significant difference between the treatments. Furthermore, TGW increased by 4% in both T_2 and T_3 treatments, relative to the FP. However, lower TGW was found in the T_0 and T_6 treatments, which were also statistically identical. As predicted, the co-application of NU with CU significantly influenced the grain yield of wheat. The higher TGW under these treatments was also reflected in grain yield (GY) (Fig. 5—f). Compared to the control, the GY increased by 17% and 18% in T_2 and T_3 treatments, respectively. These results revealed that there is no significant difference between the two treatments. The GY further increased by 7-8% in these two treatments compared with FP. Nonetheless, lower grain yields were obtained in T6 and control treatments.

All the treatments had a significant effect on wheat straw yield (SY) (Fig. 5—g). The highest SY was recorded in the T_3 treatment, followed by the T_2, whereas lower SY was found in the T_0 and T_6 treatments. The SY in the T_2 and T_3 treatments were 12% and 15% higher than that of the control, respectively. Moreover, SY increased by 3% and 7% in the T_2 and T_3 treatments, respectively, compared to that in the FP treatment.

Owing to the application of NU and CU conjointly, the harvest index (HI) also showed a similar trend (Fig. 5—h). Compared to the control, HI in the T_2 and T_3 treatments increased by 6% and 8%, respectively. In addition, relative to FP, HI increased by 1-2% in the two treatments.

Soil Properties and Nutrient Uptake

The conjoint application of NU and CU resulted in significant differences among treatments in terms of total N in soil, grain, and straw (%). The highest N content was recorded in soil (0.7%), grain (2.14%), and straw (0.53%) in T_3, which was 17%, 11%, and 4% higher than that in the control, respectively (Fig. 6—a, b and c). In T_2 treatment, the total N content in the soil and grain increased by 17% and 10%, respectively, compared to the control. These findings indicate a negligible difference between the two treatments in terms of soil and grain N content. However, straw N content varied significantly, and in the T_3 treatment, it was 2% higher than that in the control treatment. Furthermore, compared with FP, T_3 treatment increased the total N content in grain and straw by 5% and 2%, respectively. The lowest N content in the soil, grain, and straw was consistently observed in the control treatment.

The total N uptake (TNU) by the crop varied significantly among the treatments, ranging from 90.35 to 102.91 kg ha^{-1} (Fig. 6—d). The T_2 and T_3 treatments showed similar impacts on TNU, increasing by 13% and 14%, respectively, over the control. The difference between T_2 and T_3 was minimal (≈0.94%), suggesting comparable efficiency in enhancing N uptake between the two treatments. Moreover, in the T_2 and T_3 treatments, the total N uptake increased by 3% and 4%, respectively, relative to that in the FP.

As shown in Fig. 6—e, the highest NUE was recorded in T_3 (0.4%), followed by T_6 (0.34%), T_2 (0.31%), and T_4 (0.22%). NUE increased by 82% and 135% in the T_2 and T_3 treatments, respectively, compared to that in the FP. Higher N doses exhibited a decreasing trend in NUE, whereas foliar NU application further increased NUE.

The protein content (PC) percentage in grains was markedly affected by the combined application of NU and CU (Fig. 6─f). The highest PC increased by 9% and 12% in the T_2 and T_3 treatments, respectively, compared to that in the control. The difference between the T_2 and T_3 treatments was relatively small (≈2.48%), indicating almost similar results between these two treatments. However, relative to the FP, the PC increased by 4% and 6% in T_2 and T_3 treatments, respectively. The lowest PC was obtained in the control (T_0) treatment, which was attributed to lower N availability.

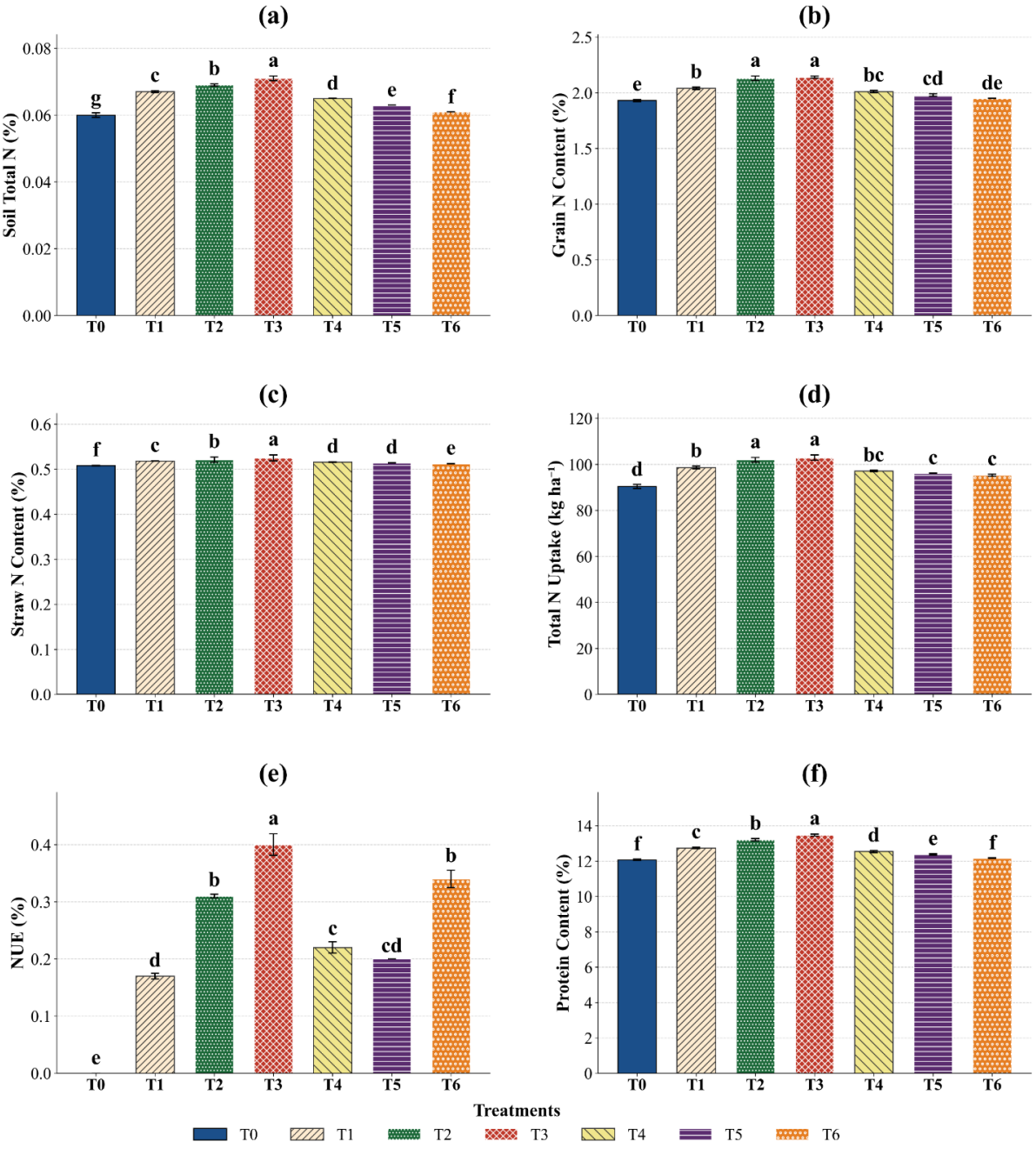


Fig. 6 N dynamics and protein accumulation in wheat; (a) soil Total-N (%) (b) Grain N content (%) (c) Straw N content (%) (d) Total N uptake (kg ha^{-1}), (e) NUE (%) (f) Protein content (%). Details of treatment were presented in Materials and Methods; Values means were calculated of three replicas for each treatment and bars represent mean ± standard error (SE). Dissimilar letters indicate statistically different (DMRT test, $p < 0.05$).

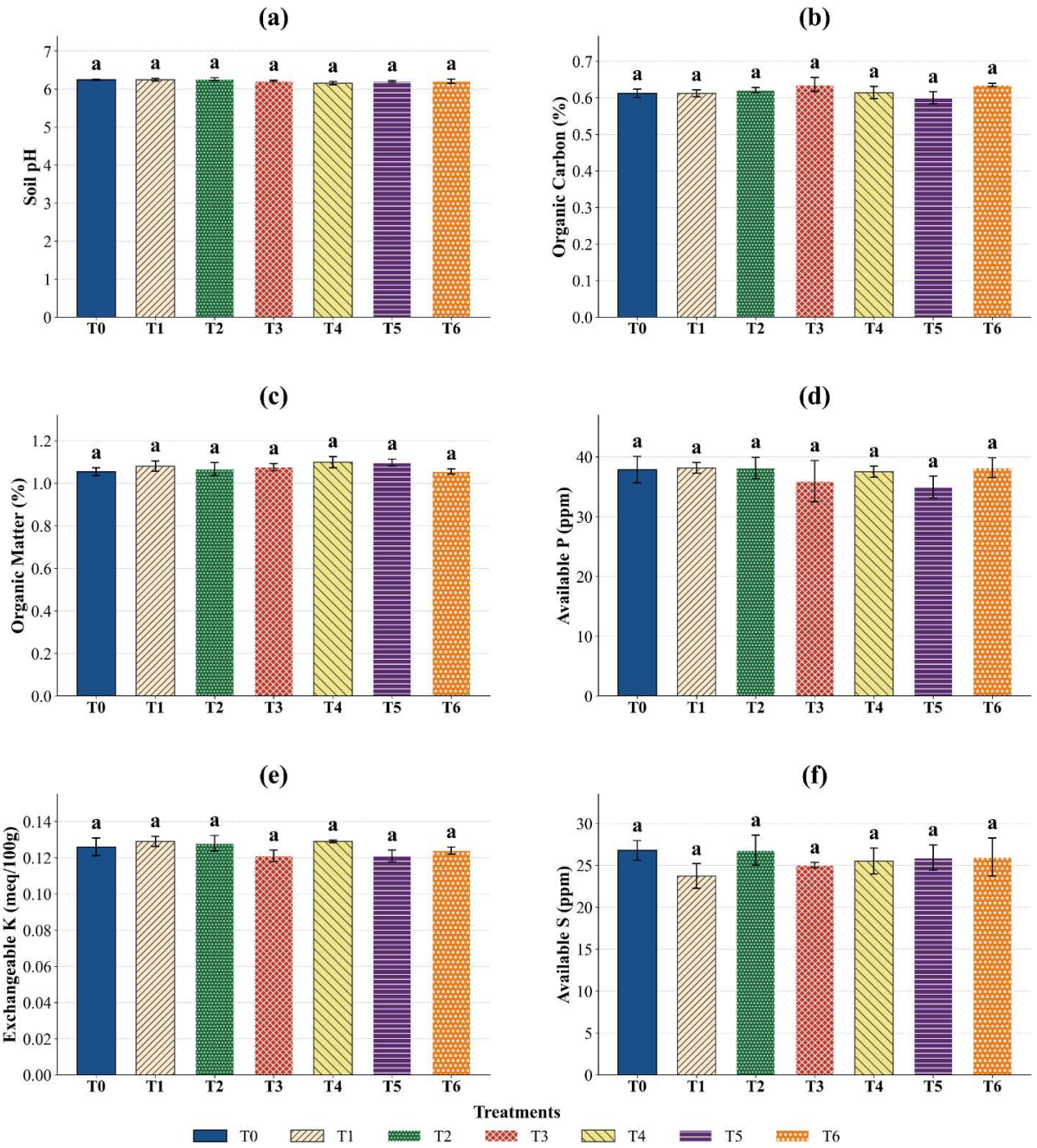


Fig. 7 Effect of NU and CU on post-harvest soil properties. Details of treatment were presented in Materials and Methods; Values means were calculated of three replicas for each treatment and bars represent mean ± standard error (SE). Dissimilar letters indicate statistically different (DMRT test, $p < 0.05$).

Other soil properties, including OC, OM, soil pH, available P, available S, and exchangeable K, did not vary significantly across the treatments due to the conjoint application of NU and CU (Fig. 7). The highest values of OC (0.63%), OM (1.10%), soil pH (6.26), available P (38.20 ppm), available S (26.79 ppm), and exchangeable K (0.129 meq/100g soil) were observed across diverse treatments. The post-harvest values of soil properties slightly changed from the initial values of soil properties. This indicates that the combined application of NU and CU had the least effect on soil properties.

Environmental Impacts

Bangladesh is an agrarian country whose economy largely depends on agriculture, importing approximately 1.6 million tons of urea during the 2023-2024 financial year to meet agricultural N requirements. In the 2023-2024 fiscal year, approximately 310,000 ha were cultivated with cereal crops such as wheat in Bangladesh. If a 16% N reduction is achieved through a single foliar application of NU, it could lead to an annual saving of approximately 9,300 tons of N (20,218 tons of urea) in wheat crops, compared to the FP (Table 5). Furthermore, a reduction in N use contributes to saving 46,128 tons of CO_2 emissions from wheat fields annually. In addition, it saved 448,826 Gigajoules (GJ) of energy over the FP. This indicates a significant step toward environmental protection, reducing urea fertilizer imports, and conserving foreign exchange. It should be noted that the additional fuel consumption associated with transporting the extra urea was not considered in this study.

Economic Analysis

The analyzed data showed that the cultivation costs increased with an increase in input (NU and CU fertilizer) and their application costs (Table 5). The highest total variable cost (TVC) was estimated in the T_4 treatment (750 \$ ha^{-1}), 21% higher than the control treatment, whereas lower TVC was recorded in the T_0 treatment. However, total return (TR) was highest in the T_3 treatment (1,014 \$ ha^{-1}), followed by the T_2 treatment (1,000 \$ ha^{-1}), which was statistically similar between these two treatments. The TR increased by 17% and 18% in T_2 and T_3 treatments, respectively, compared to the control. In addition, relative to the FP, TR in T_2 and T_3 treatments was 7% and 8% higher, respectively. The highest net benefits (NB) were recorded in T_3 treatment (304 \$ ha^{-1}), followed by the T_2 treatment (280 \$ ha^{-1}). The NB increased by 27% in the T_3 treatment compared to that in the control. Moreover, NB was 18% higher in the T_3 treatment than in the FP. However, NB showed a decreasing trend in T_4–T_6, and control treatments. The NB decreased by 25%, 14%, and 22% in the T_4–T_6 treatments, respectively, compared to the control. The highest benefit-cost ratio (BCR) was recorded in T_3 (1.42), followed by T_2 (1.39), and T_1 (1.38). The BCR increased by 3% in T_3 treatment compared to the control, whereas it decreased by 7%, 9%, and 11% in the T_4–T_6 treatments, respectively.

Table 5 N savings, environmental benefits, and economic returns associated with partial substitution of CU with NU in wheat production

Treatments	N applied kg ha^{-1}	N saved kg ha^{-1}	Total N saved in tons	Total urea saved in tons	CO2 emissions saved in tons	Energy saved GJ	Gross returns (\$ ha^{-1})	Total variable costs (\$ ha^{-1})	Net benefits (\$ ha^{-1})	BCR
T_0	0	180	-	-	-	-	859	620	239	1.38
T_1	180	0	0	0	0	0	937	680	257	1.37
T_2	180	0	0	0	0	0	1000	720	280	1.39
T_3	150	30	9300	20217.39	46128	448826.1	1014	710	304	1.42
T_4	120	60	18600	40424.78	92256	897652.2	928	750	178	1.23
T_5	120	60	18600	40424.78	92256	897652.2	920	715	205	1.28
T_6	60	120	37200	80869.57	184512	1795304	911	725	186	1.25

Relationships among Wheat Growth, Yield and NUE Under Different N Treatments

Pearson correlation analysis revealed significant and strong positive correlations among most of the measured traits, indicating a high degree of linear association among the variables (Fig. 8). The PH showed strong positive correlations with all measured traits, ranging from 0.75─0.97. These results suggest that PH is a critical factor closely associated with the expression of the measured traits of wheat. The LAI and SPAD values were strongly associated with both yield and TNU, indicating that N availability supported sustained photosynthetic activity, which in turn enhanced assimilate production and grain filling. The GY, SY and HI of wheat were highly correlated ($r \geq 0.86$) with the number of grains spike^{-1}, 1000- grain weight, LAI and TNU. These relationships demonstrate that wheat yield is strongly driven by both sink strength and source capacity. The close association between GY and TNU further indicates that improved N acquisition and assimilation effectively translated into reproductive productivity rather than vegetative luxury consumption. The TNU also showed consistently strong positive correlations ($r \geq 0.74$) with all growth and yield parameters, particularly LAI, SPAD, number of grains spike^{-1}, GY, HI and PC. These results indicate that the absorbed N supported sustained canopy photosynthetic capacity and efficient assimilate partitioning to grains. The consistently high positive correlations suggest that these measured traits are closely interrelated and may collectively contribute to improved productivity and grain quality under the conditions studied. The absence of negative correlations between parameters confirmed that NUE was enhanced without compromising plant growth or productivity, supporting the study objective.

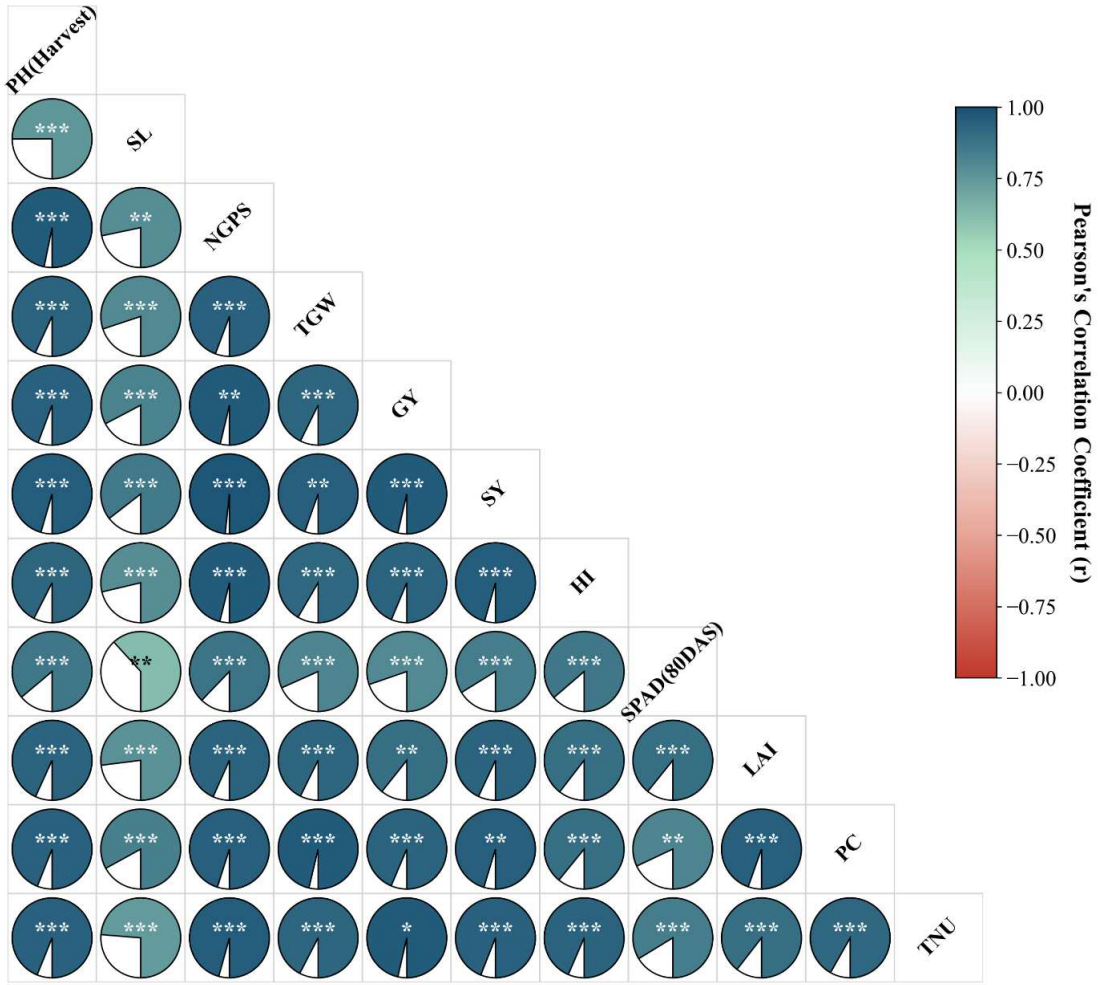


Fig. 8 Pearson correlation matrix illustrating interrelationships among wheat morphophysiological traits, yield components, N uptake, and protein content under different N application treatments. Correlation significance is denoted as ***p<0.001, **p<0.01, *p<0.05.

PCA Analysis

The PCA biplot was constructed to examine the multivariate relationship between the N management treatments and most of the measured growth, yield and N-related traits of wheat (Fig. 9). The first two principal components explained 94.4% of the overall variation, with PC1 accounting for 90.5% and PC2 contributing 3.9%. PC1 primarily represented the overall crop productivity and N-related traits. Most measured traits showed strong positive loadings on PC1, whereas the treatments were clearly separated along PC1, indicating that this axis largely represented overall crop productivity and NUE. In the PCA biplot, the N omission control (T_0) was clearly positioned on the negative side of PC1, indicating a weak association with most growth- and productivity-related traits. In contrast, treatments integrating NU with recommended dose or reduced CU, particularly T_2 and T_3 were located on the positive side of PC1 and clustered close to the growth- and yield-associated traits of wheat. This indicates improved agronomic performance compared to that of T_0 and T_1. Treatments with reduced basal CU combined with NU sprays (T_4–T_6) were positioned on the negative side of PC1. Although they showed better agronomic performance than the control (T_0), they exhibited a weaker association with growth and yield traits than treatments T_1–T_3. Overall, the PCA pattern highlighted that the partial substitution of CU with the NU was associated with favorable expression of multiple agronomic traits in wheat.

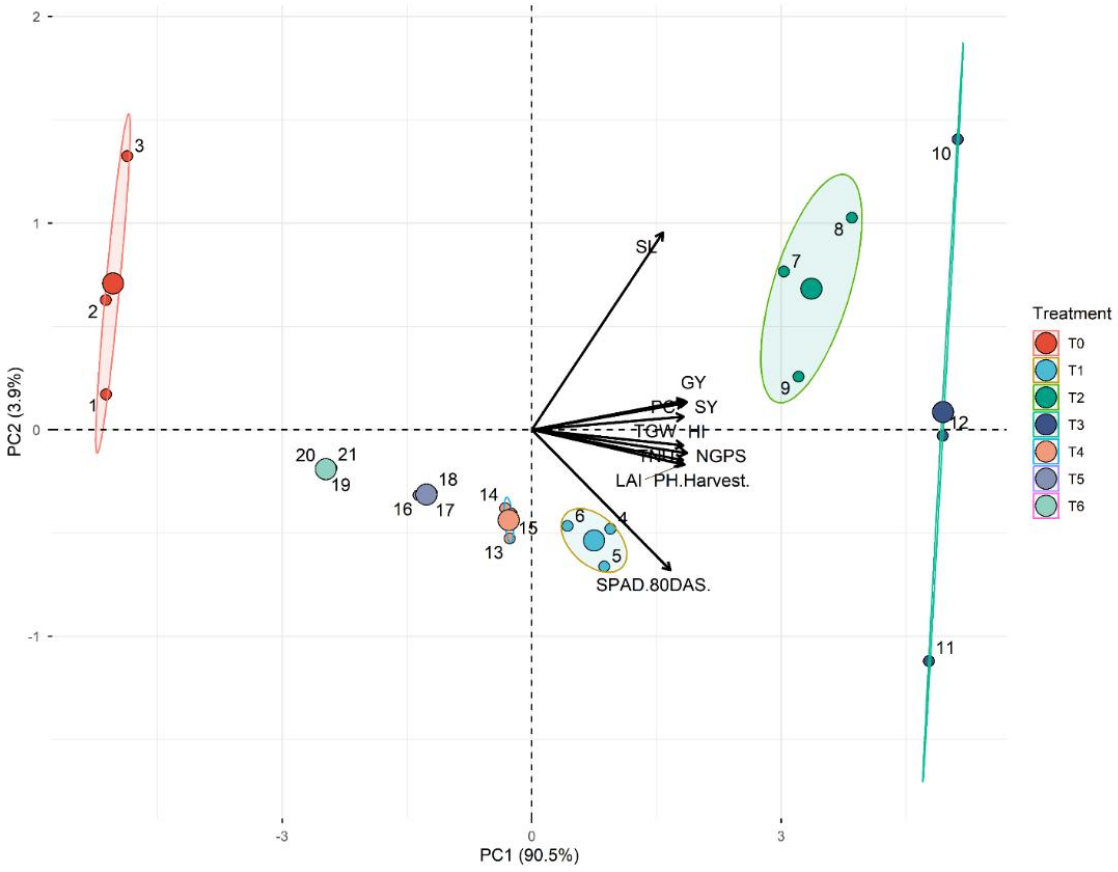


Fig. 9 Principal component analysis (PCA) biplot showing multivariate associations between N treatments and wheat growth, yield, and N-related traits, highlighting treatment clustering and trait loadings.

Discussion

The nitrogen (N) is a fundamental macronutrient that is indispensable to optimize wheat growth, yield and grain quality through its direct role in photosynthesis, chlorophyll formation, amino acid synthesis and metabolic enzyme regulation (Javed et al. 2022; Kubar et al. 2022; Sandhu et al. 2021; Shah et al. 2021; Wang Yuan et al. 2014). However, conventional N fertilization practices followed by farmers in many cropping systems often exhibits low NUE, frequently below 50% owing to rapid hydrolysis and substantial losses through volatilization, leaching, surface runoff, fixation and denitrification, thereby posing environmental and economic challenges (Ashraf et al. 2022; Govindasamy et al. 2023; Liu et al. 2019; Sarwar et al. 2026; Simelane et al. 2026; Singh et al. 2025; Swify et al. 2023; Verma et al. 2023).

Advances in nano fertilizer technologies, such as NU, provide a potential solution to these problems by increasing nutrient availability, enabling time-controlled release and targeted foliar uptake (Kumar et al. 2023). Owing to their nanoscale particle size and higher surface area, the foliar application of NU as a partial substitute for CU can enhance NUE by delivering N more efficiently to plants through the leaf epidermis and stomatal openings, followed by translocation *via* apoplastic or symplastic pathways (Tripathi et al. 2025). Therefore, this study investigated the partial replacement of CU practices with NU and its effects on wheat, growth, yield, grain nutrient content, soil nutrient status, economic returns and environmental impact. Our experimental results demonstrated that combining CU practices with foliar NU application significantly improved key growth parameters, including PH, flag leaf length, tiller density, LAI and chlorophyll content (Fig. 3 and 4). The application of either 180 kg ha^{-1} or 150 kg ha^{-1} CU together with one foliar spray of NU showed statistically similar responses; however, both treatments performed better than FP. Moreover, increases in PH (up to 8%) and flag leaf length (up to 22%) at harvest were observed compared to FP. These results suggest that NU may enhance vegetative growth, likely by supplying N in a readily assimilable form, thereby supporting cell division and expansion across growth stages (Rajput et al. 2021; Verma et al. 2023).

Our experimental results also demonstrated that the supplementing of 30 kg ha^{-1} less CU than the RFD, along with one foliar spray of NU fertilizer, notably augmented the total number of tillers m^{-2} (12%), LAI (17%) and SPAD value (6%). Improvements in these parameters indicate enhanced photosynthetic capacity, which is consistent with the findings of previous studies by Javed et al. (2022) and Verma et al. (2023). They noted that NU can boost N delivery, chlorophyll formation, photosynthetic activity and light interception efficiency, thereby supporting biomass accumulation in leaves when used as part of a balanced fertilization strategy. Comparable improvements in different crops under integrated prilled urea and NU management were also reported by Anushka et al. (2023), Kumar et al. (2023) and Sharma et al. (2022). Bhardwaj et al. (2025) reported that replacing approximately 33% of CU with NU improved the growth and yield attributes of wheat and rice, whereas higher substitution levels (e.g., 50% or more) generally resulted in similar or reduced performance compared with CU. Moreover, Sheoran et al. (2026) reported that foliar supplementation with NU enhanced 20-44% of photosynthetic activity and contributed to improved growth and productivity in wheat compared to the CU spray.

In our study, improved vegetative growth under T_2 and T_3 translated into better yield formation (Fig. 5). Under these treatments, the increases in yield attributes indicate that N nutrition remained adequate during both vegetative and reproductive stages. Increased SPAD values and LAI likely prolonged leaf functional activity and assimilate production, thereby supporting spike development and grain filling (Anushka et al. 2023).

406 Consequently, grain yield increased by about 17-18% over the control and 7-8% over farmer practice. The near-
407 equivalence of T_2 and T_3 in grain yield is agronomically important, as it suggests that one foliar NU spray can
408 compensate for a moderate reduction in top-dressed CU. This interpretation is consistent with the findings of
409 Bhardwaj et al. (2025) and Danish et al. (2025), who reported that partial substitution of CU with foliar NU can
410 optimize reproductive growth, whereas excessive substitution is less reliable. Moreover, Gopinath et al. (2025)
411 stated that in maize production N dose supplemented with NU, up to 25% recommended dose of nitrogen (RDN)
412 can be curtailed without any yield loss. In contrast, Sarkar et al. (2025) concluded that three foliar applications of
413 NU (4 ml L^{-1}) on aromatic rice showed analogous effects, but it had no consistent effect on the yield and quality.
414 The poorer performance of T_4, T_5 and particularly T_6 further supports the interpretation that NU should be
415 considered a supplementary N source rather than a complete substitute for conventional N fertilization in wheat
416 under the present conditions. Kumar et al. (2023) reported that fertilization of 150 kg ha^{-1} CU with a foliar spray
417 of NU increased wheat growth and yield attributes but it was not statistically significant when a similar dose was
418 applied as only CU. Similarly, Upadhyay et al. (2023) also stated that the success of NU depends on maintaining
419 an adequate basal supply of CU.

420 The increase in grain and straw N contents, TNU and grain PC under T_2 and T_3 in our experiment indicates that
421 the combined N application strategy (conventional +NU) not only improved agronomic traits but also enhanced
422 N acquisition and partitioning. Higher N uptake under these treatments was probably due to improved availability
423 of soil N in the plant root zone from basal doses of CU during early growth stages, or rapid adsorption of foliar
424 NU during later demand peaks due to its higher surface area and effective penetration into leaf tissues (Chawla
425 and Sharma 2026; Prajapati et al. 2026). These processes may also explain the higher grain PC, as it is closely
426 associated with post-anthesis N uptake and remobilization (Nehe et al. 2020; Sharma et al. 2023). Similar findings
427 were reported by Sheoran et al. (2026) in wheat, where a 120 ppm foliar NU spray increased the total protein
428 content by 30% compared with that in the control. The marked rise of NUE (135%) in T_3 compared to FP also
429 suggests that the crop converted applied N into grain more efficiently when 150 kg ha^{-1} of CU was applied with a
430 foliar dose of NU. This finding is consistent with the broader NUE framework outlined by Govindasamy et al.
431 (2023) and Javed et al. (2022), who emphasized that synchronizing N supply with crop demand improves both
432 uptake and utilization efficiencies.

433 Post-harvest soil pH, organic carbon, organic matter, available phosphorus, available sulfur and exchangeable
434 potassium data collected from all treatments in our study remained statistically similar. These findings suggesting
435 that the treatment effects were primarily expressed through N dynamics rather than through broad short-term
436 changes in soil physicochemical properties. Because the experiment was conducted over a single season, this
437 pattern is reasonable and indicates that the integrated N fertilization strategy did not adversely affect post-harvest
438 soil properties. Our results showed that the maximum total N in post-harvest soil was recorded under T_3 treatment
439 where 150 kg ha^{-1} CU combined with one foliar application of NU (4 ml L^{-1}). This may indicate improved N
440 retention or reduced N loss relative to less efficient treatments, although confirmation would require direct
441 measurement of volatilization, leaching or denitrification in future studies. This result also suggests that a 30 kg
442 ha^{-1} reduction in the application of CU from RDN can be supplemented through one foliar application of NU.
443 These results were supported by Gopinath et al. (2025), who reported that NU application can curtail 25% of RDN

in rainfed maize. In contrast, CU applications reduced RDN by more than 33%, regardless of supplementation with one or two foliar NU applications, resulting in the depletion of total N in post-harvest soil.

Furthermore, correlation analysis reinforced these findings (Fig. 8), revealing that the partial substitution strategy of CU with NU improved productivity, NUE and environmental sustainability. Multivariate PCA further supported these findings, showing strong positive associations between growth, yield and N related traits, particularly under the T_2 and T_3 treatments (Fig. 9). The clustering of these treatments along the positive PC1 axis indicates that the partial substitution of CU with foliar NU spray consistently promotes overall crop performance. The absence of negative correlations among traits underscores that improved NUE did not compromise productivity, aligning with the concept of a synchronized N supply for optimal wheat productivity. These findings are consistent with recent studies demonstrating that multivariate analysis, including PCA and correlation matrices, effectively identifies key physiological and agronomic traits that drive NUE and productivity in cereals (Emam et al. 2025; Jan et al. 2025; Yu et al. 2026). By highlighting clusters of positively associated traits, these analyses facilitate the identification of traits that are most responsive to optimized N management, providing a robust framework for interpreting complex trait networks in wheat and other crops.

In our study, from both economic and environmental perspectives, T_3 treatment performed best (Table 5). This treatment achieved the highest TR, NB and BCR while also reducing conventional N input relative to T_2 and FP. Our study results reported that 8% higher TR and 18% higher NB were observed under T_3 relative to FP. This economic advantage might arise from a better balance between input costs and grain yield. In contrast, T_4, T_5 and T_6, in which additional foliar applications were combined with reduced basal N inputs, did not generate sufficient yield benefits. Similarly, Huq et al. (2025) found that foliar NU application with 75% RDN was more cost-efficient than conventional fertilizer practices in finger millet. The environmental estimates in the present study also suggest substantial savings in urea requirement, energy use and associated CO_2 emissions if this strategy is adopted at scale in wheat cultivation. Although the results were obtained using secondary assumptions, they offered significant insights into the potential environmental advantages under different treatments. Our results indicated that achieving a 16% reduction in N use through T_3 treatment could save approximately 9,300 tons of N (about 20,218 tons of urea) in wheat crops, compared to the FP. Furthermore, the reduction in N use could decrease CO_2 emissions from wheat fields by approximately 46,128 tons annually. In addition, this strategy could save about 448,826 gigajoules (GJ) of energy compared with FP without any yield penalty. These findings are consistent with Kumar et al. (2023); Tripathi et al. (2025); and Upadhyay et al. (2023) who reported that partial substitution of CU with NU can improve profitability, reduce energy demand and lower emission intensity without sacrificing yield when the degree of substitution remains moderate.

Conclusion

The results of this study demonstrate that combining NU with CU can improve wheat productivity, profitability, NUE, and environmental sustainability by reducing dependence on prilled N fertilizer. Compared with sole application of CU, the integrated application of NU with CU improved key morphophysiological traits, yield-contributing attributes, grain yield, grain quality parameters, and NUE. Notably, approximately 16% substitution of CU with one foliar spray of NU (T_3) increased the total number of tillers m^{-2}, GY, SY, HI, PC, grain N content, straw N content, total N uptake, and NUE by 12%, 7-8%, 7%, 1-2%, 6%, 5%, 2%, 4% and 135%, respectively.

From an economic perspective, T_3 treatment was found to be most profitable and favorable for farmers owing to higher net returns. In addition, adoption of this approach in wheat cultivation could reduce energy demand and save approximately 20,217 tons of urea and 46,128 tons of CO_2 emissions annually. Therefore, one foliar spray of NU combined with 84% of the recommended CU dose may be considered an environmentally and economically viable strategy for farmers to boost wheat production. Future research should focus on multi-location yield trials, agronomic validation, and evaluation of the environmental benefits of NU-based fertilizer management across different agro-ecological zones.

Author Contributions

Md. Sajjad Hossain and Mohammad Mahmudul Hasan contributed to conceptualization, methodology, investigation, laboratory analysis, data curation, data analysis and writing the original draft of the manuscript. Most. Eliza Tasnim Ema, Md. Mosaddakur Rahman, Nusrat Jahan Nishi, and Sumaya Siddika Ayesha contributed to data collection, laboratory analysis, data compilation, and data curation. Mahfuj Ahmed assisted with statistical analysis and visualization. Most. Zakiya Islam contributed to manuscript review and editing. Saumik Das Pantha performed abstract visualization and manuscript review. Alok Kumar Paul contributed to the conceptualization, supervision, and editing of the manuscript. All the authors read and approved the final version of the manuscript.

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Data Availability Statement

All the analyzed data in the present study are included in this article, and the supporting datasets can be found from the corresponding author upon request.

Clinical Trial Number

Not applicable

Declarations

Ethics Approval

The study received ethical clearance from the Research and Ethics Committee of the Sher-e-Bangla Agricultural University, along with an ethical waiver. All research activities were carried out in accordance with the University's Research Ethics Guidelines.

Consent to Participate

All participants were adults (≥18 years) and were thoroughly informed about the study's aims, potential outcomes, and their right to withdraw at any time without any consequences. Written informed consent was obtained from each participant prior to involvement in the study.

Consent for Publication

Participants provided written informed consent for both participation and the submission of data for publication. They were fully aware of the study's purpose, potential implications, and their freedom to withdraw at any point.

Competing Interests

The authors confirm that there are no conflicts of interest related to this study.

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