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Assessing the scope for nano-urea to reduce nitrogen inputs while maintaining rice yields in India

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Excessive nitrogen (N) fertilizer use in rice (*Oryza sativa* L.) cultivation results in significant nutrient losses and environmental degradation. Nano fertilizers offer a promising solution to enhance nutrient use efficiency, reduce losses, and mitigate environmental impacts in rice-based systems. This study aims to evaluate the effects of nano-urea application on rice yield, economic returns, and N use efficiency in India. Field experiments (2022–2024) were conducted at Varanasi and Guwahati, assessing nine treatments in 2022 and seven treatments in 2023 and 2024 in a Randomized block design (RBD) replicated thrice. Treatments included conventional soil-applied N at 75, 66, and 50% of the recommended dose (RDN) and was tested with foliar applications of nano-urea, applied once at panicle initiation (PI) or twice at maximum tillering (MT) and PI. These were compared with control and state fertilizer N rate. Application of 66–75% RDN with nano-urea applied twice (MT and PI) produced yields comparable to 100% RDN. However, applying nano-urea with 50% RDN resulted in a yield penalty of 17% (0.88 t ha⁻¹) in Guwahati (2023–2024) and 16–19% (0.95–1.2 t ha⁻¹) in Varanasi (2022–2023). Our findings indicate that 27–40 kg N ha⁻¹ can be saved in Varanasi and 15–20 kg N ha⁻¹ in Guwahati without yield loss using RDN 66–75% with nano-urea. N₆₆–N₇₅ with nano urea sprays achieved economic returns comparable to RDN₁₀₀, with reduced N inputs. Based on these findings, the application of urea at 66–75% RDN is recommended, supplemented with two foliar applications of nano-urea at MT and PI stages to sustain yield while reducing overall N input.

KEYWORDS

nano-fertilizers, nano-urea, nitrogen use efficiency, rice yield, foliar fertilization, nitrogen savings

1 Introduction

Rice (*Oryza sativa* L.) is a crucial staple food crop, supporting nearly two-thirds of the global population (Sen et al., 2020) and is a key pillar of food security in India (Nayak et al., 2024). India, the second-largest global producer of rice, achieved an impressive milestone with a recorded production of 137.8 million tons in the 2023–2024 (Agricultural Statistics at a Glance, 2023). The rice production in India is resource-intensive (Eliazar Nelson et al., 2019) and encounters unpredictable climatic hazards, making it difficult to maintain sustainable

production (Benbi, 2018). Furthermore, inefficient fertilizer practices contribute to rapid environmental pollution (Sarkar et al., 2018; Thakur et al., 2021). The detrimental effects resulting from the intensification of agriculture and excessive resource usage cannot be overlooked (Chartres and Noble, 2015). To address the challenges faced by farmers and meet the growing demand for rice production within the limits of existing cropland, it is crucial to urgently develop and implement effective agronomic management practices. Nevertheless, the urgency to address environmental issues, optimize resource utilization, and establish sustainable agricultural practices becomes evident in the quest for increased food production (Hunter et al., 2017; Xie et al., 2019).

Fertilizers are essential for improving crop production and soil fertility and play a crucial role in maintaining a favorable nutrient balance (Penuelas et al., 2023). Nitrogen (N), a key mineral nutrient for rice, serves as a fundamental constituent of chlorophyll, promoting vegetative growth (Kumar et al., 2021b). In India, the consumption of urea fertilizer has increased significantly over the years (Khurana and Kumar, 2022), with total usage reached about 38.77 million metric tons, accounting for a major share of the overall fertilizer consumption (FAI Report, 2024–25). This increase can be largely attributed to substantial government subsidies for chemical fertilizers (Amit and Vineet, 2022), especially urea (Kumar et al., 2021b). Conventional fertilizers, with their low nutrient use efficiency (NUE) and environmental limitations, have negative impacts that extend beyond environmental concerns, affecting grower's profitability by increasing costs (Swify et al., 2023). N fertilization is essential for achieving rice grain yields, reported to have low NUE with the use of conventional urea (Sapkota et al., 2023).

Urea is the most commonly used N fertilizer due to its high N content (46%) and cost-effectiveness. The global demand for urea is projected to reach 183 million MT in 2024 (Devkota et al., 2024). In India, Rice cultivation spans 47.83 million hectares (Agricultural Statistics at a Glance, 2023), accounting for over 30% of India's total urea consumption, which amounts to 10.72 million MT (Meena et al., 2021). However, excessive use of conventional fertilizers like urea granules have contributed to substantial environmental challenges on a global scale (Congreves and Van Eerd, 2015), and exhibit low NUE, typically ranging between 30 and 40% (Solanki et al., 2015; Rakshit, 2019). The remaining N causes environmental degradation through nitrate leaching (Bijay and Craswell, 2021), eutrophication (Huang et al., 2017), and gaseous emissions such as ammonia volatilization, nitrous oxide (N₂O) emissions and denitrification (Chakraborty et al., 2023; Jiang et al., 2012). Studies indicate that 40–70% of applied N is lost from conventional fertilizers, resulting in both economic and environmental consequences (Giroto et al., 2017). To improve fertilizer efficiency and reduce environmental impacts, precision nutrient management strategies such as the 4R's (Right source, Right time, Right rate and Right place) approach offers a viable strategy to improve fertilizer efficiency and mitigate its environmental impact (Vijayakumar et al., 2024).

In response to the challenges associated with conventional fertilizers, there has been growing interest in alternative technologies, such as nano fertilizers, which offer potential improvements in NUE and environmental sustainability (Pudhuvai et al., 2024). Over the past two decades, researchers have been investigating the use of nanotechnology to enhance nutrient utilization and enable targeted delivery in plants (Su et al., 2022). Nanotechnology holds promise for

improving nutrient utilization and ensuring targeted delivery to plants (Chen and Yada, 2011; Goswami et al., 2019). Studies indicate that nano-fertilizers can enhance crop productivity by 6–17% while significantly reducing N losses (Madzokere et al., 2021). Nano clay-based N formulations provide a sustained release of nutrients, reducing leaching and volatilization losses compared to conventional fertilizers (Subramanian et al., 2015). Furthermore, nano-fertilizers prevent nutrient loss through leaching, volatilization, and denitrification, thus contributing to both economic and environmental sustainability (Geng et al., 2016; Madzokere et al., 2021). In 2023–2024, the Indian government allocated USD 16 billion for urea subsidies (Government of India, 2024). The Ministry of Chemicals and Fertilizers estimates that integrating nano urea into Indian agriculture could save USD 3 billion (INR 22,500 crore) annually in subsidy costs. At the current subsidy rate of INR 20,000 per MT of urea (Thirty-Ninth Report of the Standing Committee on Chemicals and Fertilizers, 2023).

Nano-fertilizers, particularly nano urea, offer promising advantages due to their ultra-small particle size (30–50 nm), high surface area, and controlled nutrient release, which improve nutrient absorption and utilization efficiency (Subramanian et al., 2015; Raliya et al., 2017; Asif et al., 2024). Field trials suggest that nano urea can reduce conventional urea application by 25% without significantly affecting crop yields (Gangwar et al., 2022; Upadhyay et al., 2023). Nano urea efficiently enters plant cells, enhancing N assimilation, photosynthesis, and dry matter accumulation, leading to improved grain yield and nutrient uptake (Kumar et al., 2021a; Upadhyay et al., 2023). While the potential benefits of nano urea are widely acknowledged, recent studies have reported inconsistent results regarding its impact on crop yield and soil nutrient dynamics (Sarkar et al., 2023; Sikka et al., 2025). Nano-fertilizers enhance crop growth and yield when applied at optimal doses and concentrations; however, exceeding these levels can inhibit plant growth and reduce yields (Kumar et al., 2023). Recent studies on nano-urea have shown mixed results. Some research suggests that nano-urea can reduce N fertilizer use by 25% in crops such as maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), pearl millet (*Pennisetum glaucum* L.), and mustard (*Brassica juncea* L.) without negatively impacting yields (Upadhyay et al., 2023). However, a few studies have reported that nano-urea may lead to a significant decrease in yields (Sikka et al., 2025). Studies also reported that recommend dose of nitrogen (RDN) 75% + 1 to 2 foliar sprays of IFFCO nano-urea (4% N) can achieve crop yields comparable to those obtained with 100% of the RDN (Dass et al., 2024). Similarly, Velmurugan et al. (2021) reported that reducing nitrogen fertilizer by 25–50% along with two foliar nano-urea sprays maintained yields equivalent to 100% RDN in rice.

However, limited research exists on the impact of nano-urea on rice yields, NUE and profitability. Therefore, this study aimed to evaluate the effects of nano-urea on rice yield, profitability, NUE, and soil properties in two rice-growing states of India: Uttar Pradesh (Varanasi) and Assam (Guwahati). It is hypothesized that the integrated application of nano-fertilizers can significantly enhance nutrient use efficiency and rice productivity compared to conventional fertilization, while improving the long-term sustainability of soil N supply. Accordingly, this study was undertaken with the following objectives: (i) to evaluate the effects of foliar application of nano-fertilizers with varying doses of N application on yield and NUE in rice and (ii) to assess the economic viability of these N application under both subsidized and non-subsidized input cost scenarios.

2 Materials and methods

2.1 Details of experimental sites

On-station experiments were conducted at two different locations viz. International Rice Research Institute-South Asia Regional Centre (ISARC), Varanasi, Uttar Pradesh (25.3021° N, 82.9502° E) and Indian Council of Agricultural Research - National Rice Research Institute - Regional Rainfed Lowland Rice Research Station (ICAR-NRRI-RRLRRS), Gerua, Guwahati (26°15'16.2"N 91°33'52.5"E), Assam, India. The experimental locations are visually represented, and map was generated using QGIS 3.34.10 (Figure 1). The experiments with set of treatments were conducted during the rainy (*kharif*) season (June to October) over 3 years (2022 to 2024) at both locations. The initial soil properties of both locations are detailed in Table 1. In Varanasi, the mean maximum and minimum temperatures during the crop growth period ranged from 33.8 °C to 25.5 °C in 2022, were slightly higher 34.5 °C to 26.8 °C in 2023 and 2024, respectively. In Guwahati, the mean maximum temperatures ranged from 33.8 °C to 36.8 °C, while the minimum temperatures ranged from 23 °C to 25.4 °C (Supplementary Figures 1, 2).

2.2 Treatments and experimental design

The experiment was conducted in puddled transplanted rice for three consecutive *kharif* season of 2022, 2023 and 2024 at both locations in a randomized complete block design (RCBD) with three

replications for each treatment. In 2022, nine treatments were tested. Because some treatments performed very poorly, they were dropped, and only seven treatments were continued in 2023 and 2024 at both locations. Fertilizer recommendations vary depending on agro-ecological conditions. In Eastern Uttar Pradesh, the recommended fertilizer dose for rainfed rice was 80–60–40 N-P₂O₅-K₂O kg ha⁻¹ in 2022, whereas for irrigated rice it was 120–60–60 N-P₂O₅-K₂O kg ha⁻¹ in 2023–2024. In Assam, the recommended fertilizer dose for rainfed rice was 60–20–40 kg N-P₂O₅-K₂O kg ha⁻¹ across all experimental years. Nitrogen was applied according to the treatment specifications. The N₁₀₀ treatment was applied in three splits at basal, maximum tillering (MT), and panicle initiation (PI) stages. Other N treatments (N₇₅, N₆₆, and N₅₀) were applied in two splits at basal and MT, while N₃₃ was applied only at basal. Nano-urea was applied as a foliar spray at critical growth stages depending on the treatment: one spray at PI, two sprays at MT and PI, or three sprays at MT, PI, and heading. A summary of crop management details and treatments implemented in each season is presented in Tables 2, 3. Phosphorus (P₂O₅) and potassium (K₂O), applied as muriate of potash, were uniformly supplied to all treatment plots except the control (N₀P₀).

The cultivars used at ISARC, Varanasi in 2022 was Binadhan-11 (short duration), MTU-7029 (long duration) in 2023, followed by Swarna Samriddhi Dhan (medium duration) in 2024. In Guwahati, the variety CR Dhan – 311 (medium duration) was used in 2022, and Binadhan-11 was used in 2023 and 2024. Binadhan-11, developed and released by the Bangladesh Institute of Nuclear Agriculture, is an early-maturing (120–125 days), high-yielding

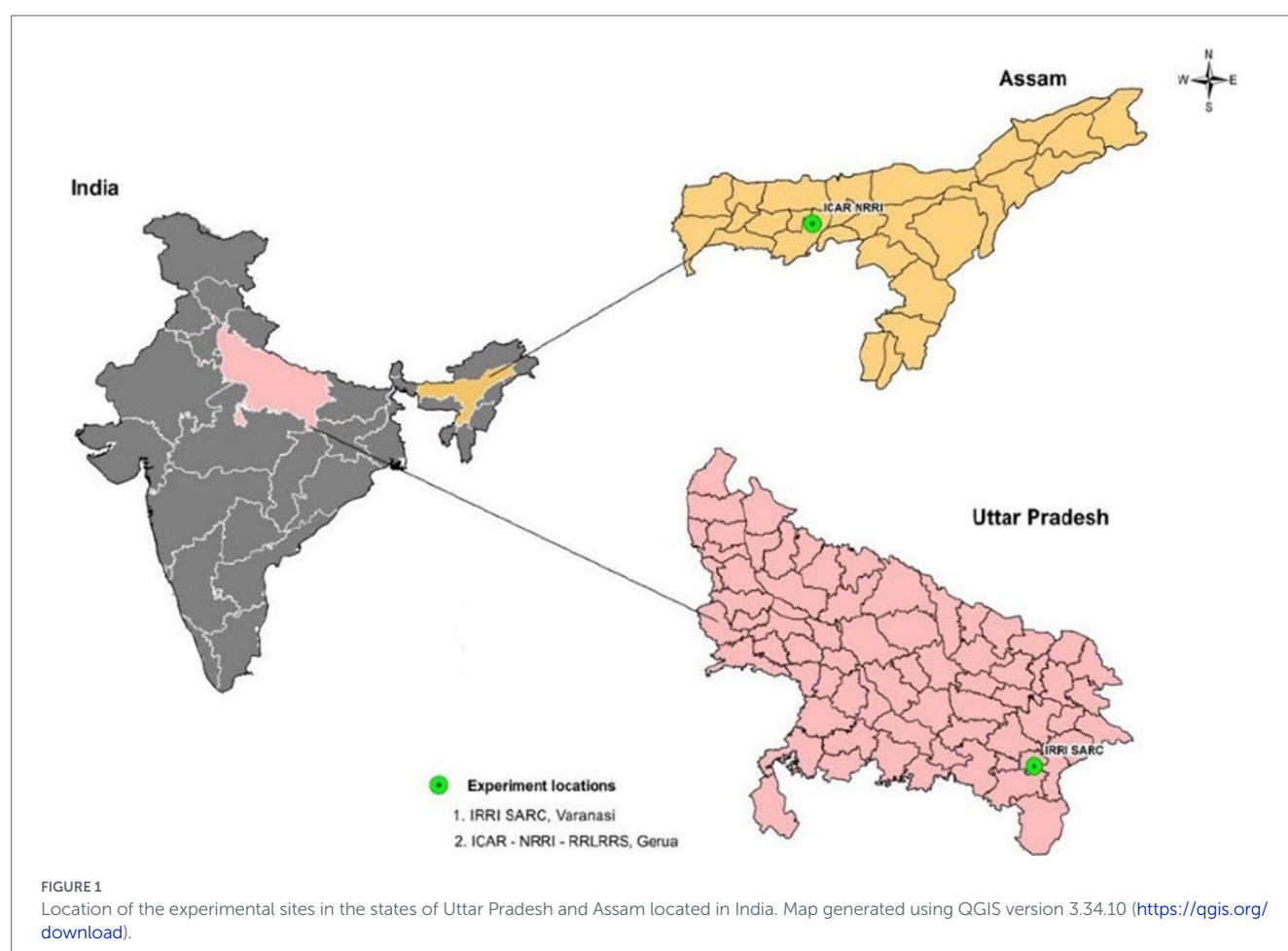


TABLE 1 Baseline soil characteristics of the experimental field before the study.

Soil property	Varanasi, Uttar Pradesh	Guwahati, Assam
Soil texture	Silty loam	Silty clay loam
pH	8.14	5.90
Electrical conductivity	0.12 dS m ⁻¹	0.21 dS m ⁻¹
Organic carbon	0.50%	0.74%
Available nitrogen	166.0 kg ha ⁻¹	229.0 kg ha ⁻¹
Available phosphorus	19.33 kg ha ⁻¹	14.75 kg ha ⁻¹
Available potassium	117.0 kg ha ⁻¹	167.0 kg ha ⁻¹

TABLE 2 Treatment details of nitrogen applications in 2022.

Treatments	Treatment details	N applied* (kg ha ⁻¹) in Varanasi, Uttar Pradesh	N applied* (kg ha ⁻¹) in Guwahati, Assam
T ₁	N ₀	0	0
T ₂	N ₁₀₀	80	60
T ₃	N ₆₆ + two sprays of nano-urea of 2 ml liter ⁻¹ at MT and PI**	52.8	39.6
T ₄	N ₆₆ + one spray nano-urea of 4 ml liter ⁻¹ at PI	52.8	39.6
T ₅	N ₅₀ + two sprays nano-urea of 2 ml liter ⁻¹ at MT and PI	40	30
T ₆	N ₅₀ + one spray nano-urea of 4 ml liter ⁻¹ at PI	40	30
T ₇	N ₃₃ + two sprays nano-urea of 2 ml liter ⁻¹ at MT and PI	26.6	19.8
T ₈	N ₃₃ + two sprays nano-urea of 4 ml liter ⁻¹ at MT and PI	26.6	19.8
T ₉	N ₃₃ + three sprays nano-urea of 2 ml liter ⁻¹ at MT, PI and heading	26.6	19.8

Recommended fertilizer dose for rainfed rice in Eastern UP is 80–60–40 N-P₂O₅-K₂O and Assam for Kharif (Sali) rice is 60–20–40 kg N-P₂O₅-K₂O kg ha⁻¹. N₀, N₁₀₀, N₆₆, N₅₀, N₃₃ denotes the percentage of recommended dose of nitrogen. *N applied as conventional granular urea **MT and PI is referred as maximum tillering and panicle initiation stages. All treatments, including T₁, received the recommended doses of phosphorus (P) and potassium (K). The only variations among the treatments pertain to the applications of nitrogen (N).

TABLE 3 Treatment details of nitrogen applications in 2023 and 2024.

Treatments	Treatment details	N applied* (kg ha ⁻¹) in ISARC, Varanasi	N applied* (kg ha ⁻¹) in Guwahati
T ₁	N ₀	0	0
T ₂	N ₅₀	60	30
T ₃	N ₁₀₀	120	60
T ₄	N ₅₀ + two sprays of nano urea of 4 ml liter ⁻¹ at MT and PI**	60	30
T ₅	N ₆₆ + two sprays of nano urea of 4 ml liter ⁻¹ at MT and PI	79.2	39.6
T ₆	N ₇₅ + one spray/ two sprays nano urea of 4 ml liter ⁻¹ at MT/ PI	90	45
T ₇	N ₁₀₀ + one spray/ two sprays nano urea of 4 ml liter ⁻¹ at MT/ PI	120	60

Recommended fertilizer dose for irrigated rice for Eastern UP is 120–60–60 N-P₂O₅-K₂O and Assam for Kharif (Sali) rice is 60–20–40 kg N-P₂O₅-K₂O kg ha⁻¹. N₁₀₀, N₇₅, N₆₆, N₅₀ here denotes the percentage of recommended dose of nitrogen. *N applied as conventional granular urea **MT and PI is referred as maximum tillering and panicle initiation stages. All treatments, excluding T₁, received the recommended doses of phosphorus (P) and potassium (K). The only variations among the treatments pertain to the applications of nitrogen (N). In 2023, only nano-urea was sprayed at the panicle initiation (PI) stage in T₆ and T₇ treatments. However, in 2024, it was sprayed twice, at the MT and PI stages.

variety with short, slender grains. It possesses submergence tolerance due to the presence of the Sub1 gene. MTU-7029 (Swarna), developed by Acharya N. G. Ranga Agricultural University (ANGRAU), Andhra Pradesh, at Maruteru, is a long-duration variety (145–150 days) with a semi-dwarf plant, high yield potential, and tolerance to various biotic and abiotic stresses. Swarna Samridhhi Dhan, developed by Indian Council of Agricultural Research - Research Complex for Eastern Region (ICAR–RCER), Patna, is a medium-duration variety (135–140 days) with high yield potential, multiple stress tolerance, and desirable cooking quality traits characterized by long, slender grains. CR Dhan-311 released by the Central Rice Research Institute (CRRI), Cuttack, is a medium-duration variety (120–125 days) with a semi-dwarf, long bold grains, and good cooking and eating quality.

2.3 Detailed description of nano urea

The IFFCO has successfully innovated and developed nano urea – liquid (nano nitrogen) at its Nano Biotechnology Research Centre (NBRC) Kalol, Gujarat. Nano urea formulations were characterized for their morphology as detailed in Table 4. The nano urea formulation containing 20% N (w/v), equivalent to 16% N (w/w), had a much higher N concentration than the previous nano urea formulation (4% N). However, both formulations had similar physicochemical and

TABLE 4 Specifications of IFFCO nano urea as per clause 20 D of FCO, 1985 as described (Kumar et al., 2021b; Kumar et al., 2022).

S. no	Parameters	Specifications	Instrument used
1.	Total nitrogen (%) by weight)	1–5*	
2.	Particle size in nano meter (nm) in one dimension		Transmission electron microscopy (test method: ISO 21363:2020)
	(a) Physical particle size	20–50	
	(b) Hydrodynamic particle size	20–80	
3.	Zeta potential in mV (+/– size)	> 30	Dynamic light scattering (test method: ISO13099-1)
4.	Viscosity in cPs	5–30	Rotational viscometer (test method: ASTM D2196–10)
5.	pH	4.5–6.0	pH meter (test method: ASTM E70-07)

*Nano Urea Plus contains a significantly higher nitrogen concentration (20% N w/v, equivalent to 16% N w/w) compared to conventional Nano Urea (4% N w/v). The formulation is enhanced with specific bio-polymers and contains multiple nitrogen forms, including urea-amide, ammoniacal, and amino nitrogen. However, the overall physicochemical characteristics are broadly similar between the two formulations.

morphological properties. Detailed characterization procedures and properties are reported in Kumar et al. (2021b).

2.4 Crop management practices

The land was thoroughly prepared using a cultivator and harrow, prior to puddling and transplanting rice in the experimental field. The seeds were soaked in water for 12 h before being incubated for 36 h. At the Varanasi experimental site, during the 2022 cropping season, the Binadhan-11 variety nursery was sown on June 13th, 2022, and transplanted on July 16th, 2022. In 2023, the MTU-7029 variety was sown in the nursery on June 20th, 2023, and transplanting was carried out on July 18th, 2023. Similarly, Swarna Samriddhi Dhan seeds were sown in the nursery on June 13th, 2024, and transplanted on July 6th, 2024. The plot size for each treatment was 38 m² (9.5 m × 4.0 m) all 3 years. At the Guwahati experimental site, during *kharif* 2022, variety CR Dhan-311, medium duration, semi-dwarf rice variety was used for the experimentation. The seeds were sown on the wet bed nursery on 5th July 2022 and 30-day old nursery seedlings were transplanted on 5th August 2022. The plot size for each treatment is 22.50 m² (3.28 m × 6.86 m). In 2023 and 2024, the variety used was Binadhan-11, a submergence-tolerant, early maturing rice variety, with a plot size of 24 m² (4.0 m × 6.0 m) for each treatment. The seeds were then sown in a wet bed nursery on 21st June 2023 and 9th July 2024. Thirty-day-old nursery seedlings were transplanted on 21st July and 9th August for the year 2023 and 2024. Seedlings were transplanted with line-to-line spacing of 20 cm and hill-to-hill

spacing of 15 cm (33 hills m⁻²), keeping 3–4 seedlings hill⁻¹. During the first year of the experiment, a long-duration rice variety was cultivated, followed by a medium-duration variety in the subsequent year to assess varietal duration responses to nano-urea application. However, uniform plant density was maintained across all cultivars using the recommended spacing to eliminate population effects, ensuring that observed differences were attributable solely to nutrient management within each year. Uniform application of phosphorus (P₂O₅) as Di-ammonium Phosphate (46% P₂O₅), and potassium (K₂O) as Muriate of Potash (60% K₂O) were given to the plots as the basal dose just prior to rice transplanting. N was applied through neem-coated urea (NCU) as per the treatments in three equal splits as 1/3rd at basal, 1/3rd at maximum tillering (MT) and 1/3rd at panicle initiation (PI) for all the years, whereas the foliar application of nano-urea was applied at, MT, PI and heading stages in accordance with the treatment in rice (Tables 2, 3). The N management treatments were based on the ‘Deduction Model’ where the amount of NCU was gradually reduced and combined with foliar spray of nano-urea (4% w/v) as per treatment details. Preparation of nano urea foliar spray for 1 ha were prepared by dissolving 700 mL of nano-urea in 350 L of water (2 mL L⁻¹) or 1,400 mL in 350 L of water (4 mL L⁻¹). In 2024, nano urea plus (20% w/v) was used and sprayed twice during the MT and PI stages in the treatments (T₄–T₇). During cropping seasons, all the plots were kept weed-free by pre-emergence application of pretilachlor at the rate of 750 g a.i. ha⁻¹ on the second day of transplanting followed by one-hand weeding at 32 days after transplanting (DAT) and need-based spot hand weeding in the experimental plots. One spray of chlorpyrifos at 2 mL liter⁻¹ of water was given to manage insect pests in infested plots. All other best agronomic practices were followed for the cultivation of rice.

2.5 Grain yield

The crop was harvested manually for recording crop yield, two border rows from all border directions were excluded to harvest the net plot area. The net plot area was harvested and threshed separately. The final grain yield was adjusted at 14% moisture and was expressed in t ha⁻¹.

2.6 Nitrogen use efficiencies

In this study NUE was measured by two ways, i.e., Partial Factor Productivity (PFP_N) measured as kg grain yield kg⁻¹ N applied (Equation 1), and agronomic efficiency (AE_N) measured as kg grain increased kg⁻¹ N applied. AE is additional grain yield produced per kilogram of N fertilizer applied (Equation 2). To calculate these efficiencies, the following formulae were used:

$$PFP = \frac{\text{Grain yield in N fertilized treatment (kg ha}^{-1}\text{)}}{\text{fertilizer N applied (kg ha}^{-1}\text{)}} \quad (1)$$

$$AE = \frac{\text{Grain yield in N fertilized treatment} - \text{Grain yield in control treatment (kg ha}^{-1}\text{)}}{\text{fertilizer N applied (kg ha}^{-1}\text{)}} \quad (2)$$

2.7 Soil sampling and analysis

Pre- and post-season soil samples were collected from a depth of 0–15 cm using an auger. Within each experimental plot, five distinct sampling points were selected, and a composite sample was prepared by thoroughly mixing the collected subsamples. The composite samples were air-dried and sieved through a 2 mm mesh for further analysis. Oxidizable organic carbon (%) was determined using the wet oxidation method (Walkley and Black, 1934). Available N was analyzed using the alkaline potassium permanganate (KMnO_4) method (Subbiah and Asija, 1956). Available phosphorus was analyzed using Olsen's method (Olsen et al., 1954) for the Varanasi samples and Bray and Kurtz's method (Bray and Kurtz, 1945) for Guwahati samples. Available potassium was determined using neutral normal ammonium acetate extraction (Hanway and Heidel, 1952). Soil pH and electrical conductivity (EC) were measured in a 1:2 soil to water (Jackson, 1967).

2.8 Economic analysis

Across the study years, gross returns (GR), and net returns (NR) were calculated. The cost of cultivation (COC) for each treatment was calculated based on the cost incurred on various inputs including seed, fertilizers, herbicides, pesticides, irrigations, and expenses for labor employed in various field operations including land preparation, sowing, weed management, pest and disease management, harvesting and threshing. The fixed costs such as land value and interest were not included in this economic analysis. The gross returns (GR) included income from the sale of rice grain based on the minimum support price (MSP) set by the Government of India during the respective cropping seasons. Net returns were calculated as: Net returns (USD ha^{-1}) = Gross returns – Cost of cultivation. Net benefit cost ratio was calculated by dividing net returns by cost of cultivation. All economic analysis was conducted in Indian rupees (INR) and subsequently converted to US dollars (USD) based on the prevailing exchange rates.

2.9 Statistical analysis

The experiment was conducted using fixed treatment plots, analysis of variance (ANOVA) was employed to evaluate the effects of treatments and year, as well as their interaction on rice yield. The experiment was conducted in a randomized block design (RBD) with three replications. ANOVA was performed separately for the locations during the study period. The least significant difference (LSD) test ($p = 0.05$) was employed to determine significant differences among treatment means. The statistical analysis of the collected data was conducted using R software (version 4.2.2) by using package “agricolae” (De Mendiburu and de Mendiburu, 2019), R packages like ggplot, and dplyr were used for preparation of figures in the study.

3 Results

3.1 Grain yields

Treatments like N_{66} with nano-urea foliar sprays produced yields comparable to N_{100} in both Varanasi and Guwahati, while reducing N below 50% led to yield penalties of 12–24% in Varanasi (Figure 2). In

Varanasi, the average grain yield for the control treatment (T_1) in 2022 was 4.0 t ha^{-1} , which was 1.64 t ha^{-1} (41%) lower than the yield recorded under N_{100} (T_2) (Figure 2). Similarly, in Guwahati, the control treatment (T_1) yielded 3.93 t ha^{-1} , which was 1.0 t ha^{-1} lower than the N_{100} (T_2) for the same period. In Varanasi, the grain yield in the control treatment (T_1) was 3.62 t ha^{-1} in 2023 and 3.93 t ha^{-1} in 2024, which were 2.7 t ha^{-1} (74%) and 2.5 t ha^{-1} (63%) lower than the yield under N_{100} (T_3), respectively (Figure 3a). Similarly, in Guwahati, the grain yield in T_1 was 2.8 t ha^{-1} in 2023 and 2.9 t ha^{-1} in 2024, which were 2.23 t ha^{-1} and 2.24 t ha^{-1} lower than N_{100} (T_3), respectively, corresponding to a yield decline of 80–83% (Figure 3b). In Varanasi in 2022, under low-input conditions (80 kg N ha^{-1}), the grain yield with N_{66} plus two foliar sprays of nano-urea surpassed that of N_{100} for the short duration variety (Figure 2). However, under high-input conditions (120 kg N ha^{-1}), the yield was lower than N_{100} in 2023 (4% of nano-urea) for the long duration variety but comparable in 2024 (20% of nano-urea) for medium duration variety (Figure 3a). However, when N application was reduced beyond N_{50} , even with two or three foliar applications of nano-urea (T_5 to T_9), there was a 12–24% yield reduction observed in Varanasi. A similar trend was observed in Guwahati in 2022, where N_{66} with two nano-urea sprays produced higher yields than N_{100} under low-input N (60 kg N ha^{-1}) for a short-duration variety in a high soil N and high rainfall area. Additionally, N_{50} with nano-urea yielded on par with N_{100} . However, in 2023 and 2024, N_{66} or N_{50} with nano-urea resulted in lower yields, while N_{75} with nano-urea sprays produced yields comparable to those of N_{100} for short duration variety (Figure 3b). The results indicate that yield penalties increased as N application decreased, regardless of the number of nano-urea foliar sprays applied.

Nano-urea N concentration from 4% N was used during 2022–2023, compared to 20% N in 2024, which led to a significant improvement in grain yields, making the N_{66} – N_{75} treatments more effective and achieving yields comparable to N_{100} (Figures 3a,b). Reducing N application to N_{50} (T_2) resulted in a yield reduction of 1.26 t ha^{-1} (20%) in 2023 and 1.15 t ha^{-1} (18%) in 2024 compared to N_{100} (T_3) in Varanasi. Similarly, in Guwahati, T_2 (N_{50}) recorded a yield reduction of 0.88 t ha^{-1} and 0.90 t ha^{-1} compared to N_{100} (T_3). Applying N_{100} with one or two foliar sprays of nano-urea (T_7) resulted in a yield increase, but the differences were not statistically significant compared to N_{100} (T_3) in both years and locations. Treatments with N_{50} or N_{66} plus two nano-urea sprays or N_{75} plus one nano-urea spray (T_4 – T_6) led to a 19–21% yield penalty in 2023 in Varanasi. However, these treatments performed significantly better in 2024, achieving yields comparable to N_{100} , due to an increase in nano-urea concentration from 4%N in 2023 to 20%N in 2024. In Guwahati, N_{75} produced statistically comparable yields to N_{100} , but yield penalties increased as N application decreased (N_{50} or N_{66}), even when one or two nano-urea applications were added.

3.2 Economics

3.2.1 Cost of cultivation

The fertilizer cost in each treatment depended on the amount of N applied, as well as the cost of nano-urea and its application. However, the reduction in fertilizer cost was not directly proportional to N savings, primarily due to the additional cost of nano-urea and the expenses associated with its application. In Varanasi, the fertilizer cost in the control treatment was USD 26, 41, and 38 ha^{-1} lower than in N_{100} during 2022, 2023, and 2024, respectively (Tables 5–7). Similarly,

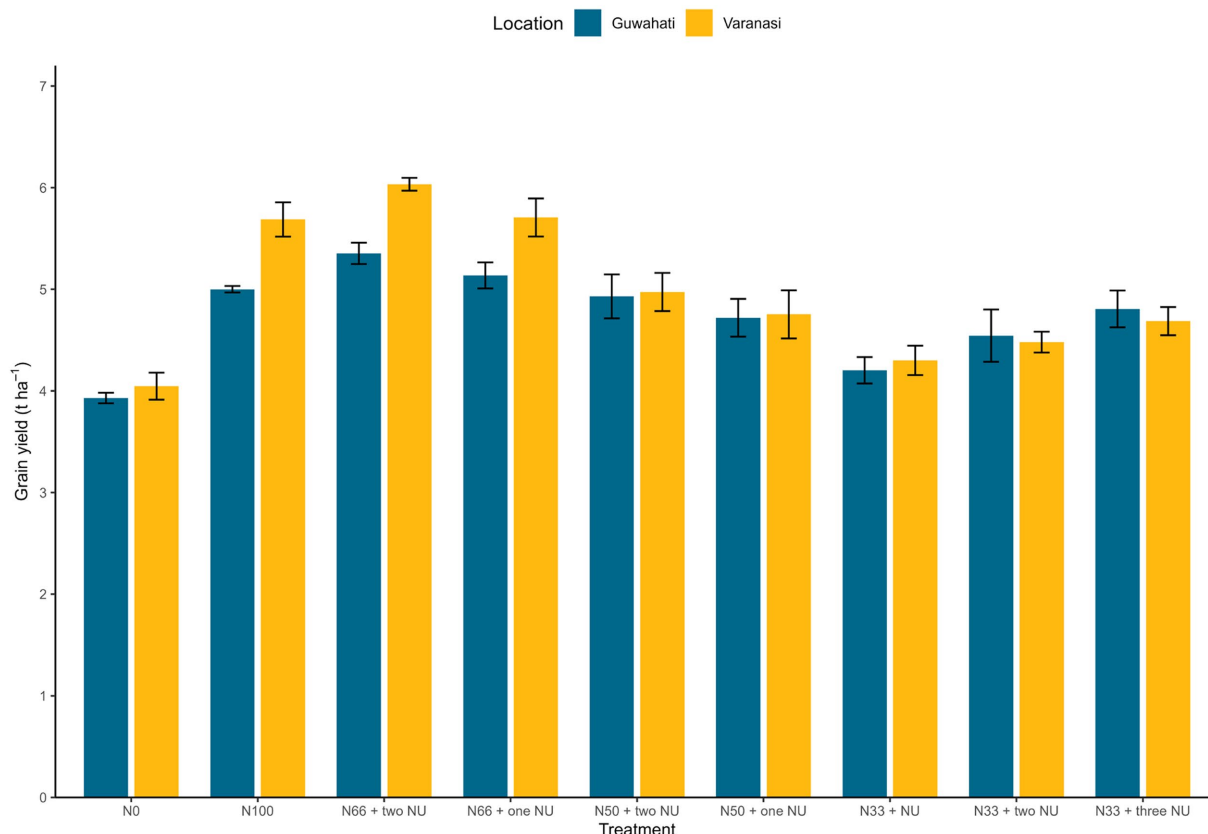


FIGURE 2

Rice grain yield (t ha^{-1}) as affected by nitrogen doses and nano urea treatments in 2022. Values represent the mean of three replicates, with error bars indicating $\pm$ standard error (SE). Significant differences at $p \leq 0.05$, as determined by LSD test.

in Guwahati, the fertilizer cost in the control treatment was USD 12.4, 43, and 36.2 ha^{-1} lower than in N_{100} for the same years. In Varanasi (2022), nano-urea treatments (T_3 to T_9) reduced N use by 27 to 52 kg ha^{-1} compared to N_{100} (T_2). However, the fertilizer cost reduction in these treatments was not proportional to N savings due to the cost of nano-urea and its application. In Varanasi (2023 and 2024), nano-urea treatments (T_4 – T_6) reduced N use by 30 to 60 kg ha^{-1} compared to N_{100} (T_3). However, the fertilizer costs in these treatments were equal to or slightly higher than in N_{100} , by USD 2–6 ha^{-1} in 2023 and USD 9 ha^{-1} (T_6) in 2024, due to the cost of nano-urea and its application (Table 6). In Guwahati (2022), nano-urea treatments reduced fertilizer costs by USD 3–15 ha^{-1} , whereas in 2023 and 2024, the fertilizer costs were USD 3–10 ha^{-1} higher, depending on the N dose (Table 7).

3.2.2 Gross and net returns

Nano-urea with N_{66} sprays achieved the highest gross and net returns, comparable to N_{100} (RDN) in both locations, indicating its economic viability with reduced N inputs. In 2022, the highest gross returns were recorded in N_{66} (T_3), which was on par with T_2 (RDN) and T_4 in both locations (Table 5). The net returns from N_{66} with one or two foliar nano-urea sprays were comparable to N_{100} (T_2). The lowest net returns were observed in T_1 (control), followed by N_{33} with nano-urea applications (T_7 to T_9) and N_{50} with one nano-urea spray (T_5) in both locations. The control (T_1) had lower net returns by USD 256 ha^{-1} and USD 348 ha^{-1} than T_2 and T_3 , in Guwahati and USD

386 ha^{-1} and USD 478 ha^{-1} in Varanasi, respectively. Benefit cost ratio followed the same trend of net returns in both locations. In Varanasi (2023 and 2024), gross returns were highest in T_7 (N_{100} with one nano-urea spray), which was on par with T_3 (N_{100}) and N_{66} , followed by N_{75} and N_{50} (Table 6). However, in 2024, gross returns were statistically similar from T_3 to T_7 . The lowest gross returns were observed in the control (T_1) and N_{50} (T_2) treatments in both years. In 2023, net returns were highest in T_7 , which was on par with T_3 (N_{100}) and N_{66} , followed by N_{75} and N_{50} . T_3 (N_{100}) recorded 28, 23, and 31% higher net returns compared to T_4 , T_5 , and T_6 , respectively. In 2024, net returns were similar across all treatments except T_1 and T_2 , which recorded the lowest values. In Guwahati in 2023, gross returns from N_{66} and N_{75} were on par with RDN, while in 2024, N_{66} had lower gross returns than RDN, whereas N_{75} performed similarly to RDN (Table 7). Compared to N_{100} (T_3), net returns in 2023 were lower by USD 547, 237, 179, and 111 ha^{-1} in T_1 , T_4 , T_5 , and T_6 , corresponding to declines of 198, 29, 22, and 13%, respectively. Similarly, in 2024, net returns were lower by USD 625, 251, 177, and 126 ha^{-1} in T_1 , T_4 , T_5 , and T_6 , corresponding to 195, 26, 19, and 13% reductions, respectively. The net benefit–cost ratio followed a similar trend to net returns in both 2023 and 2024 across both locations.

3.3 Nitrogen use efficiencies

Partial Factor Productivity (PFP) and Agronomic Efficiency (AE) of N were significantly ($p = 0.05$) influenced by N treatments across locations and varieties (Table 8). In Varanasi (2022), the highest PFP

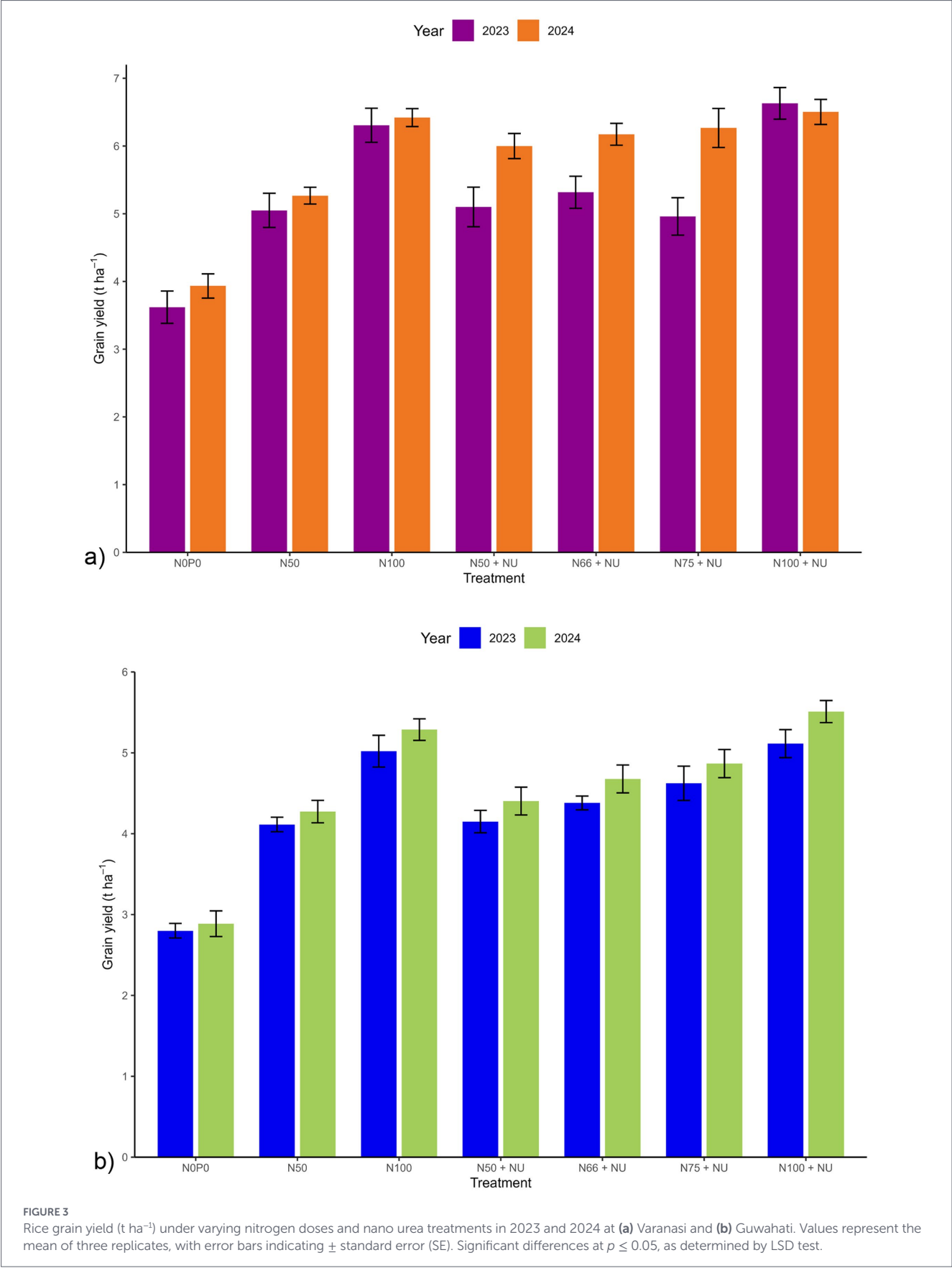


TABLE 5 Economics (USD ha⁻¹) of rice under varying nitrogen doses and nano urea treatments at Varanasi and Guwahati in 2022.

Treatment	Treatment details	Varanasi				Guwahati			
		COC	Gross returns	Net returns	Net B: C	COC	Gross returns	Net returns	Net B: C
T ₁	N ₀	444.38	1014.87 ^d	570.49 ^d	1.28 ^c	463.01	985.35 ^c	522.34 ^c	1.13 ^d
T ₂	N ₁₀₀	469.88	1426.17 ^{ab}	956.28 ^{ab}	2.10 ^a	475.46	1253.84 ^{abc}	778.38 ^{abc}	1.64 ^{ab}
T ₃	N ₆₆ + two NU sprays	464.97	1513.11 ^a	1048.14 ^a	2.19 ^a	472.08	1342.72 ^a	870.65 ^a	1.80 ^a
T ₄	N ₆₆ + one NU spray	461.20	1431.18 ^{ab}	969.98 ^{ab}	2.05 ^{ab}	468.08	1288.59 ^{ab}	820.51 ^{ab}	1.68 ^{ab}
T ₅	N ₅₀ + two NU sprays	459.99	1247.27 ^{bc}	787.28 ^{bc}	1.64 ^{bc}	466.55	1236.66 ^{abc}	770.11 ^{abc}	1.58 ^{abc}
T ₆	N ₅₀ + one NU spray	455.22	1192.09 ^{cd}	736.88 ^{cd}	1.55 ^c	462.55	1183.71 ^{bc}	721.16 ^{bc}	1.47 ^{bc}
T ₇	N ₃₃ + two NU sprays	453.00	1078.40 ^{cd}	625.40 ^{cd}	1.29 ^c	460.02	1054.25 ^{de}	594.23 ^{de}	1.21 ^d
T ₈	N ₃₃ + two NU sprays	456.67	1123.55 ^{cd}	666.87 ^{cd}	1.35 ^c	464.69	1139.36 ^{cd}	674.67 ^{cd}	1.35 ^{cd}
T ₉	N ₃₃ + three NU sprays	454.61	1175.38 ^{cd}	720.77 ^{cd}	1.45 ^c	462.86	1205.98 ^{bc}	743.12 ^{bc}	1.51 ^{bc}
	LSD (<i>p</i> = 0.05)	–	201.2	201.2	0.44	–	122.25	122.25	0.25

Values represent the mean of three replicates. Mean values with shared letters are not statistically distinct. The values under the same parameters followed by different letters are significantly different at (*p* = 0.05) as determined by LSD test.

TABLE 6 Economics (USD ha⁻¹) of rice under varying nitrogen doses and nano urea treatments at Varanasi in 2023 and 2024.

Treatment	Treatment details	Year 2023				Year 2024			
		COC	Gross returns	Net returns	Net B: C	COC	Gross returns	Net returns	Net B: C
T ₁	N ₀	476.51	960.20 ^c	483.69 ^c	1.02 ^c	491.1	1086.03 ^c	594.03 ^c	1.19 ^d
T ₂	N ₅₀	508.07	1339.42 ^b	831.35 ^{bc}	1.64 ^{abc}	518.28	1454.18 ^b	935.9 ^b	1.76 ^c
T ₃	N ₁₀₀	517.21	1672.53 ^{ab}	1155.32 ^{ab}	2.23 ^{ab}	529.21	1772.63 ^a	1243.42 ^a	2.31 ^a
T ₄	N ₅₀ + NU sprays	518.91	1352.33 ^b	833.44 ^{bc}	1.53 ^{bc}	527.81	1656.66 ^a	1128.85 ^a	1.99 ^{bc}
T ₅	N ₆₆ + NU sprays	522.74	1410.59 ^{ab}	887.84 ^{ab}	1.62 ^{abc}	531.5	1704.52 ^a	1173.03 ^a	2.06 ^{ab}
T ₆	N ₇₅ + NU sprays	520.10	1315.68 ^{bc}	795.59 ^{bc}	1.50 ^c	538.2	1730.29 ^a	1192.09 ^a	2.10 ^{ab}
T ₇	N ₁₀₀ + NU sprays	524.64	1758.26 ^a	1233.64 ^a	2.31 ^a	541.61	1795.64 ^a	1254.92 ^a	2.19 ^{ab}
	LSD (<i>p</i> = 0.05)	–	369.8	369.8	0.71	–	148.0	148.0	0.27

Values represent the mean of three replicates. Mean values with shared letters are not statistically distinct. The values under the same parameters followed by different letters are significantly different at (*p* = 0.05) as determined by LSD test.

(kg grain yield per kg N applied) was recorded in N₃₃ with nano-urea (T₇ to T₉), followed by N₅₀ with nano-urea (T₅ and T₆) and N₆₆ with nano-urea (T₃ and T₄). This trend indicates that lower N doses resulted in higher PFP. The lowest PFP value was observed in T₂ (N₁₀₀) at 71.08, demonstrating that higher N applications had reduced efficiency. Compared to T₂ (N₁₀₀), PFP increased by 61% in T₃, 52% in T₄, 75% in T₅, 67% in T₆, 127% in T₇, 137% in T₈, and 148% in T₉. However, AE was highest in N₆₆ with nano-urea spraying (T₃ and T₄), indicating optimal N utilization. The lowest AE was observed in N₃₃ with nano-urea (T₇ and T₈), suggesting that while reducing N increased PFP, excessive N reduction may not optimize AE. In Guwahati (2022), PFP followed a similar trend as in Varanasi, with the highest values recorded in N₃₃ with nano-urea (T₉, T₈, and T₇), followed by N₅₀ with

nano-urea spraying (T₅ and T₆) and N₆₆ with nano-urea (T₃ and T₄) indicating that lower N doses resulted in higher PFP. Compared to T₂ (N₁₀₀), PFP increased by 62% in T₃, 56% in T₄, 97% in T₅, 89% in T₆, 155% in T₇, 175% in T₈, and 191% in T₉. The highest PFP was observed in T₄ (N₅₀ + two nano-urea sprays) and T₂ (N₅₀), followed by T₅ (N₆₆ + two nano-urea sprays) in both locations and both years (2023 and 2024) (Figures 4, 5). In Varanasi, compared to T₃ (N₁₀₀), PFP was higher by 62, 60, and 28% in 2023 for T₄, T₂, and T₅, respectively, and higher by 99, 95, and 43% in 2024 for T₄, T₂, and T₅, respectively. The lowest PFP were recorded in T₃ (N₁₀₀), T₇ (N₁₀₀ + one/two nano-urea sprays), and T₆ (N₇₅ + one/two nano-urea sprays) in 2023, and in T₇ (N₁₀₀ + one/two nano-urea sprays) and T₃ (N₁₀₀) in 2024. In Guwahati, compared to T₃ (N₁₀₀), PFP was higher

TABLE 7 Economics (USD ha⁻¹) of rice under varying nitrogen doses and nano urea treatments at Guwahati in 2023 and 2024.

Treatment	Treatment details	Year 2023				Year 2024			
		COC	Gross returns	Net returns	Net B: C	COC	Gross returns	Net returns	Net B: C
T ₁	N ₀	465.60	741.81 ^d	276.21 ^d	0.59 ^b	478.10	797.59 ^e	319.45 ^d	0.81 ^c
T ₂	N ₅₀	502.08	1090.17 ^c	588.09 ^c	1.17 ^{ab}	510.1	1179.61 ^d	669.51 ^c	1.31 ^b
T ₃	N ₁₀₀	508.81	1331.99 ^{ab}	823.18 ^{ab}	1.62 ^a	514.27	1459.57 ^{ab}	945.30 ^a	1.84 ^a
T ₄	N ₅₀ + NU sprays	513.24	1099.68 ^c	586.44 ^c	1.14 ^{ab}	521.24	1215.07 ^d	693.87 ^c	1.26 ^b
T ₅	N ₆₆ + NU sprays	517.34	1161.35 ^{bc}	644.01 ^{bc}	1.22 ^{ab}	522.8	1290.59 ^{cd}	767.80 ^{bc}	1.39 ^b
T ₆	N ₇₅ + NU sprays	512.46	1225.32 ^{abc}	712.86 ^{abc}	1.39 ^a	524.5	1343.78 ^{bc}	819.3 ^{bc}	1.49 ^b
T ₇	N ₁₀₀ + NU sprays	514.31	1356.31 ^a	842.00 ^a	1.64 ^a	526.6	1521.37 ^a	994.01 ^a	1.81 ^a
	LSD (<i>p</i> = 0.05)	–	195.2	195.2	0.61	–	124.9	124.9	0.24

Values represent the mean of three replicates. Mean values with shared letters are not statistically distinct. The values under the same parameters followed by different letters are significantly different at (*p* = 0.05) as determined by LSD test.

TABLE 8 Partial factor productivity of N (PFP_N) (kg grain kg⁻¹ N applied) and Agronomic efficiency (AE_N) (kg grain increased kg⁻¹ N applied) of rice as influenced by nitrogen doses along with nano urea at Varanasi and Guwahati in 2022.

Treatment	Treatment details	Varanasi		Guwahati	
		PFP	AE	PFP	AE
T ₁	N ₀	–	–	–	–
T ₂	N ₁₀₀	71.08 ^c	20.50 ^{bc}	83.33 ^e	17.84 ^{bcd}
T ₃	N ₆₆ + two NU sprays	114.27 ^b	37.63 ^a	135.20 ^d	35.98 ^{ab}
T ₄	N ₆₆ + one NU spray	108.08 ^b	31.44 ^{ab}	129.75 ^d	30.53 ^{abc}
T ₅	N ₅₀ + two NU sprays	124.33 ^b	23.17 ^{abc}	164.37 ^c	33.40 ^{ab}
T ₆	N ₅₀ + one NU spray	118.83 ^b	17.67 ^{bc}	157.33 ^c	26.36 ^{abc}
T ₇	N ₃₃ + two NU sprays	161.65 ^a	9.52 ^{cd}	212.31 ^b	13.87 ^{cd}
T ₈	N ₃₃ + two NU sprays	168.42 ^a	16.29 ^c	229.45 ^{ab}	31.02 ^{abc}
T ₉	N ₃₃ + three NU sprays	176.19 ^a	24.06 ^{abc}	242.86 ^a	44.43 ^a
	LSD (<i>p</i> = 0.05)	17.69	14.96	20.15	19.28

Values represent the mean of three replicates. Mean values with shared letters are not statistically distinct. The values under the same parameters followed by different letters are significantly different at (*p* = 0.05) as determined by LSD test.

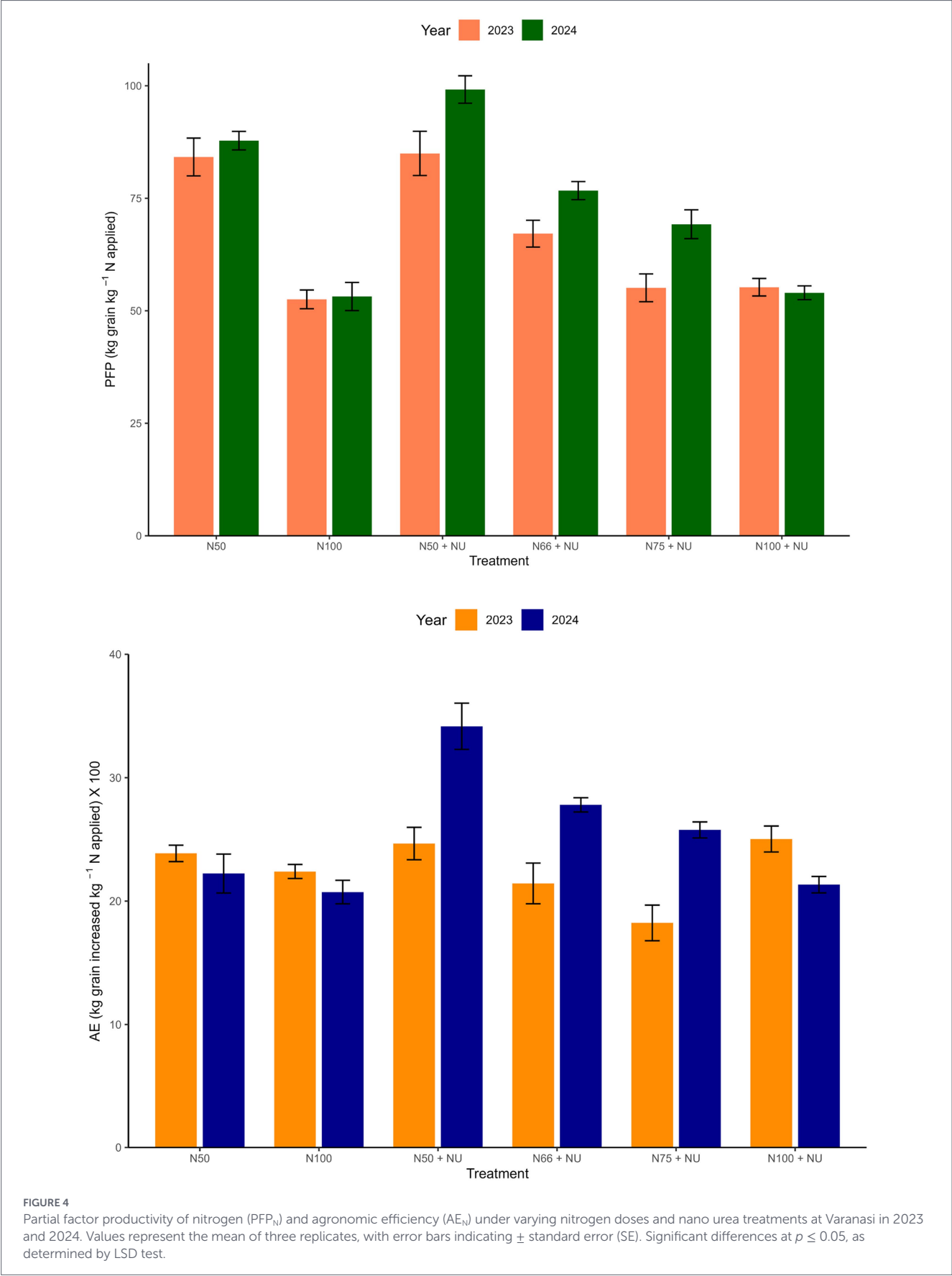
by 65, 64, 32, and 23% in 2023 for T₄, T₂, T₅, and T₆ respectively, and higher by 143, 35, 52 and 44% in 2024 for T₄, T₂, T₅, and T₆, respectively. The lowest PFP were recorded in T₃ (N₁₀₀), and T₇ (N₁₀₀ + one/two NU sprays) in both years. In Varanasi in 2023, the differences in AE among treatments were not significant (NS). However, in 2024, the highest AE values were observed in T₄ (N₅₀ + two NU sprays) and T₂ (N₅₀), followed by T₅ (N₆₆ + two NU sprays). Compared to T₃ (N₁₀₀), AE was higher by 101, 87, and 34% in T₄, T₂, and T₅, respectively. The lowest AE values were recorded in T₇ (N₁₀₀ + one/two NU sprays) and T₃ (N₁₀₀), indicating lower N use efficiency at higher N levels. The AE in Guwahati was higher in 2024 compared to 2023 and followed a similar trend to Varanasi. The highest AE was observed in T₄ (N₅₀ + two NU sprays) and T₂ (N₅₀), while the lowest AE was recorded in T₃ (N₁₀₀).

3.4 Soil chemical properties

Nitrogen doses combined with nano-urea have recorded notable variations in soil organic carbon (SOC), nitrogen (N), and phosphorus (P), across treatments at both locations (Tables 9, 10). At Varanasi in

2023, N₆₆ + one nano-urea spray (T₅) treatment resulted in the highest available N content, while further reducing N doses in combination with nano-urea did not significantly affect N availability. In 2024, N₁₀₀ (T₃) and N₁₀₀ + nano urea (T₇) had higher N values (146 kg ha⁻¹) and remained statistically similar to other nano urea treatments. However, when compared to 2023, there was slightly decrease in the available N in soil decreased to the tune of 21–33 kg ha⁻¹ (Table 9). Moreover, pH, EC and available potassium remained non-significant during both years. At Varanasi, there was no impact of nano urea treatments and N doses on available P and SOC, except control (no nitrogen) in both the years of experimentation. In contrast, the N₀ (control) treatment showed the lowest values for most soil parameters.

Similarly, in Guwahati for year 2023, the N₁₀₀ + one nano-urea spray treatment resulted in the highest available N compared to other treatments and remained statistically similar to all the treatments with nano urea sprays (Table 10). The N availability for N₆₆ + nano sprays (T₅) had significantly lower N availability in 2023, and in 2024. Phosphorus availability in soil showed significant differences among treatments, with the highest phosphorus observed under N₁₀₀ in 2023 and N₁₀₀ + nano-urea in 2024. Unlike phosphorus, soil potassium



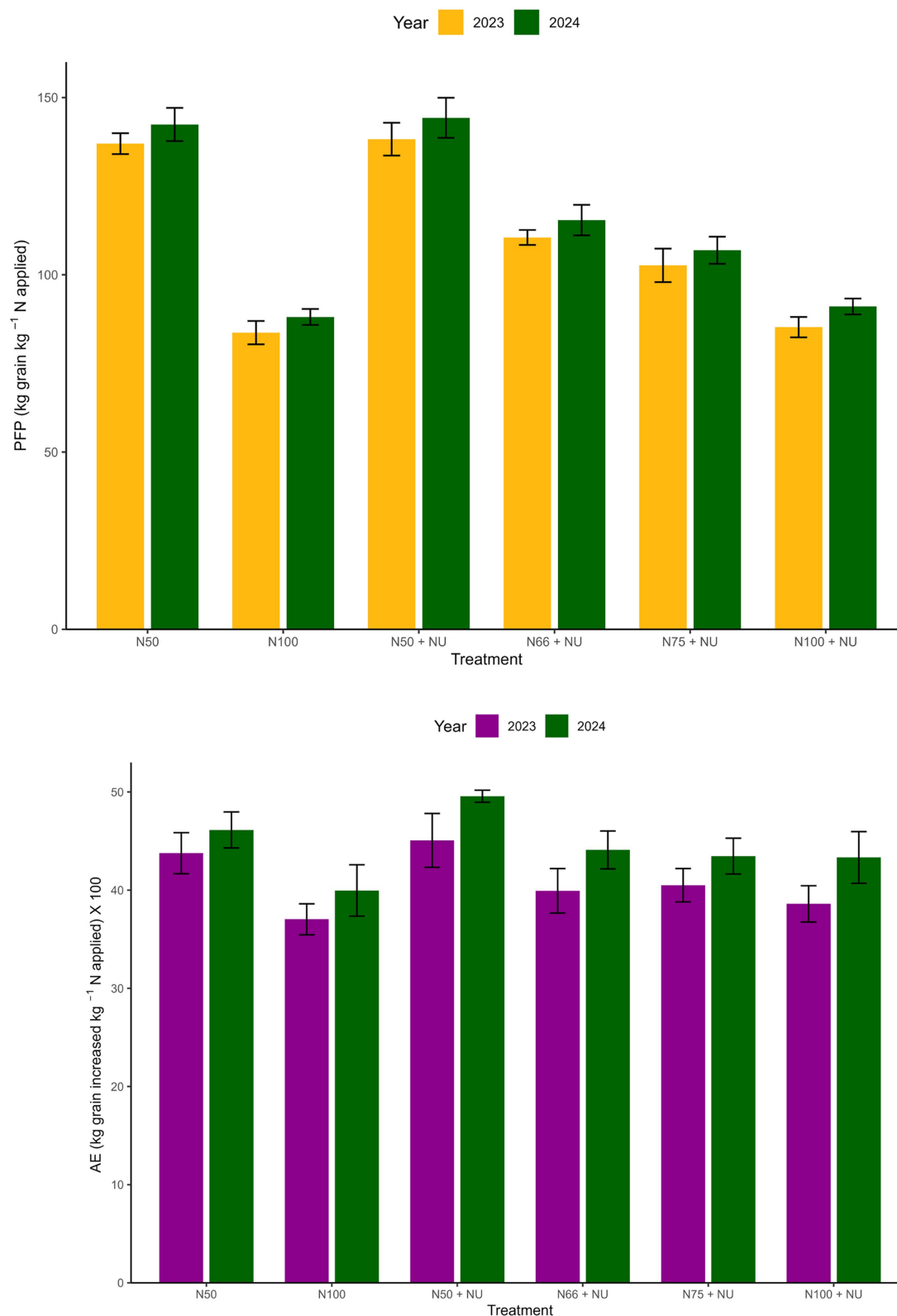


FIGURE 5

Partial factor productivity of nitrogen (PFP_N) and agronomic efficiency (AE_N) under varying nitrogen doses and nano urea treatments at Guwahati in 2023 and 2024. Values represent the mean of three replicates, with error bars indicating $\pm$ standard error (SE). Significant differences at $p \leq 0.05$, as determined by LSD test.

availability was significantly influenced by N doses and nano-urea treatments. However, when compared to 2023, there was slightly decrease in the available N in soil decreased to the tune of 50–86 kg ha⁻¹ (Table 10). It is possible that maintaining lower N doses

over the next 2–3 cropping seasons could lead to a gradual reduction in soil N levels. However, SOC and EC remained non-significant during both the study years. pH, EC, SOC and K remained non-significant across treatments in 2024. The N₀ treatment exhibited the

TABLE 9 Soil chemical properties under varying nitrogen doses and nano urea treatments at Varanasi.

Treatments	Treatment details	Year 2023									Year 2024		
		pH	EC (dS m ⁻¹)	SOC (%)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)	pH	EC (dS m ⁻¹)	SOC (%)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)
T ₁	N ₀	8.11	0.13	0.37	153	19.04	121.9	8.36	0.14	0.36	130	16.92	105
T ₂	N ₅₀	8.11	0.14	0.35	170	21.12	115.9	8.34	0.15	0.44	142	19.82	100
T ₃	N ₁₀₀	8.28	0.13	0.35	167	20.38	120.4	8.17	0.15	0.37	146	23.53	105
T ₄	N ₅₀ + NU sprays	8.20	0.13	0.40	170	20.47	119.1	8.32	0.15	0.38	142	23.64	105
T ₅	N ₆₆ + NU sprays	7.86	0.14	0.37	171	21.14	113.1	8.36	0.14	0.37	138	20.40	107
T ₆	N ₇₅ + NU spray	7.81	0.13	0.38	170	20.32	116.8	8.28	0.13	0.43	142	18.08	107
T ₇	N ₁₀₀ + NU spray	8.14	0.13	0.43	170	20.28	115.7	8.26	0.15	0.40	146	23.06	113
	LSD (<i>p</i> = 0.05)	NS	NS	0.05	14	1.79	NS	NS	NS	0.08	NS	NS	NS

Values represent the mean of three replicates. NS represents non-significant and with values represent are significantly different at (*p* = 0.05) as determined by LSD test.

TABLE 10 Soil chemical properties under varying nitrogen doses and nano-urea treatments at Guwahati.

Treatments	Treatment details	Year 2023									Year 2024		
		pH	EC (dS m ⁻¹)	SOC (%)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)	pH	EC (dS m ⁻¹)	SOC (%)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)
T ₁	N ₀	5.58	0.20	0.68	226	14.93	136	5.94	0.21	0.72	164	18.08	114
T ₂	N ₅₀	5.78	0.28	0.73	255	20.04	135	5.42	0.26	0.78	182	20.51	122
T ₃	N ₁₀₀	5.92	0.26	0.71	251	23.72	141	5.58	0.25	0.84	188	21.90	97
T ₄	N ₅₀ + NU sprays	5.88	0.27	0.72	255	20.46	155	5.85	0.27	0.75	176	17.56	122
T ₅	N ₆₆ + NU sprays	5.25	0.23	0.72	238	22.61	147	5.69	0.28	0.76	188	19.30	129
T ₆	N ₇₅ + NU sprays	5.89	0.24	0.73	247	22.02	129	5.80	0.30	0.79	182	23.47	136
T ₇	N ₁₀₀ + NU sprays	6.02	0.28	0.72	268	22.58	130	5.88	0.28	0.80	182	24.34	111
	LSD (<i>p</i> = 0.05)	0.41	NS	NS	27	3.32	15	NS	NS	NS	NS	6.10	NS

Values represent the mean of three replicates. NS represents non-significant and with values represent are significantly different at (*p* = 0.05) as determined by LSD test.

lowest values for most soil parameters, underscoring the importance of N fertilization for maintaining soil fertility.

4 Discussion

Nitrogen fertilization is essential for achieving optimal rice grain yields. However, the use of conventional prilled urea results in lower NUE, contributing to environmental pollution and increasing the government's subsidy burden (Sapkota et al., 2023). Given the need to optimize fertilizer use while maintaining productivity, this study explores alternative nutrient management strategies to minimize fertilizer input without compromising rice grain yields. Nano fertilizers like nano urea, with higher absorption efficiency and reduced nutrient losses, offer a sustainable alternative by improving NUE and decreasing reliance on conventional urea, ensuring efficient N management for future food demands (Pudhuvai et al., 2024). Our study evaluated the impact of different N doses (N_{75} , N_{66} , N_{50} , and N_{33}) combined with foliar applications of nano-urea at 2 or 4 mL L⁻¹ (4% N) in 2022 and 2023, and 4 mL L⁻¹ (20% N) in 2024, applied at the maximum tillering (MT) and panicle initiation (PI) stages.

Our results show that the foliar application of nano-urea twice-at the maximum tillering (MT) and panicle initiation (PI) stages-combined with N_{66} produced yields comparable to N_{100} in all 3 years in Varanasi and in two out of 3 years in Guwahati, despite an 11% yield reduction in the third year. Likewise, applying nano-urea either twice (MT and PI) or once (PI) with N_{75} maintained yields comparable to N_{100} across all years and both locations (Figures 2, 3). However, applying nano-urea twice (MT and PI) or once (PI) with N_{50} resulted in a yield penalty of 17% (0.88 t ha⁻¹) in Guwahati in 2023 and 2024, and 16% (0.95 t ha⁻¹) in 2022 and 19% (1.2 t ha⁻¹) in 2023 in Varanasi. Our findings indicate that 27–40 kg N ha⁻¹ can be saved in Varanasi and 15–20 kg N ha⁻¹ in Guwahati without yield loss by applying N_{66} – N_{75} combined with nano-urea foliar application twice at the MT and PI stages. No yield penalty was observed in N_{66} or N_{75} , likely due to the application of the optimum N dose at the basal/transplanting stage, which supported better initial crop establishment.

This, in turn, enabled the crop to efficiently absorb and utilize the applied nano-urea at later stages, such as PI. Additionally, the enhanced absorption and penetration of nano-urea through foliar application may have stimulated chloroplast activity and enzyme function, further improving yield attributes (Jangir et al., 2024; Kumar A. et al., 2024). The increased nutrient availability from nano-urea likely contributed to greater dry matter accumulation, enhanced chlorophyll content, and yield enhancement (Kumar et al., 2021a; Upadhyay et al., 2023). Several studies have reported increased grain yields in cereals with the application of nano-fertilizers (Dapkekar et al., 2018; Kumar et al., 2022). Foliar-applied nano-urea can penetrate leaf tissues through stomatal openings due to its small particle size and high surface area (Kumar et al., 2021a). These nano-sized particles enable rapid absorption and efficient translocation within the plant, thereby improving nitrogen use efficiency (Babu et al., 2022). Once inside the plant, nano-urea releases nitrogen in a controlled manner, ensuring sustained nutrient availability. This enhanced nitrogen supply supports physiological processes such as photosynthesis, leading to increased photosynthate production and effective partitioning to grains (Kottegoda et al., 2017; Fernando et al., 2021). Additionally, nano-urea may stimulate root growth and enhance nitrogen

availability in the rhizosphere, improving nutrient uptake and dry matter accumulation (Kaysar et al., 2022). Movement of nano-fertilizers through apoplastic and symplastic pathways further enhances nitrogen utilization efficiency, ultimately contributing to higher grain yield (Cheng et al., 2022; Upadhyay et al., 2023). Nano-urea also increased dry matter accumulation and growth rates, as reflected in the increase in the number of tillers and yield attributes (Kumar N. et al., 2024). Additionally, research indicates that the foliar application of nano-urea does not negatively affect overall rice grain yield (Dass et al., 2024; Reddy et al., 2025). Previous research has shown that nutrient-intensive crops like rice and wheat can partially meet their nutrient requirements through nano fertilizers (Srivastava and Malhotra, 2017). However, some studies have reported a yield penalty with nano-urea applications (Sarkar et al., 2023; Sikka et al., 2025).

The results from 2022 showed that treatment T_3 (N_{66} + two nano urea sprays) have the potential to reduce reliance on conventional chemical fertilizers and improve environmental sustainability, particularly under low input conditions (60 to 80 kg N ha⁻¹) and high rainfall areas for short duration rice varieties. Whereas N_{75} with nano urea sprays can serve as effective strategies to reduce nitrogenous chemical fertilizers in rice production without compromising yield in high input conditions (120 kg N ha⁻¹) for short or medium duration rice varieties (Figure 3). These results confirm that grain yield can be enhanced or maintained by applying nano fertilizers alongside reduced N doses (N_{75} or N_{66}), consistent with previous studies (Upadhyay et al., 2023; Dass et al., 2024) highlighting the role of nano fertilizers in improving nutrient use efficiency and promoting environmental sustainability. The findings from the 2023 study demonstrated that the treatment combining N_{100} with nano-urea produced higher yields, comparable to the standard N_{100} treatment. However, reducing N doses (N_{66} , N_{50}) in combination with nano-urea led to a decline in yields at both Varanasi and Guwahati locations. This yield reduction could be due to the use of long duration variety (MTU 7029) and 4% N content in the nano-urea formulation (Sarkar et al., 2023; Reddy et al., 2024; Sikka et al., 2025) in 2023. This highlights the challenges of reducing N inputs while maintaining optimal productivity in long duration varieties. In contrast, the results from 2024 showed a notable improvement in yield performance with the use of nano-urea. The significant yield advantage observed in 2024 can likely be attributed to the introduction of an improved version of nano-urea (Nano-Urea Plus) containing 20% N and use of medium duration rice variety (Swarna Samriddhi Dhan). The enhanced N content in 2024 appears to have addressed some of the limitations observed in the previous years (2022 or 2023). The effectiveness of nano-urea in enhancing nutrient use efficiency and crop yields depends on multiple factors, including varietal differences and seasonal rainfall patterns (Kumar et al., 2021b; Tiwari et al., 2021). In the present study, the response to nano-urea application was more pronounced in the short-duration (Binadhan-11) and medium-duration (Swarna Samriddhi Dhan) rice varieties than in the long-duration variety (MTU-7029). This differential response may be attributed to the limited capacity of foliar-applied nano-urea to supply nitrogen over the extended growth period of long-duration cultivars. Short- and medium-duration varieties have relatively shorter crop cycles and faster nutrient demand, allowing them to utilize the foliar-supplied nitrogen more efficiently during critical growth stages. In contrast, long-duration varieties require a sustained nitrogen supply over a longer period to support prolonged vegetative growth and grain filling, which may not be adequately met through foliar nano-urea applications alone. Additionally, the well-distributed rainfall in 2024 likely contributed to better nano-urea uptake and higher yields, whereas

the irregular rainfall distribution in 2023 may have affected its efficiency (Supplementary Figure 1). Rice yields in Assam are impacted by erratic rainfall and increasing flooding events due to climate change (Mujumdar et al., 2020). While fertilizers boost productivity, poor rainfall and poor fertilizer management are major factors limiting rice production growth in the region (Barman et al., 2023). The variation in treatment responses across years can be attributed to differences in nitrogen levels, varietal duration, and environmental conditions at the experimental sites. In 2022 at Varanasi, treatments included N_{66} , N_{50} , and N_{33} combined with nano-urea (NU) sprays under rainfed conditions using the variety Binadhan-11. The lowest nitrogen level (N_{33}) resulted in poor crop performance, indicating that such a limited nitrogen supply was insufficient to sustain crop growth even with supplemental nano-urea application (Sikka et al., 2025). In 2023, treatments were adjusted to include higher nitrogen levels (N_{50} , N_{66} , N_{75} , and N_{100}) along with NU sprays to better evaluate the potential of nano-urea in complementing conventional nitrogen fertilization. Varietal duration was also considered, with a long-duration rice variety grown in 2023, followed by a medium-duration variety in the subsequent season. The limited yield response observed in the long-duration variety may be attributed to the relatively low nitrogen supply from nano-urea, which may not adequately meet the prolonged nitrogen demand of such cultivars (Kumar et al., 2023). At Guwahati, although the treatments remained the same, varietal duration differed with a medium-duration variety grown in 2022 and a short-duration variety in the following year. These site-specific adjustments, together with seasonal environmental variability, likely contributed to the observed inter-annual differences in treatment responses. Similarly, these findings highlight the importance of nano-urea formulation, duration of varieties as well as rainfall, in influencing crop yields. The enhanced performance observed, further underscores the potential benefits of incorporating nano-urea plus (20% N) into fertilization strategies, suggesting its suitability for improving crop productivity while potentially reducing fertilizer dependency.

Reducing the cost of rice production is essential for both farmers and the government. For farmers, lower production costs enhance net profit margins and bolster resilience during periods of low yields caused by climatic shocks. For the government, reducing urea consumption helps curtail fertilizer subsidy expenditures. This raises the question of whether improving urea efficiency or adopting alternative fertilizers like nano-urea could ease the financial burden on both farmers and the government. Our study suggests that two foliar applications of nano-urea can replace up to 25–34% of the recommended N dose, potentially reducing overall urea consumption. In India, urea is highly subsidized, with unsubsidized urea costing USD 29.5 per 45 kg fertilizer bag, compared to subsidized urea at just USD 3.13 per bag. According to the Ministry of Chemicals and Fertilizers, the adoption of nano-urea could potentially save the government approximately USD 3 billion (INR 22,500 crore) annually in fertilizer subsidy costs (Thirty-Ninth Report of the Standing Committee on Chemicals and Fertilizers, 2023). In 2022–23, India's urea consumption reached 35.73 million metric tons (MT), with 28.50 million MT (79.7%) produced domestically and 7.58 million MT (21.3%) imported (FAI Report, 2024–25). In our study, the reduction in fertilizer cost was not directly proportional to N savings, primarily due to the additional cost of nano-urea, its application expenses, and the highly subsidized price of urea. In Varanasi, despite nano-urea treatments reducing N use by 27 to 52 kg ha⁻¹ in 2022 and 30 to 60 kg ha⁻¹ in 2023–24, the fertilizer cost savings remained disproportionate due to the higher cost of nano-urea and labor for its application. As a result, fertilizer costs in

these treatments were either equal to or slightly higher than N_{100} in Varanasi, while in Guwahati, the cost varied being slightly lower or higher depending on the N dose (Tables 6, 7). In contrast, without fertilizer subsidies, nano-urea treatments could match or even reduce fertilizer costs compared to N_{100} treatments, making them a viable long-term solution for sustainable rice production. Our study highlights the economic viability of reducing N application while incorporating nano-urea sprays to optimize gross returns, net returns, and benefit–cost ratios (B: C ratio) across different locations and years. The N_{66} and N_{75} treatments, when combined with nano-urea sprays, maintained or even improved economic returns compared to N_{100} , demonstrating the potential for N optimization in rice production. More than 30% of India's total urea consumption is used for rice cultivation (Meena et al., 2021), amounting to 10.72 million metric tons (MT). If 25% of the recommended N dose is saved through the application of nano-urea, this would lead to a reduction of 2.68 million MT of urea. Net returns and gross returns were consistently lower in the N_{33} and N_{50} treatments, particularly with only one nano-urea spray, indicating that excessive N reduction without adequate supplementation is not economically viable. This is in accordance with study showed that reducing N-dose by 50% RDN + nano urea sprays reduced net returns by 19–20% (Dass et al., 2024), compared to 100% RDN. In Guwahati, the N_{66} treatment was profitable in 2023 but showed a decline in 2024, suggesting location-specific variability in N response. However, the N_{75} treatment remained comparable to N_{100} in both years. In Varanasi, gross returns from N_{66} to N_{100} (T_3 – T_7) were statistically similar in 2024, suggesting that beyond a certain N level, additional fertilizer inputs may not yield significant economic gains. The benefit–cost ratio followed a similar trend to net returns, reinforcing the economic feasibility of reducing N inputs while supplementing with nano-urea.

From our study, the NUE in rice cultivation highlight the benefits of using nano urea, which resulted in better PFP and AE compared to recommended dose. In particular, the higher agronomic efficiency (AE_N) based on grain yield and optimum N use (Mejias et al., 2021). Our findings highlight the importance of optimizing N application by reducing N by 34% (N_{66}) with nano-urea to enhance NUE, PFP, and maintain AE. While excessive N reduction (N_{33}) improved PFP, it led to lower AE, suggesting that N supply was insufficient for optimal crop response. In contrast, N_{66} with two nano-urea sprays consistently achieved high PFP and AE, indicating that moderate N reduction combined with nano-urea supplementation optimizes N utilization. N_{100} treatments (T_3 , T_7) recorded the lowest PFP and AE, confirming that excessive N application reduces efficiency without yielding additional economic or agronomic benefits. AE showed an improving trend over time (2024 vs. 2023), likely due to better rainfall distribution during the season, along with the use of a medium-duration rice variety in 2024 compared to a long-duration variety in 2023. The increase in efficiency can be attributed to the optimum dose of conventional granular urea, and effective and consistent nutrient uptake facilitated by nano urea, as its smaller particle size and larger surface area allow the particles to penetrate the plant's stomatal pores more efficiently, enables nutrients to remain available to the plants over a prolonged period, enhancing overall nutrient utilization (Kumar et al., 2021a,b; Reddy et al., 2024). Our findings align with scientific studies conducted by researchers across various regions of India, which have demonstrated improved nutrient use efficiency, higher yields, and enhanced economic returns through the use of nano-urea (Tiwari et al., 2021; Kumar et al., 2021a, 2022; Upadhyay et al., 2023).

Several studies show that nano-urea affects soil properties, including N availability, which may enhance yields through improved fertilizer efficiency or soil N mineralization (Khardia et al., 2022; Kumar et al., 2023; Sikka et al., 2025). In our experiment, the foliar application of nano-urea combined with different N doses did not significantly affect soil N availability at Varanasi. However, in Assam, a slight reduction in N availability was observed with the use of nano-urea. Compared to 2023, soil N availability decreased in 2024 at both locations, and we observed that the 50% RDN treatment resulted in lower soil N and phosphorus availability than the 100% RDN treatment in Assam (Tables 9, 10), similar to the findings of Sikka et al. (2025). The increased N and phosphorus levels were observed in nano urea treatments, which could be attributed to reduced nutrient uptake from the soil due to the use of nano-formulated urea fertilizers, contain N in a nano form, are more efficiently utilized by crops, leading to a higher concentration of nutrients in the soil after harvest (Hasaneen et al., 2016). The application of nano urea has demonstrated promising results, particularly when N doses (N_{66} , N_{75}) are combined with nano urea sprays of 4 mL liter⁻¹, as these treatments effectively maintained yields comparable to the recommended N dose (N_{100}). The outcomes of nano urea application appear to be influenced by specific agro-climatic conditions, highlighting the need for region-specific recommendations, as predicting its precise response across diverse environments remains challenging. To better understand the impact of nano-urea foliar spray on rice, detailed studies on N assimilation and related enzymatic activities is essential. Furthermore, recent research on the molecular and morpho-physiological traits of nano fertilizers (Kumar et al., 2024b; Shanker et al., 2024) underscores their efficacy, though isotopic ¹⁵N-labeled nano urea studies are needed for precise quantification. While nano urea presents significant promise as a sustainable solution for rice cultivation, further meticulous scientific investigations are required to validate its potential across diverse environments and cropping systems. Additionally, it is essential to assess the long-term effects of continuous use of N_{75} or N_{66} with nano urea on the soil's N supply capacity and other soil properties.

5 Conclusion

Our study highlights that application of optimum dose of N through conventional granular urea (66 to 75% RDN) at the basal/transplanting stage and active tillering stages, along with two foliar applications of nano-urea– at maximum tillering (MT) and panicle initiation (PI) stages produced yields comparable to N_{100} . This effect was particularly evident in short- and medium-duration rice varieties and when using the improved version of nano-urea (Nano-Urea Plus) containing 20% N. However, applying nano-urea twice (MT and PI) or once (PI) with 50% RDN resulted in a yield penalty. More than 30% of India's total urea consumption is used for rice cultivation and if 25% of the recommended N dose is saved through the application of nano-urea, this would lead to a reduction of 2.68 million MT of urea for the Indian Government. Further long-term research is needed to assess the sustained impact of continuous use of nano-urea with N_{66} or N_{75} on soil N availability, nutrient interactions, and its overall effects on yield and economic returns. Further research is needed to standardize nano-urea formulations, optimize dosage, and refine application methods to fully unlock its benefits and assess its long-term impact on sustainable agricultural production.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PP: Data curation, Visualization, Methodology, Resources, Software, Writing – review & editing, Project administration, Supervision, Investigation, Writing – original draft, Funding acquisition. KR: Methodology, Writing – review & editing, Formal analysis, Software, Data curation. SKu: Resources, Formal analysis, Investigation, Supervision, Writing – review & editing, Conceptualization, Methodology. AS: Project administration, Formal analysis, Resources, Conceptualization, Methodology, Writing – review & editing. DN: Visualization, Investigation, Resources, Writing – review & editing, Formal analysis. VipK: Writing – review & editing, Methodology, Validation, Investigation, Data curation. SKh: Validation, Investigation, Data curation, Methodology, Writing – review & editing, Supervision. VirK: Supervision, Project administration, Writing – review & editing, Funding acquisition, Conceptualization. SS: Project administration, Supervision, Writing – review & editing, Funding acquisition. KS: Investigation, Writing – review & editing, Validation, Methodology.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2026.1759447/full#supplementary-material>

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