

## ORIGINAL ARTICLE

Agrosystems

Agrosystems, Geosciences &amp; Environment



# Integrated nitrogen management enhances yield, nitrogen use efficiency, and grain quality in scented rice (*Oryza sativa* L.) under field conditions

Mo Danish<sup>1</sup> | Virendra Singh<sup>1</sup> | Satybhyan Singh<sup>1</sup> | S. L. Jat<sup>2</sup>

<sup>1</sup>School of Agricultural Sciences and Engineering, IFTM University, Moradabad, India

<sup>2</sup>ICAR-Indian Institute of Maize Research, Ludhiana, India

**Correspondence**

Virendra Singh, School of Agricultural Sciences and Engineering, IFTM University, Moradabad 244 102, India.

Email: [virendra.singhed@gmail.com](mailto:virendra.singhed@gmail.com)

Assigned to Associate Editor Daniel Forestieri.

**Abstract**

Effective nitrogen management is vital for maximizing yield and maintaining soil health in Basmati rice cultivation. A 2-year field study (2023–2024) was carried out to investigate the effects of integrated nitrogen management on yield traits, grain quality, and nitrogen use efficiency (NUE) in three Basmati rice (*Oryza sativa* L.) cultivars: Pusa Basmati 1718, Pusa Basmati 1847, and Pusa Basmati 1886. The experiment employed a split-plot design, with cultivars as main plots and six nitrogen treatments in sub-plots, incorporating prilled urea, foliar nano urea, and green manuring in various combinations. Pusa Basmati 1847 consistently showed superior performance in panicle length, grain count, 1000-grain weight, and overall yield. Among nitrogen regimes, the treatment comprising 75% prilled urea combined with a single nano urea spray and green manuring achieved the highest grain yield (5.29 t ha<sup>-1</sup>), biological yield (11.97 t ha<sup>-1</sup>), and NUE (32.33%). Integrated nitrogen approaches significantly improved nitrogen accumulation in both grain and straw without depleting residual soil nitrogen. These findings highlight the potential of combining conventional fertilizers with nano and organic sources to enhance productivity, grain quality, and nitrogen use efficiency in aromatic rice systems.

**Plain Language Summary**

Basmati rice, a high-value aromatic crop, requires precise nitrogen management to optimize yield and grain quality. Traditional methods using only prilled urea often result in low nitrogen use efficiency and environmental loss. A 2-year field study evaluated the impact of integrating nitrogen sources—green manure and nano urea—with conventional fertilizers. Three Basmati varieties were tested under six nitrogen regimes. The combination of 75% prilled urea, green manuring, and one nano urea

**Abbreviation:** NUE, nitrogen use efficiency.

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spray achieved the highest grain and biological yields and improved nitrogen use efficiency. Among the varieties, Pusa Basmati 1847 showed superior performance in yield traits and nitrogen uptake. The results indicate that integrating organic, conventional, and nano nitrogen sources offers a sustainable approach to enhancing Basmati rice productivity while reducing nitrogen losses.

## 1 | INTRODUCTION

Rice (*Oryza sativa* L.) is a major staple crop globally, feeding more than half of the world's population, with India ranking as the second-largest producer after China (Food and Agriculture Organization, 2021; International Rice Research Institute, 2020). In 2021–2022, rice was cultivated on 43.79 million hectares in India, yielding 116.42 million tonnes (Department of Agriculture, Cooperation & Farmers Welfare, 2022). With the global population in rice-consuming regions steadily rising, projections suggest that rice production must increase by at least 40% by 2030 to meet future food demands (Khush, 2005; Prasad & Power, 1997). Given the limited scope for horizontal expansion of cultivated area due to land and water constraints, enhancing productivity through improved nutrient and input management remains a crucial strategy for sustainable intensification (Ladha et al., 2005; Pathak et al., 2011).

Nitrogen (N) is the most critical macronutrient influencing rice growth, grain quality, and yield (Fageria et al., 2008; U. Singh & Singh, 2020). In India, nitrogenous fertilizers, particularly urea, account for over 82% of total nitrogen inputs. Around 33 million tonnes of urea are applied annually, with imports surpassing 11 million tonnes in 2021–2022 (Department of Fertilizers, Government of India, 2021; Fertiliser Association of India, 2022). However, conventional urea application suffers from low nitrogen use efficiency (NUE), with substantial losses through leaching, volatilization, and denitrification (Islam et al., 2009; Ju et al., 2009). These inefficiencies not only raise production costs but also pose environmental concerns such as nitrate leaching and greenhouse gas emissions (Azusa et al., 2016; X. Zhang et al., 2015). Improving NUE through precise nutrient management is essential, especially for high-value crops such as Basmati rice, which are sensitive to both the quantity and timing of nitrogen (Moring et al., 2021; Prasad, 2011).

Basmati rice, a premium aromatic variety extensively cultivated in the Indo-Gangetic plains, is highly responsive to nitrogen nutrition, which significantly influences its yield, aroma, and grain elongation ratio. Excessive nitrogen, particularly at inappropriate stages, can reduce grain quality, lodging resistance, and aromatic compound synthesis. Conventional nitrogen management practices often fall short in optimizing both yield and quality. Therefore, integrating

novel approaches such as nano urea and organic amendments like green manures offers potential for improving nitrogen recovery and reducing environmental losses (Chhipa, 2017).

Nanotechnology has emerged as a promising tool in nutrient management, particularly through the development of nano urea—a liquid formulation with ultra-small particles (~30 nm diameter) and a surface area 10,000 times greater than conventional urea granules. A single 500-mL bottle of nano urea is considered equivalent to a 45-kg bag of granular urea in terms of nutrient delivery (Indian Farmers Fertiliser Cooperative Ltd, 2021). Foliar application of nano urea at critical crop stages has shown to enhance NUE, maintain yield levels, and reduce dependency on bulk fertilizer imports. Moreover, combining nano urea with conventional and organic sources may synergistically improve nutrient availability and crop performance (Prasad et al., 2017).

Despite numerous studies evaluating individual nitrogen sources, integrated nutrient management strategies that combine inorganic fertilizers, organic amendments, and nano-based inputs remain underexplored in Basmati rice systems. Therefore, this study was undertaken to evaluate the interactive effects of integrated nitrogen management practices and varietal responses on yield, grain quality, and nitrogen dynamics in Basmati rice under field conditions in western Uttar Pradesh. The goal is to identify sustainable and economically viable nitrogen strategies tailored to regional needs while improving NUE and crop performance.

## 2 | MATERIALS AND METHODS

### 2.1 | Experimental site

The field experiment was conducted during the *kharif* seasons of 2023 and 2024 at the Agronomy Research Farm, IFTM University, Moradabad, Uttar Pradesh (28.83°N, 78.78°E; 186 m above mean sea level). The site falls under a humid sub-tropical monsoon climate (Köppen classification Cwa). The region experiences extreme pre-monsoon heat during June, with average maximum temperatures of 41.2 and 40.8°C (Figure 1) in 2023 and 2024, respectively, and minimum temperature of 28.9°C and 29.2°C. Rainfall in June was low, recorded at 42.7 mm (7 rainy days) in 2023 and 38.9 mm (8 rainy days) in 2024.

The southwest monsoon, active from July to September, brought substantial rainfall. In 2023, July and August received 288.3 and 265.7 mm rainfall (18 and 19 rainy days), while in 2024, the figures were 275.5 and 251.2 mm (17 and 18 rainy days), respectively. During this period, maximum temperatures ranged from 33.6 to 34.4°C, minimum temperatures from 26.1 to 27.1°C, and relative humidity averaged 77%–80%. Monsoon withdrawal in September led to reduced rainfall of 158.6 mm (2023) and 170.8 mm (2024) over 9 and 10 rainy days, respectively. Annual rainfall averaged 1093 mm, mostly concentrated in the *kharif* season, making the area suitable for both rainfed and irrigated rice cultivation.

The soil of the experimental field was sandy loam, well-drained, and uniform in texture, with a neutral to slightly alkaline reaction (pH 7.3), moderate organic carbon content (0.48%), and low-to-medium levels of available nitrogen (230 kg ha<sup>-1</sup>), phosphorus (15.3 kg ha<sup>-1</sup>), and potassium (162 kg ha<sup>-1</sup>).

Parameter	Value	Method
pH (1:2.5)	7.3	Jackson (1973)
Organic carbon (%)	0.48	Walkley and Black (1934)
Available N (kg ha <sup>-1</sup> )	230	Subbiah and Asija (1956)
Available P (kg ha <sup>-1</sup> )	15.3	Olsen et al. (1954)
Available K (kg ha <sup>-1</sup> )	162	Jackson (1973)

The experiment was laid out in a split-plot design with three replications. The main plot consisted of three rice varieties:

### Core Ideas

- Integrated nitrogen management improves grain yield and nitrogen use efficiency in Basmati rice.
- Combining prilled urea with green manuring and nano urea spray increases productivity without depleting soil nitrogen.
- Pusa Basmati 1847 exhibited superior performance in yield traits and nitrogen uptake.
- Partial substitution of conventional nitrogen with nano and organic sources enhances grain quality and sustainability.
- This approach offers a regionally adapted solution for high-efficiency nitrogen use in aromatic rice systems.

V<sub>1</sub>—Pusa Basmati 1718, V<sub>2</sub>—Pusa Basmati 1847, and V<sub>3</sub>—Pusa Basmati 1886. The sub-plots comprised six nitrogen management treatments:

N<sub>0</sub>: Control

N<sub>1</sub>: 100% prilled urea

N<sub>2</sub>: 50% prilled urea + 2 foliar sprays of nano urea

N<sub>3</sub>: 50% prilled urea + green manuring + 1 foliar spray of nano urea

N<sub>4</sub>: 75% prilled urea + 2 foliar sprays of nano urea

N<sub>5</sub>: 75% prilled urea + green manuring + 1 foliar spray of nano urea

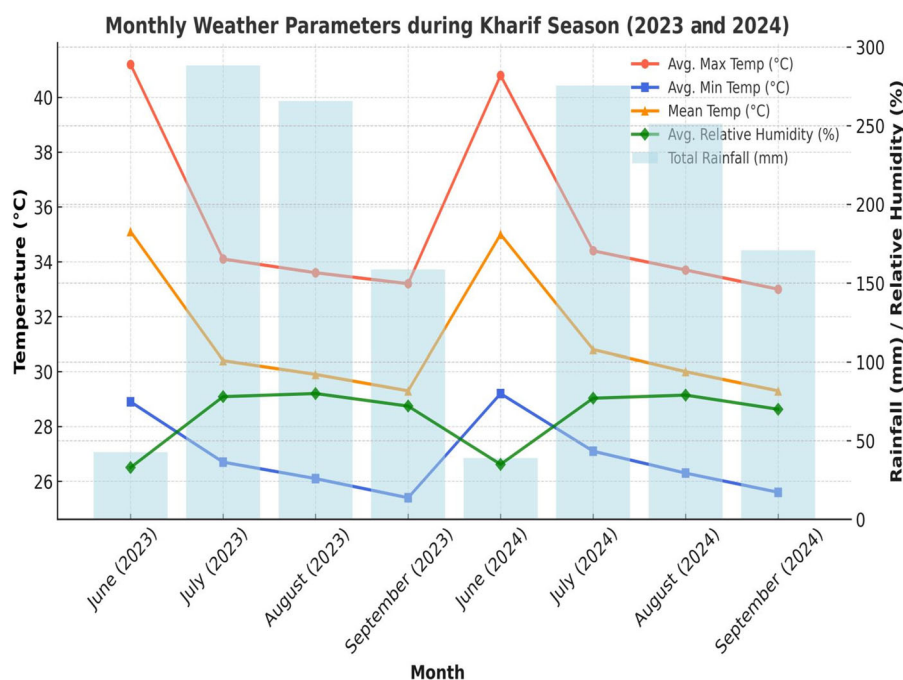


FIGURE 1 Monthly weather parameters during kharif (2023 and 2024).

In India, application of nitrogen in rice mainly relies on prilled urea applied in two or three split doses commonly basal, active tillering, and panicle initiation stages. However, due to significant nitrogen losses from conventional broadcasting, integrated nitrogen management approaches are being promoted, combining organic and nano-based fertilizers to improve NUE. The recommended nitrogen rate for basmati rice in this region is 120 kg N ha<sup>-1</sup>, which serves as the basis for all treatments. In treatments receiving 100% prilled urea, the total nitrogen (120 kg N ha<sup>-1</sup>) was applied in three splits one third as basal, one third as active tillering, and one third at panicle initiation.

*Sesbania aculeata* (dhaincha) was used as the green manure crop. It was sown 30 days before transplanting rice at a seed rate of 25 kg ha<sup>-1</sup> as the broadcasting method. The crop was grown with adequate moisture and incorporated into the soil at 30 days after sowing, when it reached about 40–45 cm in height. Tractor-mounted rotavator was used to incorporate it into the soil. The incorporated biomass was allowed to decompose for 10 days before transplanting of rice seedlings. The estimated green biomass added to the soil was approximately 5.5–6.0 t ha<sup>-1</sup>, contributing around 60–65 kg N ha<sup>-1</sup>.

Nano urea (liquid) manufactured by the Indian Farmers Fertiliser Cooperative Limited (IFFCO) was used in this study. The formulation contains 4% nitrogen (w/v) in nano-sized particles (~30–50 nm). The product was applied as a foliar spray at a rate of 1250 mL ha<sup>-1</sup>, diluted in 500 L of water, using a knapsack sprayer fitted with a fine nozzle to ensure uniform coverage. The spray was applied once at the active tillering stage and second at the panicle initiation stage, depending on the experimental treatment.

## 2.2 | Data collection

Observations were recorded on yield attributes including panicle length (cm), number of filled and unfilled grains per panicle, and test weight (1000 grains<sup>-1</sup>). Yield parameters such as grain yield, straw yield, biological yield (grain + straw), and harvest index (%) were also assessed. Soil and plant nitrogen status were evaluated through the measurement of available nitrogen in the soil (kg ha<sup>-1</sup>), nitrogen content in grain and straw (%), and NUE (%). All analytical procedures followed standard methods described by Jackson (1973) and AOAC (1990).

NUE was calculated using the agronomic efficiency approach as:

$$\text{NUE (\%)} = \frac{(\text{N uptake in treated plot} - \text{N uptake in control})}{\text{N applied}} \times 100,$$

where N uptake represents the total nitrogen assimilation in grain and straw.

## 2.3 | Statistical analysis

Experimental data were analyzed using analysis of variance appropriate for a split-plot design through the OPSTAT software (CCS HAU). Treatment means were compared using the least significant difference at  $P = 0.05$  (Gomez & Gomez, 1984). Standard error of the mean and critical difference values were reported for significant treatment effects.

## 3 | RESULTS AND DISCUSSION

### 3.1 | Yield attributes

Significant variations were observed among rice varieties and nitrogen treatments for all yield attributes across both years (Tables 1 and 2). Among the varieties, Pusa Basmati 1847 (V<sub>2</sub>) recorded the longest panicle (26.0 and 26.7 cm in 2023 and 2024, respectively), highest total grains per panicle (146.9 and 152.6), and maximum test weight (27.7 and 28.0 g 1000 grains<sup>-1</sup>). In contrast, Pusa Basmati 1886 (V<sub>3</sub>) consistently produced the lowest values. This indicates a genetic superiority of V<sub>2</sub> in terms of sink capacity and grain development.

Nitrogen application significantly influenced all yield components. The treatment receiving 75% prilled urea + green manuring + 1 foliar spray of nano urea (N<sub>5</sub>) recorded the highest panicle length (26.9 and 27.6 cm), grain number (151.8 and 157.7), and test weight (28.6 and 29.0 g) in both years. In contrast, the control plots (N<sub>0</sub>) had the lowest values. These findings suggest that partial substitution of prilled urea with green manuring and foliar nano urea can optimize reproductive growth, likely by improving nitrogen availability and uptake during critical growth phases (Gautam et al., 2008; Goyal et al., 2023), and some studies have emphasized the role of integrated nitrogen management in enhancing rice panicle development and grain weight can improve physiological efficiency and yield attributes. Green manuring improves the soil organic matter content and microbial biomass. It increases the mineralization of nitrogen and its gradual increase in availability to the rice crop. This sustained supply of nitrogen support to tiller development and spikelet initiation (Baral et al., 2024; Rajput & Mishra, 2023). Filled grain number followed the same trend, with N<sub>5</sub> recording the highest values (129.2 and 138.7 grains panicle<sup>-1</sup>), while the lowest (104.1 and 112.2) was under N<sub>0</sub> (Table 2). Unfilled grains decreased significantly with nitrogen treatments, particularly under N<sub>5</sub>, which indicates improved pollination, assimilate partitioning, and grain filling efficiency. These results are consistent with the findings of previous studies (Bashir et al., 2024; Gogoi et al., 2024; Hussain et al., 2019; Shivay et al., 2016; Sravan et al., 2020), which observed better spikelet fertility and grain set under combined nitrogen and organic sources.

**TABLE 1** Effect of different nitrogen levels on yield attributes of scented rice.

Treatments	Yield attributes					
	Panicle length (cm)		Total number of grain panicle <sup>-1</sup>		Test weight (g)	
	2023	2024	2023	2024	2023	2024
Varieties (main plot)						
V <sub>1</sub> —Pusa Basmati 1718	25.0a	25.7a	141.1b	146.4b	26.5b	26.8b
V <sub>2</sub> —Pusa Basmati 1847	26.0a	26.7a	146.9a	152.6a	27.7a	28.0a
V <sub>3</sub> —Pusa Basmati 1886	23.9b	24.6 b	134.8c	140.3c	25.8c	25.9c
SEM±	0.27	0.32	1.00	0.85	0.17	0.19
CD ( <i>p</i> = 0.05)	1.08	1.24	3.92	3.32	0.68	0.75
Nitrogen levels (sub-plot)						
N <sub>0</sub> —control	21.1c	21.7c	122.4d	127.2d	23.1c	23.7d
N <sub>1</sub> —100% N (prilled urea)	26.3a	26.8ab	146.6b	152.3b	27.5ab	27.8b
N <sub>2</sub> —50% N (prilled urea) + 2 foliar application of nano urea	24.2b	25.2b	136.7c	142.1c	26.0b	26.1c
N <sub>3</sub> —50% N (prilled urea) + green manuring +1 foliar application of nano urea	24.9b	25.8b	139.6c	144.9c	26.4b	26.6c
N <sub>4</sub> —75% N (prilled urea) + 2 foliar application of nano urea	26.5a	26.9ab	148.7ab	154.2ab	28.2ab	28.3ab
N <sub>5</sub> —75% N (prilled urea) + 1 foliar application of nano urea + green manuring	26.9a	27.6a	151.8a	157.7a	28.6a	29.0a
SEM±	0.38	0.37	1.33	1.44	0.41	0.33
CD ( <i>p</i> = 0.05)	1.08	1.08	3.85	4.15	1.19	0.96

Note: Means sharing a common lowercase letter are statistically similar at *p* < 0.05 (LSD).

Abbreviation: CD, critical difference.

**TABLE 2** Effect of different nitrogen levels on the number of filled grains panicle<sup>-1</sup> and the number of unfilled grains panicle<sup>-1</sup> of scented rice.

Treatments	Number of filled grains panicle <sup>-1</sup>		Number of unfilled grains panicle <sup>-1</sup>	
	2023	2024	2023	2024
	Varieties (main plot)			
V <sub>1</sub> —Pusa Basmati 1718	119.9b	128.9b	21.2b	17.5b
V <sub>2</sub> —Pusa Basmati 1847	125.1a	134.3a	21.9a	18.3a
V <sub>3</sub> —Pusa Basmati 1886	114.8 c	123.7c	20.0c	16.6c
SEM±	0.92	1.00	0.08	0.41
CD ( <i>p</i> = 0.05)	3.63	3.93	0.33	1.59
Nitrogen levels (sub-plot)				
N <sub>0</sub> —control	104.1d	112.2d	22.6c	19c
N <sub>1</sub> —100% N (prilled urea)	124.6b	133.9b	20.8b	17.1b
N <sub>2</sub> —50% N (prilled urea) + 2 foliar application of nano urea	116.2c	125.0c	22.0c	18.2bc
N <sub>3</sub> —50% N (prilled urea) + green manuring + 1 foliar application of nano urea	118.8c	127.9c	22.1c	18.4c
N <sub>4</sub> —75% N (prilled urea) + 2 foliar application of nano urea	126.6ab	136.0ab	20.4b	17b
N <sub>5</sub> —75% N (prilled urea) + 1 foliar application of nano urea + green manuring	129.2a	138.7a	18.3a	15a
SEM±	1.14	1.22	0.24	0.43
CD ( <i>p</i> = 0.05)	3.3	3.51	0.69	1.24

Note: Means sharing a common lowercase letter are statistically similar at *p* < 0.05 (LSD).

Abbreviation: CD, critical difference.

**TABLE 3** Effect of different nitrogen levels on grain yield, straw yield, biological yield, and harvest index (%) of scented rice.

Treatments	Grain yield (t ha <sup>-1</sup> )		Straw yield (t ha <sup>-1</sup> )		Biological yield (t ha <sup>-1</sup> )		Harvest index (%)	
	2023	2024	2023	2024	2023	2024	2023	2024
Varieties (main plot)								
V <sub>1</sub> —Pusa Basmati 1718	4.58b	4.63b	6.11b	6.15b	10.69b	10.78b	42.8b	42.9b
V <sub>2</sub> —Pusa Basmati 1847	5.62a	5.64a	6.39a	6.43a	12.01a	12.07a	46.8a	46.7a
V <sub>3</sub> —Pusa Basmati 1886	4.38c	4.43c	5.90c	5.91c	10.28c	10.34c	42.5b	42.8b
SEM±	0.04	0.06	0.04	0.05	0.08	0.10	0.11	0.23
CD ( <i>p</i> = 0.05)	0.16	0.23	0.16	0.20	0.31	0.39	0.45	0.91
Nitrogen levels (sub-plot)								
N <sub>0</sub> —control	4.18d	4.18d	5.32d	5.29d	9.50d	9.47d	43.8	43.9
N <sub>1</sub> —100% N (prilled urea)	5.08b	5.10b	6.35b	6.42b	11.43b	11.52b	44.3	44.2
N <sub>2</sub> —50% N (prilled urea) + 2 foliar application of nano urea	4.70c	4.81c	5.97c	5.97c	10.67c	10.78c	43.9	44.5
N <sub>3</sub> —50% N (prilled urea) + green manuring + 1 foliar application of nano urea	4.80c	4.84c	6.08c	6.13c	10.8c	10.97c	44.0	43.9
N <sub>4</sub> —75% N (prilled urea) + 2 foliar application of nano urea	5.12ab	5.18ab	6.48ab	6.49ab	11.61ab	11.68ab	44.0	44.3
N <sub>5</sub> —75% N (prilled urea) + 1 foliar application of nano urea + green manuring	5.28a	5.29a	6.61a	6.67a	11.88a	11.97a	44.3	44.1
SEM±	0.05	0.06	0.07	0.07	0.12	0.12	0.15	0.20
CD ( <i>p</i> = 0.05)	0.16	0.16	0.21	0.20	0.35	0.34	NS	NS

Note: Means sharing a common lowercase letter are statistically similar at *p* < 0.05 (LSD).

Abbreviation: CD, critical difference.

### 3.2 | Grain and straw yield

Grain yield showed significant improvements with variety and nitrogen treatments (Table 3). Among varieties, Pusa Basmati 1847 (V<sub>2</sub>) outperformed others with yields of 5.62 and 5.64 t ha<sup>-1</sup> in 2023 and 2024, respectively. This was 24.6%–28.8% higher than the lowest yielding variety, Pusa Basmati 1886 (V<sub>3</sub>). Higher yields in V<sub>2</sub> can be attributed to superior panicle traits, higher grain weight, and better source–sink relationships.

Among nitrogen treatments, N<sub>5</sub> produced the maximum grain yields (5.28 and 5.29 t ha<sup>-1</sup>), followed by N<sub>4</sub> (5.12 and 5.18 t ha<sup>-1</sup>) and N<sub>1</sub> (5.08 and 5.10 t ha<sup>-1</sup>). The lowest yields were recorded in N<sub>0</sub> (4.18 t ha<sup>-1</sup> in both years). Straw yield and biological yield followed similar trends. The superior grain yield under N<sub>5</sub> treatment can be attributed to a balanced and sustained nitrogen supply from both organic and inorganic sources. It ensures better canopy development. Green manuring improved soil health and microbial mineralization rates, which provide a steady nitrogen release that complemented the rapid assimilation of nano urea through foliar pathways. This combination enhanced the photosynthetic activity and carbohydrate translocation to developing grain, resulting in higher grain yield. The combined use of green manuring and nano urea likely provided a synchronized nitrogen release pattern, enhancing both vegetative and

reproductive growth (Singh & Shivay, 2016; Zhang et al., 2019; Baral et al., 2024; Deng et al., 2022; Namasharma et al., 2023; J. Singh et al., 2022; Subhan et al., 2023; Shivay et al., 2016; Yadav et al., 2021; Sarathi et al., 2024). Although yield increased with higher nitrogen application, harvest index remained statistically unchanged across treatments, suggesting that both grain and straw yields increased proportionally. This indicates efficient assimilate partitioning in the tested treatments.

### 3.3 | Nitrogen dynamics and use efficiency

Nitrogen treatments significantly influenced nitrogen content in grain and straw, while available soil nitrogen did not vary significantly across varieties (Table 4). The highest nitrogen content in grain (1.37% and 1.53%) and straw (0.42% and 0.45%) was recorded under N<sub>5</sub>. Improved nitrogen content reflects better uptake and translocation facilitated by green manuring and foliar nano urea supplementation.

NUE also varied among treatments, with the maximum observed under N<sub>5</sub> (32.18 and 32.33%), followed by N<sub>4</sub> and N<sub>3</sub>. The control and 100% prilled urea (N<sub>0</sub> and N<sub>1</sub>) had lower NUE, indicating sub-optimal or excessive nitrogen availability at critical stages. The integration of green manuring and nano urea likely reduced nitrogen losses and improved plant

**TABLE 4** Effect of different nitrogen levels on available nitrogen, nitrogen content in grain, and nitrogen content in straw (%) of scented rice.

Treatments	Available N (kg ha <sup>-1</sup> )		Nitrogen content in grain (%)		Nitrogen content in straw (%)		Nitrogen use efficiency (%)	
	2023	2024	2023	2024	2023	2024	2023	2024
Varieties (main plot)								
V <sub>1</sub> —Pusa Basmati 1718	190.2	194.3	1.26b	1.36b	0.41b	0.42b	26.81	N27.04
V <sub>2</sub> —Pusa Basmati 1847	190.5	194.7	1.31a	1.42a	0.46a	0.47a	32.50	31.21
V <sub>3</sub> —Pusa Basmati 1886	189.9	193.7	1.21c	1.31c	0.42b	0.43b	25.24	25.95
SEM±	0.79	0.85	0.01	0.01	0.02	0.01	2.79	2.65
CD ( <i>p</i> = 0.05)	NS	NS	0.04	0.04	0.06	0.03	NS	NS
Nitrogen levels (sub-plot)								
N <sub>0</sub> —control	189.3	185.0c	1.06d	0.93e	0.35c	0.36b	24.22a	23.18b
N <sub>1</sub> —100% N (prilled urea)	190.5	196.7ab	1.31b	1.47c	0.39ab	0.38b	27.46a	27.66a
N <sub>2</sub> —50% N (prilled urea) + 2 foliar application of nano urea	189.6	195.0ab	1.23 c	1.37 d	0.38b	0.37b	28.63a	28.44a
N <sub>3</sub> —50% N (prilled urea) + green manuring + 1 foliar application of nano urea	189.4	194.8b	1.26 c	1.40d	0.37c	0.38b	29.34a	28.86a
N <sub>4</sub> —75% N (prilled urea) + 2 foliar application of nano urea	190.9	196.8ab	1.33b	1.49bc	0.39ab	0.40ab	30.47a	29.10a
N <sub>5</sub> —75% N (prilled urea) + 1 foliar application of nano urea + green manuring	191.6	197.3a	1.37a	1.53a	0.42a	0.45a	32.18a	32.33a
SEM±	0.89	0.85	0.01	0.01	0.01	0.02	3.12	2.89
CD ( <i>p</i> = 0.05)	NS	2.45	0.03	0.03	0.03	0.06	9.35	8.54

Note: Means sharing a common lowercase letter are statistically similar at *p* < 0.05 (LSD).

Abbreviations: CD, critical difference; NS, not significant.

uptake (Bhardwaj et al., 2023; Farooq et al., 2022; Kaur et al., 2021; Kumar & Singh, 2024; Rajput & Mishra, 2023; Rana et al., 2024; Shahane et al., 2018; S. Singh & Shivay, 2003). Among varieties, V<sub>2</sub> had higher nitrogen content and NUE than V<sub>1</sub> and V<sub>3</sub>, indicating better nutrient uptake and conversion into economic yield. The foliar application of nano urea provided immediate nitrogen to the canopy during panicle initiation, resulting in improved photosynthetic efficiency, chlorophyll content, and division of assimilates. Nano urea particles due to their ultra small size and high reactivity are immediately absorbed by the leaf stomata and translocated to growing tissue. It improves nitrogen uses efficiency (Kaur et al., 2021). The combined effect of green manure and nano urea thus created both short- and long-term nitrogen availability, reducing the risk of nitrogen deficiency during critical growth phase. On the other hand, under control and 100% nitrogen applied through inorganic sources resulted in lower panicle traits and reduced grain filling due to temporal nutrient imbalance, caused by either early excess nitrogen availability or deficiency during later stages. Therefore, synergistic use of organic, conventional, and nano nitrogen sources not only enhances yield attributes but also improves the physiological efficiency of nitrogen utilization by the plant.

## 4 | CONCLUSION

The present study demonstrated that the performance of scented rice varieties under varying nitrogen management practices significantly influenced yield attributes, grain yield, and NUE over two consecutive *kharif* seasons. Among the tested varieties, Pusa Basmati 1718 consistently produced higher yields and responded more efficiently to integrated nitrogen applications. The treatment comprising 75% prilled urea + green manuring + one foliar spray of nano urea (N5) was found to be most effective in improving panicle length, filled grains per panicle, test weight, and overall productivity while enhancing NUE. Therefore, adopting integrated nitrogen strategies, particularly involving organic amendments and nano fertilizers, offers a promising pathway for enhancing yield and nutrient efficiency in scented rice cultivation under sub-tropical agro-ecologies.

## AUTHOR CONTRIBUTIONS

**Mo Danish:** Conceptualization; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Virendra Singh:** Formal analysis; project administration; resources; software; supervision; validation; writing—original draft; writing—review and editing. **Satybhan Singh:**

Data curation; software; supervision; visualization; writing—review and editing. **S. L. Jat**: Resources; software; validation; writing—original draft; writing—review and editing.

## ACKNOWLEDGMENTS

This research was supported by IFTM University, Moradabad, India.

## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## ORCID

Virendra Singh  <https://orcid.org/0000-0002-8826-155X>

S. L. Jat  <https://orcid.org/0000-0002-3816-2318>

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**How to cite this article:** Danish, M., Singh, V., Singh, S., & Jat, S. L. (2025). Integrated nitrogen management enhances yield, nitrogen use efficiency, and grain quality in scented rice (*Oryza sativa* L.) under field conditions. *Agrosystems, Geosciences & Environment*, 8, e70272. <https://doi.org/10.1002/agg2.70272>