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| RESEARCH ARTICLE

Minimizing Nitrogen Requirement in Monsoon Rice through Foliar Feeding of Nano Urea

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| ABSTRACT
Nitrogen is one of the primary nutrient elements in rice cultivation and is mainly supplied through conventional prilled urea. Foliar application of nano urea in combination with conventional urea has recently emerged as a promising strategy to enhance nitrogen use efficiency (NUE), leading to increased crop productivity and profitability. This study was conducted to evaluate the effects of different split applications and timing of nano urea (2 litre per hectare), in combination with varying urea doses, on BRRI dhan49 T aman rice performance. The experiment comprised 10 treatments, T_1= Only recommended urea, T_2= 100% Recommended urea + Nano urea at 20 days after transplanting (DAT) and 40 DAT, T_3= 100% Recommended urea + Nano urea at 30 DAT and 50 DAT, T_4= 100% Recommended urea + Nano urea at 40 DAT and 60 DAT, T_5= 75% Recommended urea + Nano urea at 15 DAT, 30 DAT and 45 DAT, T_6= 75% Recommended urea + Nano urea at 20 DAT, 35 DAT and 50 DAT, T_7= 75% Recommended urea + Nano urea at 25 DAT, 40 DAT and 55 DAT, T_8= 50% Recommended urea + Nano urea at 15 DAT, 25 DAT, 35 DAT and 45 DAT, T_9= 50% Recommended urea + Nano urea at 20 DAT, 30 DAT, 40 DAT and 50 DAT, T_{10}= 50% Recommended urea + Nano urea at 25 DAT, 35 DAT, 45 DAT and 55 DAT . The study was conducted in a randomized complete block design with three replications. Among the treatments, T2 and T5 were superior to the others considering yield attributes and yield of BRRI dhan49 T aman rice. T2 recorded the highest number of effective tillers hill^{-1} at harvest (18.9), thousand grain weight (18.13 g), and grain yield (4.02 tha^{-1}), while T5 produced the highest number of grains panicle^{-1} (115.43), the lowest number of sterile spikelets panicle^{-1} (10.06), and the highest harvest index (48.43). The highest net return (50,212), benefit–cost ratio (1.39), and monetary advantage (140,700) were obtained from T2, closely followed by T5, and both outperformed the control. In contrast, reducing the recommended urea dose to 50% with four splits of nano urea resulted in higher agronomic NUE but negative grain yield merit (%). Overall, the results suggest that split application of nano urea during the early and active tillering stages, combined with 100% recommended urea doses, is the most effective strategy for maximizing yield performance and economic returns in BRRI dhan49 T aman rice cultivation.

| KEYWORDS

Nano urea; Foliar spray; Agronomic nitrogen use efficiency; Grain yield merit; Economic return; Benefit cost ratio.

| ARTICLE INFORMATION

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1. Introduction

Rice is a staple crop that feeds a large section of the world's population. Nano urea, a game-changing invention in modern agriculture, represents a big step forward in terms of sustainable and efficient crop production. It is predicted that there will be 8.1 billion people on the planet by 2030. In order to maintain rice production self-sufficiency, a growth of 2 to 3% must be maintained annually using the available land and water resources (Jamal et al., 2023; Rana et al., 2025)

Nitrogen is one of the major nutrients required for rice cultivation. Low NUE of rice has led to excessive use of conventional urea and it is continuing over many years which results in serious environmental pollution issues besides the gradual degradation of soil health (Bhatt et al. 2025). Several studies have found that volatilization of urea (to NH_3) and hydrolysis of urea followed by nitrification and denitrification mediated production of gaseous forms of N, mainly nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O) cause environmental pollution (Luo et al., 2025). While, surface runoff, leaching into ground water and assimilation by soil microorganisms (immobilization) cause ground water pollution and soil health degradation.

According to IFFCO, nano-urea contains nano nitrogen particles of the size range (20- 50 nm) dispersed in water which surface area is 10,000 times higher than conventional urea and around 55,000 nano-sized nitrogen particles are equivalent to a single 1 mm prilled urea. Nanoscale urea has greater adsorption capacity because of its large surface area, less volume and more reactive with other compounds (Dele et al., 2025). Liquid Nano fertilizer which is currently the best alternative to urea fertilizer. Foliar application of Nano urea liquid at critical crop growth stages of a plant effectively fulfils its nitrogen requirement and leads to higher crop productivity and quality in comparison to conventional urea (Singh et al., 2026).

Nano urea treatments having 25 % less nitrogen (N) provided higher total N (TN) in grain suggesting possible nutritional enrichment while checking the yield penalty and substantial increase in N use efficiency (NUE) (Jahan et al., 2018; Asif et al., 2024). Field trials conducted in India (including multi-location trials between 2019–2022) showed that replacement of 25–50% of conventional nitrogen fertilizer with two foliar sprays of nano urea resulted in a 3–12% yield increase. Studies from ICAR (Indian Council of Agricultural Research) also indicated improved nitrogen use efficiency (up to 85–90% compared to 30–40% in conventional urea), better grain filling, and reduced nitrogen losses through leaching and volatilization (Kamuruzzaman et al., 2024). Typically, nano urea is applied at 4 ml per liter of water, with two sprays at the active tillering and panicle initiation stages ensures nitrogen availability during spikelet differentiation, grain formation& grain filling. This reduces chaffy grains and increases harvest index. However, complete replacement of conventional urea is not always recommended; balanced nitrogen management gives the best yield response.

The major objective of this study was to determine the most suitable time of nano-urea application for achieving higher productivity and ensuring best yield. This study also aims for reduction of the amount of conventional nitrogen fertilizer that badly impacts the environment & overall ecosystem.

2. Materials and Methods

2.1 Experimental Site, Soil, and Climatic Characteristics

The study was carried out at the Agronomy Field Laboratory of Bangladesh Agricultural University, Mymensingh (coordinates 24°72′ N, 90°42′ E) at an elevation of 18 meters above sea level, during June to November 2023. The experimental field comprised non-calcareous soil belonging to the Sonatala soil series within the Old Brahmaputra Floodplain Agro-Ecological Zone (AEZ-9) (UNDP and FAO, 1988). The land was moderately high, with silty loam soil texture and adequate drainage. The soil pH was nearly neutral at 6.45, and organic matter content was low at 0.85%. The soil's nutrient profile included a total nitrogen content of 0.68%, available phosphorus of 16.67 ppm, exchangeable potassium of 0.20 meq/100 g of soil, and available sulfur of 12.75 ppm.

The climate in the area is subtropical, characterized by high temperatures and substantial rainfall during the growing season. The maximum air temperature recorded was 33.4°C in August, while the minimum was 18.3°C in November. Total rainfall during the experiment was 934.56 mm. The average relative humidity was 83.80%, and the mean monthly sunshine duration was approximately 187.63 hours.

2.2 Experimental Treatments and Design

The experiment employed a single-factor randomized complete block design (RCBD) with three replications, comprising ten different fertilizer treatment combinations. The treatments included:

1. **T1:** Only the recommended dose of nitrogen (RDN) using prilled urea.
2. **T2:** 100% RDN with prilled urea + nano-urea applied at 20 and 40 days after transplanting (DAT).
3. **T3:** 100% RDN + nano-urea at 30 and 50 DAT.
4. **T4:** 100% RDN + nano-urea at 40 and 60 DAT.
5. **T5:** 75% RDN + nano-urea at 15, 30, and 45 DAT.
6. **T6:** 75% RDN + nano-urea at 20, 35, and 50 DAT.
7. **T7:** 75% RDN + nano-urea at 25, 40, and 55 DAT.
8. **T8:** 50% RDN + nano-urea at 15, 25, and 35 DAT.
9. **T9:** 50% RDN + nano-urea at 20, 30, 40, and 50 DAT.
10. **T10:** 50% RDN + nano-urea at 25, 35, 45, and 55 DAT.

A total of 39 plots, each measuring 10 m^2 (4.0 m × 2.5 m), were established. Nano-urea was applied at a rate of 2 liters per hectare across relevant treatments.

2.3 Crop Husbandry

The rice variety BRRI dhan49, developed by the Bangladesh Rice Research Institute (BRRI), was used for this study. It is a high-yielding variety with a grain protein content of approximately 8.5%. Seeds were sourced from the BAU Agronomy Field Laboratory, Mymensingh, and were selected using a specific gravity method to ensure quality. Seeds were soaked in water for 24 hours, then kept in gunny bags until sprouting, which began after 48 hours.

A suitable highland area was chosen for nursery raising. After puddling the nursery bed and leveling it, seeds were sown on June 28, 2023. The nursery was maintained in wet conditions to facilitate sprouting. After 30 days, seedlings were carefully uprooted and transplanted into the prepared main field on July 25, 2023, at a spacing of 25 cm between rows and 15 cm between plants, at a rate of two seedlings per hill.

Soil fertilization followed BRRI recommendations, with basal application of Triple Super Phosphate (100 kg/ha), Murate of Potash (165 kg/ha), and Gypsum (110 kg/ha). Urea was top-dressed in three equal splits at 15, 30, and 45 days after transplanting. Nano-urea was applied via foliar spray at specified intervals according to treatment plans.

Throughout the crop's growth period, standard cultural practices were maintained. Weed control was initiated three days after transplanting with Pendimethalin (Panida 33 EC) at 5 mL per liter of water, followed by hand weeding at 30 and 45 DAT. To control pests, Spinosad 45% SC was applied twice, and brown spot disease was managed with Tilt 250EC. The field was irrigated with floodwater to a depth of about 5 cm during transplanting, with no additional irrigation needed due to reliance on monsoon rains. The field was drained 15 days before harvest.

2.4 Harvesting and Data Collection

Harvesting was conducted on November 13, 2023, when approximately 90% of the rice grains had turned yellow. For data collection, five randomly selected rice hills per plot (excluding boundary hills) were sampled. Measurements included plant height, total tillers per hill at 45 and 60 DAT, and at harvest. Additional yield-related attributes such as the number of effective tillers per hill, grains per panicle, sterile spikelets per panicle, and 1000-grain weight (at 14% moisture) were recorded. Post-harvest, grain yield (at 14% moisture) and straw weight (air-dried) were measured and expressed in tons per hectare.

2.5 Economic Analysis and Calculations

Economic evaluation involved calculating gross and net returns and the benefit-cost ratio (BCR) for each treatment. Input costs, including labor wages and fertilizer prices, were based on local market rates. The following parameters were also computed:

$$\text{Nitrogen use efficiency (NUE)} = \frac{\text{Total grain yield (kg/ha)}}{\text{Amount of applied nitrogen (kg/ha)}}$$

$$\text{Grain yield merit (\%)} = \frac{\text{Grain yield of N applied plot} - \text{ grain yield of control plot}}{\text{Grain yield of control plot}} \times 100$$

$$\text{Monetary advantage} = \text{Total grain yield (t/ha)} \times \text{Unit price of the grain}$$

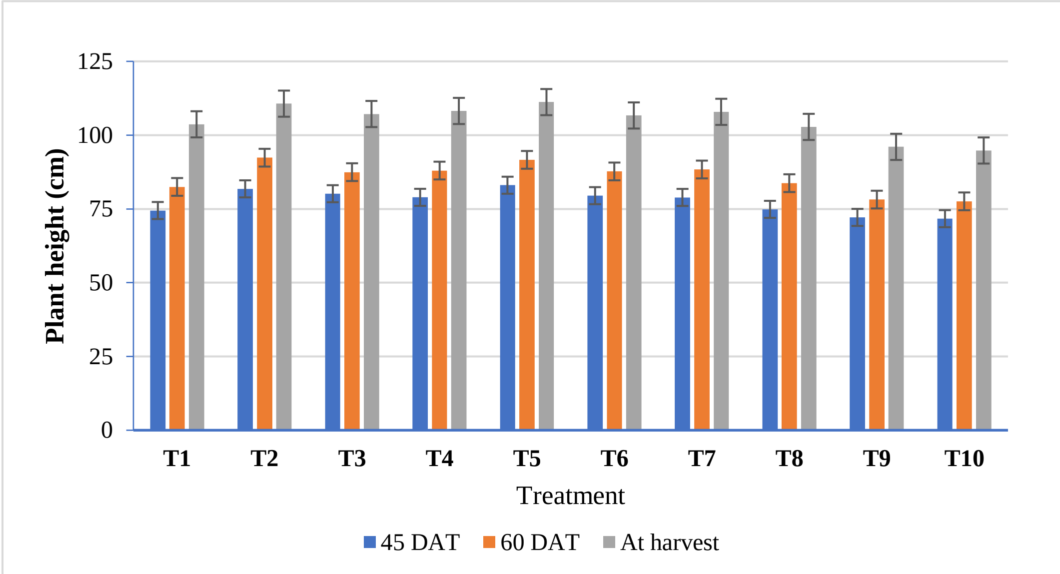
2.6 Statistical Analysis

All collected data were analyzed statistically using the MSTAT software package. Means were calculated, and an analysis of variance (ANOVA) was performed for each parameter using the F-test. Differences among treatment means were evaluated through the Least Significant Difference (LSD) test at 1% or 5% probability levels, as appropriate (Gomez and Gomez, 1984).

3. Result

3.1 Effect of treatment on plant height at different days after transplanting

The application schedule of nano urea and prilled urea had a significant influence on plant height (Figure 1). Plant height data were systemically measured at 45 and 60 DAT, and again at the time of harvest. Findings showed that at harvest, the tallest plant (111.20 cm) was obtained from (T_5) applying 75% recommended urea + 2 Lha^{-1} nano urea at 15 DAT, 30 DAT and 45 DAT, in this case the shortest plants (94.80 cm) was obtained from (T_{10}) applying 50% recommended urea + 2 Lha^{-1} nano urea at 25 DAT, 35 DAT, 45 DAT and 55 DAT. Study showed that, 100% recommended urea+ 2 Lha^{-1} nano urea at 20 DAT and 40 DAT (T_2) had best output on plant height (92.36 cm) at day 60, almost same height of plant (91.63) showed at T_5. Among the treatments, T_{10} again showed the lowest plant height (77.567 cm) at 60 DAT. Plant height data showed that, at 45 DAT tallest plant obtained from T_5 whither shortest plant observed with $T_{10.}$



3.2 Effect of treatment on total tillers hill^{-1} at different days after transplanting

Tillering ability of the plant was significantly influenced by the scheduling of nano urea application and the percentage of recommended urea fertilizer (Figure 2). The maximum number of tillers hill^{-1} was recorded in T_2 (100% recommended urea + 2 L ha^{-1} nano urea at 20 and 40 DAT), with 18.20 at 45 DAT, 21.80 at 60 DAT, and 20.36 at harvest. In contrast, the minimum number of tillers hill^{-1} was observed in T_{10} (50% recommended urea + 2 L ha^{-1} nano urea at 25, 35, 45, and 55 DAT), recording 10.80 at 45 DAT, 13.86 at 60 DAT, and 12.60 at harvest. Treatment T_2 was statistically at par with T_5 (75% recommended urea + 2 Lha^{-1} nano urea at 15 DAT, 30 DAT and 45 DAT) in tiller number at 45 DAT and 60 DAT at the 1% level of significance.

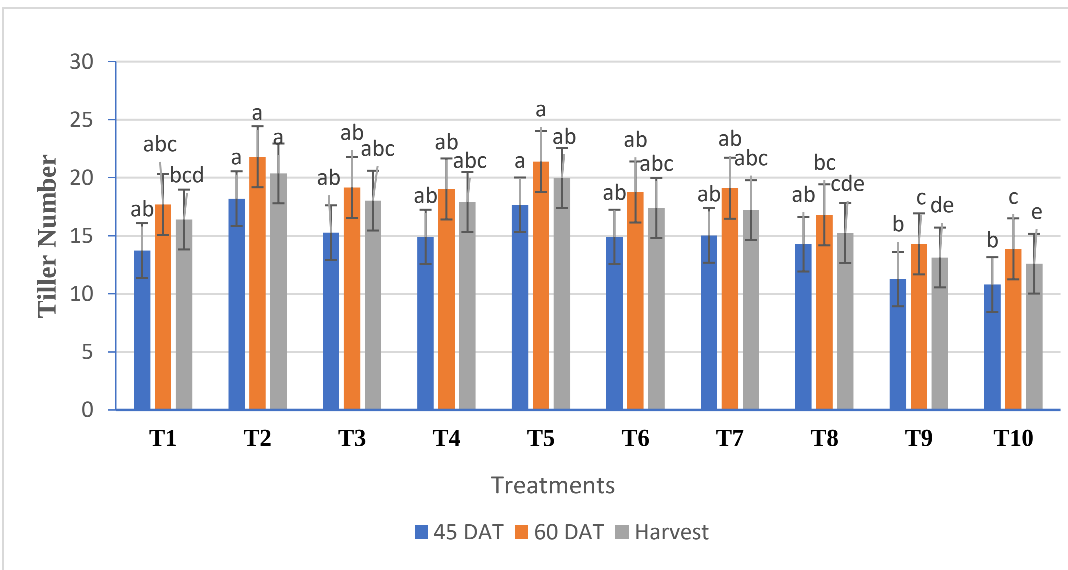


Figure 2. Effect of treatment on plant height at different days after transplanting.

3.3 Effect of treatment on yield contributing characters

3.3.1 Effective tiller hill^{-1}

The data presented in the table 1 indicate that the timing of urea fertilizer application had a significant influence on the yield and yield contributing characters. Maximum no. of effective tillers hill^{-1} (18.90) at harvest was found from the application of 100% recommended urea + 2 Lha^{-1} nano urea at 20 DAT and 40 DAT (T_2) whereas minimum no. of tillers hill^{-1} (11.23) was found from 50% recommended urea + 2 Lha^{-1} nano urea at 25 DAT, 35 DAT, 45 DAT and 55 DAT (T_{10}).

3.3.2 Grains panicle^{-1}

Result presented in table 1 reveal that the maximum number of grains panicle^{-1} (115.43) was obtained from treatment T_5 where 75% recommended urea + 2 Lha^{-1} nano urea used at 15 DAT, 30 DAT and 45 DAT, which was statistically at per with T2. Conversely, treatment (T_{10}) 50% recommended urea + 2 Lha^{-1} nano urea at 25 DAT, 35 DAT, 45 DAT and 55 DAT produced the minimum number of grains panicle^{-1} (97.50).

3.3.3. Sterile spikelets panicle^{-1}

Sterile spikelets panicle^{-1} was significantly influenced by application schedule of nano urea and prilled urea (Table1). The maximum number of sterile spikelets panicle^{-1} (15.26) was observed with the application of 50% recommended urea + 2 Lha^{-1} nano urea at 25 DAT, 35 DAT, 45 DAT and 55 DAT (T_{10}) and the minimum number of sterile spikelets panicle^{-1} (10.06) was found by applying 75% recommended urea + 2 L/ha nano urea at 15 DAT, 30 DAT and 45 DAT (T_5).

3.3.4 1000-Grain weight

Study showed that weight of the grain were also different due to different treatment combination (Table 1). Highest 1000- grain weight (18.16) obtained from (T_5) 75% recommended urea + 2 Lha^{-1} nano urea at 15 DAT, 30 DAT and 45 DAT which was statistically at per with T_2. 50% recommended urea + 2 Lha^{-1} nano urea at 20 DAT, 30 DAT, 40 DAT and 50 DAT (T_9) treatment combination provided lowest weight of 1000- grain (15.86 g).

3.4 Effect of treatment on Yield Performance and harvest index:

3.4.1 Grain Yield (t ha^{-1})

Different application date significantly influenced on grain yield. Table 1 showed that highest amount of grain yield (4.02 t ha^{-1}) obtained from (T_2) 100% recommended urea + 2 Lha^{-1} nano urea at 20 DAT and 40 DAT and lowest amount of grain yield (3.05 t ha^{-1}) annexed with application of 50% Recommended urea + Nano urea at 25 DAT, 35 DAT, 45 DAT and 55 DAT (T_{10}).

3.4.2 Straw Yield (t ha^{-1})

Straw yield was significantly influenced by the application schedule of urea fertilizer (Table1). The highest straw yield (4.72 t ha^{-1}) was observed by the application of 100% recommended urea + 2 Lha^{-1} nano urea at 40 DAT and 60 DAT (T_4) which statistically similar with T_3 (100% Recommended urea + Nano urea at 30 DAT and 50 DAT) and T_6 (75% Recommended urea + Nano urea at 20 DAT, 35 DAT and 50 DAT). The lowest amount of straw yield (3.76 t ha^{-1}) obtained from T_9 (50% recommended urea + 2 L/ha nano urea at 20 DAT, 30 DAT, 40 DAT and 50 DAT).

3.4.3 Harvest Index%

Highest harvest index (48.43%) was recorded with 75% recommended urea + 2 Lha^{-1} nano urea at 15 DAT, 30 DAT and 45 DAT (T_5). And lowest % of harvest index (42.26%) was observed from (T_1) only recommended urea which was followed by (T_4) 100% recommended urea + 2 Lha^{-1} nano urea at 40 DAT and 60 DAT (Table 1).

Table 1. Effect of treatment on yield and yield contributing characters

Treatments	Effective tiller hill^{-1} at harvest	Grains panicle^{-1}	Sterile spikelets panicle^{-1}	1000-grain weight (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest Index (%)
T_1	15.23bcd	104.33bc	10.73 bc	17.10ab	3.31 cd	4.52ab	42.26 c
T_2	18.90a	114.27a	11.33abc	18.13a	4.02a	4.61ab	46.60ab
T_3	16.43abc	111.43ab	10.73 bc	17.30ab	3.66abc	4.65a	44.00 bc
T_4	16.26abc	109.73ab	11.43abc	17.23ab	3.55 bc	4.72a	42.96 c
T_5	18.30ab	115.43a	10.06 c	18.16a	3.95ab	4.20 bc	48.43a
T_6	15.80abc	109.20ab	11.46abc	17.43ab	3.71ab	4.66a	44.33 bc
T_7	16.06abc	110.10ab	10.56 bc	17.20ab	3.63abc	4.45ab	44.93abc
T_8	13.96 cde	103.70bc	14.76ab	16.93ab	3.29 cd	4.21 bc	43.85 bc
T_9	11.80 de	98.37c	14.06abc	15.86 b	3.10 d	3.76 d	45.18abc
T_{10}	11.23 e	97.50c	15.26a	16.16 b	3.05 d	3.89 cd	43.95 bc
Level of significance	**	**	**	**	**	**	**
CV (%)	**7.99**	**3.16**	**12.68**	**3.56**	**3.84**	**3.38**	**2.70**

** =Significant at 1% level of probability

3.5 Economic analysis

The economic analysis showed noticeable differences among the treatments in terms of production cost and profitability (Table 2). Although the total production cost varied only slightly (Tk. 126,234–127,368) because most input expenses were similar, differences in urea application and labor requirement influenced the final returns. Treatment T_2 (100% recommended urea + 2 Lha^{-1} nano urea at 20 DAT and 40 DAT) performed the best economically, giving the highest gross return (Tk. 177,580), net return (Tk. 50,212), and B:C ratio (1.39). This indicates that the nutrient combination used in T_2 was the most profitable under the present conditions. Treatments T_5 (75% Recommended urea + Nano urea at 15 DAT, 30 DAT and 45 DAT) and T_6 (75% Recommended urea + Nano urea at 20 DAT, 35 DAT and 50 DAT) also generated good economic returns, suggesting that reducing urea while supplementing with nano-urea can still maintain satisfactory profitability.

On the other hand, T_8 (50% Recommended urea + Nano urea at 15 DAT, 25 DAT, 35 DAT and 45 DAT), T_9 (50% recommended urea + 2 L/ha nano urea at 20 DAT, 30 DAT, 40 DAT and 50 DAT) and T_{10} (50% recommended urea + 2 Lha^{-1} nano urea at 25 DAT, 35 DAT, 45 DAT and 55 DAT) resulted in comparatively lower net returns and B:C ratios (1.09), indicating that excessive reduction of nitrogen may negatively affect economic performance.

Table 2: Effect of treatment on economic return and benefit cost ratio

Treatment	Variable cost except urea and nano-urea cost	Urea cost	Nano-urea cost	Labor cost	Total cost	Gross return	Net return	B:C ratio
T_1	120000	4468	0	0	124468	152010	27542	1.22
T_2	120000	4468	1800	1100	127368	177580	50212	1.39
T_3	120000	4468	1800	1100	127368	165300	37932	1.29
T_4	120000	4468	1800	1100	127368	162010	34642	1.27
T_5	120000	3351	1800	1650	126801	171850	45049	1.35
T_6	120000	3351	1800	1650	126801	167130	40329	1.32
T_7	120000	3351	1800	1650	126801	162650	35849	1.28
T_8	120000	2234	1800	2200	126234	148830	22596	1.18
T_9	120000	2234	1800	2200	126234	138580	12346	1.09
T_{10}	120000	2234	1800	2200	126234	137870	11636	1.09

Urea = 27 BDT Kg^{-1} , Nano-urea = 900 BDT L^{-1} , Rice = 35 BDT Kg^{-1} , Straw = 8 BDT Kg^{-1}, Labor = 550 BDT day^{-1}. 1US$= 120 BDT

3.6 Agronomic Nitrogen Use Efficiency, Grain Yield Merit and Monetary Advantage

Agronomic nitrogen use efficiency (NUE), grain yield merit, and monetary advantage were markedly influenced by the level of recommended urea and timing of nano urea application (Figure 3). The control (T_1: only recommended urea) recorded moderate NUE (47.91) and monetary advantage (115,850). Among 100% recommended urea treatments, T_2 (100% recommended urea + 2 Lha^{-1} nano urea at 20 DAT and 40 DAT) produced the highest grain yield merit (21.15%) and maximum monetary advantage (140,700), followed by T_3 (100% Recommended urea + Nano urea at 30 DAT and 50 DAT) and T_4 (100% Recommended urea + Nano urea at 40 DAT and 60 DAT), indicating that earlier nano application was more effective than delayed application. Under 75% recommended urea, T_5 (75% Recommended urea + Nano urea at 15 DAT, 30 DAT and 45 DAT) achieved high ANUE (76.21) with 19.33% yield merit and 138,250 monetary advantage, which was comparable to T_2, suggesting that 25% urea reduction is feasible with proper nano supplementation.

Although the 50% recommended urea treatments (T_8–T_{10}) recorded the highest NUE (88.20–95.14), they showed negative grain yield merit and lower monetary returns, indicating yield limitation due to excessive nitrogen reduction. Overall, T_2 and T_5 were the most productive and economically viable treatments.

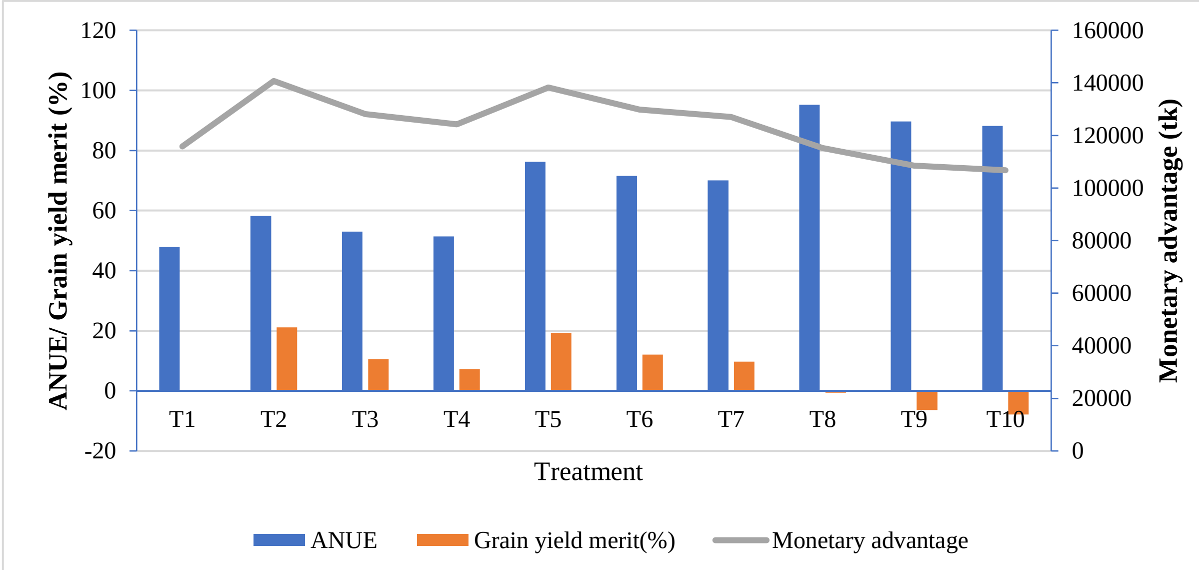


Figure 3: Effect of treatment on agronomic nitrogen use efficiency, grain yield merit and monetary advantage.

4. Discussion

Rice crops typically utilize only 30–40% of applied nitrogen fertilizer, with the remainder lost through volatilization, leaching, and runoff. Applying nano-urea in split doses offers a promising strategy to enhance nitrogen use efficiency (up to 70%) in rice, including flooded systems, thereby reducing nutrient losses and associated environmental impacts (Asif et al., 2024; Chandra et al., 2025). The positive role of nano-urea applied in combination with conventional urea in improving crop performance is well documented (Anwar et al., 2025; K. B. Chandra et al., 2025). This study investigated the performance of nano-urea applied at 2 L ha^{-1} in 2, 3, and 4 splits at different DAT, in combination with 100%, 75%, and 50% of the recommended urea dose, respectively on plant growth, yield attributes and yield of rice.

Our study demonstrates that T_5 and T_2 were the most effective treatments in enhancing plant height and tiller number. This indicates that optimized split application of nano urea at early and active tillering stage, even with reduced conventional urea, can effectively promote vegetative growth. Behera et al., (2025), found that nano urea application significantly enhanced plant height at different growth stages of transplanted rice. The application of 75% recommended nitrogen along with 100% PK and two foliar sprays of nano urea (0.4%) at tillering and panicle initiation stages resulted in increased plant height at active tillering, panicle initiation, flowering, and maturity stages (Behera et al., 2025). Foliar application of nano-urea enhances nitrogen uptake through stomatal absorption, stimulating cell division, meristematic activity, and cell elongation. These physiological processes promote increased plant height and tiller production (Ranjan et al., 2023). Moreover, nitrogen, as a key component in tryptophan biosynthesis, plays a central role in regulating rice growth and development. These findings are consistent with previous studies (Velmurugan et al., 2022; Ramesh et al., 2025).

In contrast, T_8, T_9, and T_{10} consistently produced the lowest number of tillers, which may be attributed to the percentage of recommended urea and time of nano-urea application. Four split applications of nano-urea at 2 L ha^{-1} combined with only 50% of the recommended urea dose were insufficient to meet the crop's nitrogen demand. Sikka et al., (2024) also found that nano-urea in combination with 50% recommended nitrogen were insufficient to enhance nitrogen use efficiency. Moreover, since maximum tiller formation in rice occurs within the first 45 days after transplanting, nitrogen supply during this period is critical for optimal growth. The timing of nano-urea application is more crucial than the number of splits in enhancing plant height and tiller development (Dhamankar et al., 2023).

T_2 produced the highest number of effective tillers hill^{-1}, closely followed by T_5. However, T_5 recorded the maximum number of grains panicle^{-1} and highest 1000 grain weight (g) which was statistically comparable to T_2. This indicates that three splits of 2 L ha^{-1} nano-urea were able to substitute 25% of the recommended urea without any negative impact on these three important yield contributing traits. Substituting 25% of the recommended nitrogen with two or three foliar applications of nano-urea resulted in outcomes comparable to the complete nitrogen dose was also reported by Ramesh et al., (2025). T_5 recorded the lowest number of sterile spikelets panicle^{-1}, while highest grain yield was obtained from T_2. Overall, the results showed that nano-urea applied at 20 and 40 DAT with 100% of the recommended urea dose, and at 15, 30, and 45 DAT with 75% of the recommended urea dose, outperformed all other treatments.

Nutrient uptake in rice increases with the foliar application of nano urea, which may be attributed to the large surface area and ultra-small particle size of nano fertilizers. Their particle size, being smaller than the pore size of roots and leaves, facilitates easier penetration into plant tissues from the applied surface, thereby enhancing nutrient absorption. This boosts photosynthesis, leading to higher dry matter production and crop yield. These findings are in close agreement with the results of Lahari et al., (2021) and Meshram et al., (2024). Foliar application of nano urea (liquid) at tillering and booting stages in cereal crop was reported to fulfill the nitrogen requirement and reflect higher crop productivity (Soundarya et al., 2024).

The results revealed considerable variation in agronomic nitrogen use efficiency among the treatments, mainly influenced by the total amount of nitrogen applied and the resulting grain yield per treatment. Higher ANUE values were observed in the 50% recommended urea treatments (T_8, T_9 and T_{10}). A similar trend in agronomic nitrogen use efficiency was reported by Saha et al., (2020) who observed that increasing nitrogen levels led to a decline in NUE. This is primarily because these treatments recieved a lower total amount of nitrogen. When nitrogen input decreases, even a moderate grain yield results in higher grain production per unit of applied nitrogen. Excessive application of nitrogen fertilizer led to a reduction in physiological nitrogen use efficiency (Singh et al., 2014). Therefore, the elevated ANUE in these treatments reflects greater efficiency of nitrogen utilization relative to the amount supplied. However, although ANUE was highest under 50% nitrogen application, these treatments did not produce the highest grain yield merit or monetary return. This indicates that while nitrogen was used more efficiently on a per-unit basis, the total nitrogen supplied was insufficient to achieve maximum yield potential. In contrast, T_2 produced the highest grain yield and economic benefit, even though its ANUE was comparatively lower than the 50% treatments. This suggests that adequate nitrogen supply combined with properly timed nano-urea application ensured both sufficient nutrient availability and effective uptake, leading to superior productivity. Among the 75% urea treatments, T_5 showed a desirable balance, maintaining relatively high ANUE along with strong yield and economic performance. This indicates that moderate nitrogen reduction supported by nano-urea application can enhance nitrogen efficiency without substantially compromising yield.

The economic analysis indicated that although the inclusion of nano urea increased the total cost of cultivation, it remained more profitable than the control treatment up to a 50% reduction of the recommended urea dose. Treatment T_2 recorded the highest net return and benefit–cost ratio (BCR), followed by T_5, primarily due to their superior grain yields. The result also highlight that both the rate of conventional urea and the timing (number and schedule of splits) of nano urea application play a crucial role in determining economic returns (Kumar et al., 2025). Therefore, integrating conventional and nano fertilizers at appropriate rates and growth stages may promote economically viable and sustainable crop production.

5. Conclusion

This study demonstrates that the scheduling of nano urea application—specifically the number of splits and their timing combined with appropriate urea doses, significantly influences productivity and profitability in rice cultivation. Application of nano urea at 20 and 40 DAT with 100% recommended urea proved to be the most effective strategy for achieving maximum yield and economic return. Moreover, nano urea application at 15, 30, and 45 DAT with 75% recommended urea outperformed the later applications of nano urea with 100% urea, indicating that a 25% reduction in conventional urea is feasible when nano urea is applied at optimal growth stages.

However, the findings are based on a single-season and single-location study. Therefore, long-term and multi-locational trials, including detailed assessment of soil and other factors, are necessary to validate these results and to develop more precise and sustainable nitrogen management strategies for rice cultivation.

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