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Evaluation of Nano-Urea Application on Growth and Yield Performance of Basmati Rice under Flooded Conditions

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Authors' contributions

This work was carried out in collaboration among all authors. Authors VP, RP, PKU designed the experiment. Authors KBC, VP, RP, RCM, PKU carried out work. Authors KBC and VP did statistical analysis. All the authors have contributed equally for wrote of manuscript, gone through it and approved it for submission. All authors read and approved the final manuscript.

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ABSTRACT

Introduction: Rice crop utilizes only 30 to 40% of applied nitrogenous fertilizers and rest of the nitrogen (N) goes waste. Introduction of nano-urea in India had come with claims that it offers promising solution in enhancing nitrogen use efficiency for crops including flooded rice cultivation and thereby reduction in losses and associated environmental problems.

Aim: A study was undertaken to examine the effect of nano-urea formulation (a.i., 4% nano-N w/v) on Basmati rice under normal-sown and flooded-condition.

Methodology: Experiment was laid down with five treatments. Control (T_1) received recommended doses of fertilizers to soil. Remaining four treatments received either 50% of recommended N dose (T_2 and T_4) or 75% of recommended N dose (T_3 and T_5) to the soil along with two foliar applications of either normal-urea @ 2% w/v (T_2 and T_3) or nano-urea @ 0.016% w/v (T_4 and T_5).

Results: It was found that regardless of foliar applications either with normal-urea or nano-urea, plant growth and yield parameters were lower in T_2 and T_4 and higher in T_3 and T_5. Responses obtained with foliar applications of nano-urea were comparable to foliar application of normal-urea, separately at 50% N and at 75% N. This short-term study although indicated the possibility of saving about 25% and 17% of N through foliar applications of nano-urea (T_5) and normal-urea (T_3), respectively however, outcomes were discussed based on the current knowledge and understanding. It was also noted that rice plants under limited availability of N showed tendency of reduction in yield (by 8.7% in T_5) in spite of possible mining of N from the soil, N that was made available by N-fixation and also *via* rains during the monsoon season.

Conclusion: Findings suggested that use of nano-urea as partial substitute to the reduced application of N to the soil is not supporting for sustained production potential of rice crop and soil health. Future lines of work are therefore suggested so that suitable decision on large-scale use of nano-urea/nano-formulations can be taken up.

Keywords: Basmati rice; foliar application; normal-urea; nano-urea; growth; yield

1. INTRODUCTION

Rice (*Oryza sativa L.*) is one of the most important grains in the world serving as staple food for more than 3.5 billion people and accounting for nearly 20% of the global dietary energy (Abeysekara and Rathnayake, 2024). Global milled rice production is projected at 543.6 million tonnes (M t) in 2024-25, representing a 1.5% increase over the previous year primarily due to expanded cultivation in Asia. India's production is expected to rise from 137.8 M t (2023-24) to 145.0 M t (2024-25). To meet the demands of growing global population, an additional 200 M t of rice need to be produced by 2030 (Rahman and Zhang, 2023). This requires continuous effort in the direction of productivity enhancement in rice. To achieve this goal, one of the key approaches is the judicious and efficient use of fertilizers, particularly the nitrogenous fertilizers (Tyagi et al., 2022).

Nitrogen (N) is one of the essential macro-nutrients for plants, serving as a key element for chlorophylls, amino acids (constitute plant proteins) and other organic compounds. N is crucial in promoting crop growth, tiller development and increasing yields in rice like any other crop, particularly the cereals (Gawdiya et al., 2023). Urea (with N content of 46%) is the most used N fertilizers. In India, urea has been made affordable because of very high subsidy on it however it has low N use efficiency (NUE) reaching maximum only up to 30-40% (Kunwar et al., 2025; Sapkota and Takele, 2023). Low NUE of rice has led to its excessive use and it is continuing over many years resulting in serious environmental/pollution issues besides the gradual degradation of soil health. Volatilization of urea (to NH_3) and hydrolysis of urea followed by nitrification and denitrification mediated production of gaseous forms of N, mainly nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O) cause environmental pollution. While, surface runoff, leaching into ground water and assimilation by soil microorganisms (immobilization) cause ground water pollution and soil health degradation (Miao et al., 2025). Demand for urea in India during 2022-23 reached 35.73 M t, wherein 28.50 M t (79.7%) was produced domestically and remaining 7.58 M t (21.3%) was imported (Reddy et al., 2025). Government of India (GoI) provides a subsidy of ₹ 2700 on each bag of urea weighing 45 kg, thereby reducing the effective cost for the farmers to about ₹ 242 per bag. This led to subsidy amounting to ₹ 1.30 lakh crore for the year 2023–24 by the GoI (Sinha and Mishra, 2024). In the light of above said challenges, there has been a growing focus on enhancing NUE. Development of slow-release N fertilizers is one of the steps in this direction because slow-release regulates the nitrification process so that N availability can be sustained for longer time during the crop period (Suman et al., 2023).

Indian Farmers Fertilizer Cooperative Limited (IFFCO) introduced nano-urea formulation for the first time in the year 2021 as a breakthrough technology and solution to various drawbacks observed while using normal-urea (Kumar et al., 2021; IFFCO, 2022). As per specifications of nano-urea formulation, it is a liquid with particle size of 20-50 nm with *zeta* potential > 30 and shelf-life of about 2 years (Kumar et al., 2020a; IFFCO, 2022; Kantwa and Yadav, 2022). Nano-urea has more surface area and number of particles per unit area than the normal-urea. As claimed by IFFCO, one bottle of nano-urea (500 mL) is equivalent to a bag of 45 kg of normal-urea fertilizer (Kumar et al., 2021; IFFCO, 2022). Cost of one bottle of nano-urea (500 mL) is 10% less than the actual cost of subsidized normal-urea bag of 45 kg. Based on the trials conducted by IFFCO on farmers' field at multi-locations for many crops, it was claimed that two foliar applications with nano-urea formulation can replace the use of normal-urea by 50% and that too with an average yield enhancement of 8% (Kumar et al., 2021; IFFCO, 2022). Based on several such short-term studies, a report by Ministry of Chemicals and Fertilizers, suggested that adopting nano-urea could help the GoI to save subsidy cost of approximately ₹ 22,500 crore (USD 3 billion) annually. This projection was based on the current urea subsidy of around ₹ 20,000 per M t, as outlined by Thirty-Ninth Report of the Standing Committee on Chemicals and Fertilizers, 2023). Based on these findings it was assumed that over a period of time, use of nano-urea could also bring down the import of urea fertilizer. Here it becomes important to mention that these projections were based on the claims made by IFFCO provided that such claims prove to be true and sustainable in long-term. However, this appears far from reality as the claims made by IFFCO were seriously questioned by Frank and Husted (2024).

Thorough survey of literature showed that some studies support the above claims (Velmurugan et al., 2021; Midde et al., 2022) but some other studies have reported that use of nano-urea (as foliar application) along with soil application of either 50% or 75% of recommended N dose (*via* normal-urea) resulted in significant reduction in rice grain yield and also the grain N content as compared to control (100% of recommended N dose to the soil with no foliar application) (Namasharma et al., 2023; Sikka et al., 2024). Similar results were also reported in wheat by Kumar et al. (2023). In an important and timely study by Frank and Husted (2024), outcomes were argued in terms of knowledge gap and a need for more research for a sound evaluation of nano-fertilizers to avoid any possible risk involving food security, social disruption and conflicts. Thus, conflicting status on beneficial effects of nano-urea needs to be resolved. In view of reported claims, counterclaims, projections, predictions and concerns, a field experiment was undertaken to arrive at comparative effects of foliar applications of nano-urea as a partial substitute to the use of normal-urea in terms of growth and yield of rice crop. This investigation is also relevant in the direction of arrive at any decision pertaining to the recommendation for larger-scale sale and large-scale use of nano-urea in India.

2. MATERIALS AND METHODS

2.1 Experimental Site and Climate

A study was conducted during *Kharif* season at experimental field of ICAR-Indian Agricultural Research Institute (IARI), New Delhi, India. The experimental site was situated at 28.4°N latitude and 77.1°E longitude, with an elevation of 250 m above sea level. The climate was characterized as a semi-arid, sub-tropical with hot summers and cold winters.

2.2 Experimental Design and Crop Management

The experiment was laid out in a randomized block design with six replications. Basmati rice variety i.e., Pusa Basmati-1692 (developed by ICAR-IARI) with characteristics of high-yielding, early-maturing (short-duration), semi-dwarf, non-lodging and non-shattering habit was used. Optimum seed rate for this variety is 12.5 kg ha^{-1}. Rice crop was transplanted in field during third week of July with a spacing of 20 cm (row to row) and 10 cm (plant to plant). Fertilizers namely normal-urea, single super phosphate and muriate of potash were used to provide recommended doses of N, P and K @ 120, 60 and 40 kg ha^{-1}, respectively. For each treatment, N was applied in three split doses (1/3 as basal, 1/3 as top-dressing at active tillering stage at 30 days after transplanting (DAT) and 1/3 as top-dressing before flowering stage at 50 DAT). Complete P and K were uniformly applied as a single basal dose across all the treatments @ 60 kg ha^{-1} and 40 kg ha^{-1}, respectively. The control (T_1) received the recommended doses of fertilizers [N: P: K::120: 60: 40 (kg ha^{-1})]. While, the remaining four treatments received either 50% of recommended N dose (T_2 and T_4) or 75% of recommended N dose (T_3 and T_5) to the soil along with two foliar applications of either normal-urea (2% w/v) (T_2 and T_3) or nano-urea (0.016% w/v) (T_4 and T_5). First foliar application was applied at 30 DAT (corresponding to active tillering stage) and second at 50 DAT (matching with pre-anthesis stage). The complete details of experimental treatments of T_1 to T_5 are outlined in Supplementary Table 1. Experimental crop was sown in total planted area of 7920 m^2 with individual treatment area of 1584 m^2 wherein equal area of 246 m^2 was allotted for each of the six replications for a given treatment. Various physicochemical properties of nano-urea formulation (a.i., 4% nano-N w/v) as documented in available literature are compiled and presented in Supplementary Table 2. The rice crop was grown as per the recommended agronomic practices and was harvested in the last week of October (100 DAT).

2.3 Studies on Growth, Yield Components and Yield of Basmati Rice

Growth-related parameters like plant height, stem cross sectional area (SCSA), circumference of stem cross section (CSCS), fresh weight of above ground parts, dry weight of above ground parts, number of tillers, shoot dry weight, number of leaves, leaf dry weight, leaf area, number of panicles and dry weight of panicles were recorded on per plant basis as per the procedures outlined by Pandey et al. (2017). These parameters were recorded across the treatments either at required sampling stages or at all the three sampling stages i.e., 1st sampling (10-12 days after first foliar application, active tillering stage, 42 DAT) 2nd sampling (10 days after second foliar application, anthesis stage, 60 DAT) and 3rd sampling (33 days after second foliar application, post-anthesis stage, 84 DAT). Leaf area of fresh leaves was assessed by using leaf area meter (Model LICOR 3000, USA) and expressed in cm^2 per plant (Pandey et al., 2017). For the measurement of SCSA (mm^2) and CSCS (mm), a digital vernier calliper (Model: Mitutoyo 500-196-30; accuracy: ± 0.01 mm) was used. For this, all the measurements were always taken at the same point on the stem, usually 2–3 cm above the soil surface. The jaws of vernier calliper were carefully closed around the stem, avoiding any compression of the tissue, to ensure precise readings. For each rice stem, two perpendicular diameter measurements were recorded one was length-wise (a) and other was width-wise (b). The SCSA and CSCS were then calculated assuming an elliptical cross-section using the following formulas as given by Ramanujan (1914).

$$SCSA\ (mm^2) = \pi\ a\ b, \quad CSCS\ (mm) = 2\pi\sqrt{(a^2+b^2)/2}$$

Where a and b are the semi-axes of an ellipse in the length-wise diameter and in the width-wise diameter, respectively.

A few parameters such as fresh weight of above ground parts per plant & shoot dry weight per plant (Table 2), number of leaves per plant and leaf area per plant (Table 3) at 3rd sampling (84 DAT) for some of the treatments had relatively lower values in terms of comparison of time-series data. This was primarily due to the fact that dried leaves were present at this stage but they were not considered as a part of the sample. Furthermore, some of the lower leaves had already shaded from the plant due to senescence followed by abscission.

Number of grains, grain (husked) weight per plant and 1000-grain (husked) weight were recorded at 3rd sampling (33 days after second foliar application, post-anthesis stage, 84 DAT) to get overall idea of on-going reproductive growth and yield-forming components. At crop maturity (100 DAT), length of main panicle, dry weight of main panicle, weight and number of spikelets on main panicle (total, filled and unfilled) and length of main flag leaf were recorded. All the above said data were collected from 210 main panicles (already tagged at the time of emergence of main panicle) randomly spread across six replications per treatment. Each replication was thereby represented by 35 main panicles. Finally, based on random and replicated (six) samplings [each replication covering a land area of 6 m^2 (3 m x 2 m)], straw yield and grain (husked) yield were calculated and expressed as tonne per hectare (t ha^{-1}). Husked grains at the time of harvest had on an average 14% of moisture level.

2.4 Statistical Analysis

The obtained replicated data were statistically analyzed using one-factor analysis in a randomized block design, as per standard guidelines by Gomez and Gomez (1984). All statistical analyses including separation of mean values using Duncan's Multiple Range Test were performed by using statistical software available at webpage http://opstat.pythonanywhere.com (Sheoran et al., 1998, last updated in June, 2025).

3. RESULTS AND DISCUSSION

3.1 Climatic Conditions during the Rice Crop Growth Period

Different agro-meteorological observations as recorded during the period of cultivation of experimental rice in crop season (*Kharif*) from 04 July to 30 October are presented in terms of metrological week (MW) and weather data in Supplementary Table 3 along with the graphical presentation of same data with some additional details in Supplementary Fig. 1. During the rice crop growth period, weekly mean maximum temperature ranged from 28.76ºC to 37.5ºC, with an overall average of 33.73ºC. The weekly mean minimum temperature varied from 16.43°C to 28.44°C with overall average of 23.94°C. Relative humidity fluctuated from to 65.50% to 84.21%, with an average of 75.31%. Over the cropping season (July to October), a total rainfall of 739.5 mm was recorded from total of 35 rainy days (Supplementary Table 3, Supplementary Fig. 1). The prevailing weather data ensured that abiotic factors remained relatively stable and suitable for rice crop. Variability in rainfall was offset by timely supplementary irrigation, ensuring consistent moisture and uniform growth conditions.

3.2 Crop Growth

At active tillering stage (42 DAT), T_1 (control, 100% of recommended N dose with no foliar applications) recorded higher values for plant height, SCSA and CSCS (Table 1). Although plant height remained unaffected by treatments but, SCSA and CSCS were influenced by treatments. Both of these parameters followed the order of T_1 (control) ≥ T_3 (75% of recommended N dose with two foliar applications of normal-urea) > T_5 (75% of recommended N dose with two foliar applications of nano-urea) > T_2 (50% of recommended N dose along with foliar applications of normal-urea) ≥ T_4 (50% of recommended N dose along with foliar applications of nano-urea) and thereby responded proportionally to the doses of N (Table 1). Likewise, other growth-related parameters namely; number of tillers, fresh weight & dry weight of above ground parts, shoot dry weight (Table 2), number of leaves, leaf dry weight and leaf area (Table 3) were maximum in T_1 (control). Number of tillers, dry weight of above ground parts and shoot dry weight remained unaffected by treatments but all other parameters were found to be treatment dependent (Tables 2, 3). Fresh weight of above ground parts (Table 2), number of leaves, leaf dry weight and leaf area (Table 3) had maximum and significantly higher values for T_1 (control) than the T_4, while values for other treatments fell in between T_1 and T_4 in the order of T_3, T_5 and T_2 (with either significant difference or non-significant difference among them). Thus, growth-related parameters for rice plants at active tillering stage as presented in Table 1-3, were in proportion to the doses of N i.e., T_1 (control) > T_3 > T_5 > T_2 > T_4 (Supplementary Table 1). Although, by this time basal dose of 1/3 of total N was applied with only one split application of 1/3 dose of total N along with the specified foliar application (either with normal-urea or nano-urea) as per the treatment (Supplementary Table 1). N supply dependent enhancements in cell division, stem thickening, leaf expansion and fresh weight of biomass accumulated were reported for vegetative growth of rice plants (Yang et al., 2025). Further, in accordance with our findings, Lu et al. (2025) reported that differential doses of N significantly increase fresh weight of above ground parts without substantial changes in dry weight of above ground parts i.e., structural biomass up to vegetative stage (Table 2). Indicating that enhancement in fresh biomass across the treatments was primarily due to higher tissue hydration and cell expansion rather than due to dry matter accumulation.

At anthesis stage (60 DAT), plant height (Table 1) of treatments with 50% of recommended N dose along with foliar applications either with normal-urea (T_2) or nano-urea (T_4) were at par and comparable to control (T_1). On the other hand, treatment T_3 had maximum plant height of 106.4 cm but it was at par with plant height of T_5. Both, T_3 and T_5 treatments, had plant height higher than the control (97.0 cm) (Table 1). SCSA and CSCS (Table 1) in T_3 and T_5 were at par with control (T_1) but lower in T_2 and T_4. Exactly similar trend was recorded for fresh weight & dry weight of above ground parts (Table 2) and leaf dry weight & leaf area (Table 3). Higher number of tiller (Table 2) and more number of leaves (Table 3) in control (T_1) at anthesis stage (60 DAT) suggested for more allocation of assimilates towards tillering and leaves than for the vertical growth. This explained for the less plant height in control (T_1) than the T_3 and T_5 at anthesis stage (60 DAT). In contrast to this, shoot dry weight per plant (Table 2) was highest in T_5 followed by T_3 which was statistically comparable to control (T_1). Comparable values for most of the vegetative growth-related parameters (SCSA, CSCS, fresh weight & dry weight of above ground parts, leaf dry weight and leaf area) in T_3 and T_5 with that of control (T_1) can be due to lesser plant height (Table 1) and shoot dry weight (Table 3) in control. This thereby supported the observation that when 75% of recommended N dose was applied to soil with foliar applications of either normal-urea (T_3) or nano-urea (T_5) then these treatments can compensate for 25% less of N input applied to the soil as number of tillers and number of leaves in these treatments were less than the control (T_1). But, control (T_1) at anthesis stage outperformed in terms of other growth-related parameters such as; number of tillers per plant (Table 2) and number of leaves (Table 3). In contrast to T_3 and T_5, other two treatments with 50% of recommended N dose applied to soil with foliar applications of either normal-urea (T_2) or nano-urea (T_4) showed significantly lower values for most of the parameters (SCSA, CSCS, number of tillers, fresh weight of above ground parts, number of leaves, leaf dry weight and leaf area) in comparison to control (T_1) (Tables 1 to 3). Thus, results at anthesis stage had limited growth under sub-optimal dose of N (50% of RD of N) to the soil even after supplementation of N with foliar applications of either normal-urea (T_2) or nano-urea (T_4).

Post-anthesis stage (84 DAT) is a better stage for assessing cumulative and overall effects of treatments and both the foliar applications. At this stage, key growth-related parameters such as; plant height, SCSA & CSCS (Table 1), number of tillers, shoot dry weight (Table 2) were significantly lower in T_2 and T_4 than T_3 and T_5. With respect to plant height, Wu et al. (2023) documented that during late stages plant height may or may not get affected by differences in N doses due to the competition of inter-nodal elongation and shift towards reproductive phase. Values obtained for SCSA, CSCS (Table 1), fresh weight of above ground parts (Table 2), number of leaves & leaf area (Table 3) in T_3 and T_5 were comparable to control (T_1). While, shoot dry weight per plant (Table 2) was significantly lower in T_3 as well as in T_5 than the control (T_1), possibly due to less dry matter accumulation and/or early and faster remobilization of stem reserves to facilitate growth of reproductive parts or developing grains in panicle during post-anthesis phase (Zhu et al., 2025).

Overall, results (Tables 1 to 3) indicated that while the treatments T_2 and T_4 were insufficient in maintaining optimal growth but, treatments T_3 and T_5 can somehow matched with the growth performance of control T_1. In treatments T_3 and T_5 it became possible that the amount of N supplied to soil, foliage (by foliar applications) and possibly also by mining of N from the soil, N became more or less sufficient to meet the growth requirements of rice plants. On the other hand, in treatments T_2 and T_4, where N supply to the soil was reduced to only 50% of the recommended N dose to the soil (with foliar applications and even after mining of N from the soil), there was inability to sustain in terms of required growth of rice plants despite of foliar applications and mining of N from the soil. Thus, net reduction in growth-related parameters in T_2 and T_4 was due to overall lesser availability of N to an extent of below the threshold need of N to support adequate growth of rice plants.

Some studies have documented that nano-particles stick to leaf surfaces and enter through stomata, hydathodes and other openings present on leaves and other surfaces of plant where transport proteins and plasmodesmata also play important role in the movement and transportation of nano-particles within the plant (Wang et al., 2023). Nano-urea can also enter *via* endocytosis and can be transported within the symplasm besides getting stored in vacuoles and from here it gets released gradually or in controlled fashion (Babu et al. 2022a; Babu et al. 2022b; IFFCO, 2022). However, Pérez-de-Luque, (2017) noted no evidence in support of nano-particles being taken up by transport proteins (including aquaporins and ion channels) as nano-particles are typically too large to fit through these transport proteins. Thus, uptake and transport pathway described by IFFCO remained purely speculative (Frank and Husted, 2024). This further raised doubts and concerns on the claims made by IFFCO (Amrit, 2022).

Data obtained in present study on growth of the rice plants indicated that up to some extent vegetative growth of rice plant can be supported by T_3 and T_5 but not by T_2 and T_4 over the control. But still in T_3 and T_5, compensation for less of applied N (25% less than the recommended N) *via* excessive mining of N from the soil cannot be ruled out. It was reported by Jia et al. (2023) that sub-optimal application of N to rice triggers excessive mining of N from the residual soil N as a compensatory step to meet out the demands and to support vegetative and reproductive growth of rice plant. Further, Upadhyay et al. (2023) and Gopinath et al. (2025) provided empirical evidence that treatments applying only 50% of the recommended N dose along with nano-urea sprays resulted in significantly lower yields compared to the full recommended dose of normal-urea fertilizer ($N_{100\%}$). Thereby reinforcing that nano-urea supplementation alone is insufficient for optimal yields and led to a depletion of available nitrogen in the soil and significantly lower yields, while at least 75% of the recommended N dose was needed with nano-urea spray to maintain soil nitrogen and crop productivity. Likewise, Mejías et al. (2021) emphasized that nano-fertilizers cannot fully replace the recommended N due to their lower N content.

3.3 Yield-related Components

Yield-related components in their developing phases at 2nd sampling and or 3rd sampling are presented in Table 4. These traits provide reflection of impact of different treatments on the on-going reproductive growth and yield-related components of rice.

At post-anthesis stage (84 DAT), significantly lower number of panicles, dry weight of panicles and grain (husked) weight per plant were recorded in T_4 over the control (Table 4). This was due to the fact that among all the treatments, lowest level of N was made available to T_4 treatment (Supplementary Table 1). On the other hand, all the parameters in T_5 at post-anthesis stage were equivalent to that of control (T_1) (Table 4). 1000-grain (husked) weight, however, remained unaffected across the treatments suggesting that grain size in terms of grain-filling was not much affected with reduction in the supply of N to the soil (that was partly substituted by foliar applications) but it was the grain number per plant that was affected. Same was evident from statistically significant reduction of 20.6% in number of grains per plant in T_4 (717.14) over the control (903.13) (Table 4). This in turn was reflected in in terms of significant reduction in grain (husked) weight per plant in T_4 (18.56) over the control (22.44), a reduction of 17.3% (Table 4). Other treatments i.e., T_2, T_5 and T_3 also showed reductions over the control by 5.0, 6.0 and 7.7% respectively, but statistically non-significant (Table 4). Sui et al. (2013) reported much pronounced effect of reduction in N supply to rice plant on grain number rather than on 1000 grain weight. This highlights the importance of optimal supply of N in deciding grain number per plant, because this key yield-determining factor is decided at quite early growth stages in cereals including the rice (Yoshida et al., 2006; Makino, 2011). Studies by Hussain et al. (2023) and Prasad and Shivay (2016) reported that reduced N availability limits the N required to sustain key metabolic functions thereby led to an estimated 10% reduction in yield. These findings are consistent with report that adequate supply and availability of N improves plant growth and yield (Shahane et al., 2023).

3.4 Main Panicle- and Flag Leaf-Related Parameters at Crop Maturity (Harvest)

Length & weight of main panicle and weight & number of spikelets on main ear (total, filled and unfilled) as recorded at crop maturity (100 DAT) (Table 5) showed non-significant difference across the treatments. These findings indicated for uniform floral development and spikelet fertility among the treatments for main panicle. This trend was however not true for yield-components on per plant basis, as evident from the differences among the treatment for parameters such as; number of panicles, dry weight of panicles, number of grains, grain (husked) weight on per plant basis (Table 4). Length of main flag-leaf at crop maturity (100 DAT) was longest in T_5 (26.9 cm) and this decreased in the order of T_3 (26.6 cm), T_4 (25.9 cm), T_1 (25.4 cm) and T_2 (25.2 cm) (Table 5). Length of main flag-leaf was higher in T_3 than the control (T_1) and this must be due to lesser number of tillers in control as recorded at anthesis stage (84 DAT) (Table 2). A study by Huang et al. (2013) clearly showed that number of tillers per plant and length/size of main flag-leaf in rice are governed by supply/availability of N.

3.5 Grain and Straw Yield

Data on straw and grain (husked) yield of rice on per hectare basis are presented in Fig. 1. Statistically, straw yield showed non-significant difference across the treatments. But, even then, in comparison to control (T_1) there was reduction by 19.7% (T_4), 15.7 (T_2), 9.5% (T_3) and 6.5% (T_5). Indicating for more reduction in treatments where 50% of recommended N dose was given along with foliar applications (T_2 and T_4) and less reduction in treatments where 75% of recommended N dose was given along with foliar applications (T_3 and T_5) (Fig. 1).

Grain yield was maximum (4.79 t ha^{-1}) in control (T_1) and this was followed by T_5 (4.37 t ha^{-1}), T_3 (4.24 t ha^{-1}), T_2 (3.58 t ha^{-1}) and T_4 (3.45 t ha^{-1}) (Fig. 1). In comparison to control, treatments T_4, T_2 and T_3 showed significant reductions of 27.9%, 25.2% and 11.5%, respectively. While, the treatment T_5 showed reduction in grain yield by 8.7% in comparison to control but statistically both were at par. Overall trend as recorded for straw yield was parallel with the trend for grain yield as well. Like the case of straw yield, grain yield reduction was also more and significant in treatments where 50% of recommended N dose was given to soil along with foliar applications (T_2 and T_4) and less in treatments where 75% of recommended N dose was given to along with foliar applications (T_3 and T_5) (Fig. 1). The highest grain yield in T_1 (control) can be attributed to higher shoot dry weight per plant (Table 3), number of grains per plant (Table 4). Data thus clearly indicated that rice crop under lesser available/availability of N showed tendency to reduce straw yield and paddy yield. This was contradictory to the claims made by IFFCO where at least 8.0 % increase in the yield was documented with the use of nano-urea ((Kumar et al., 2021; IFFCO, 2022). The reduction in grain yield per hectare, in comparison to control, was statistically evident at 50% of recommended N dose (T_2 and T_4) while the reduction was there at 75% of recommended N dose (T_3 and T_5) but statistically non-significant. This being a short-term experiment where T_5 = T_1 and T_5 = T_3 and therefore possibility of mining of N from the soil itself cannot be ruled out.

Foliar application of nutrients either directly or indirectly (*via* enhancing bio-availability of a given nutrient) to the crop plant are important strategies for enhancing grain yield and quality of different crops including fine Basmati rice (Kamran et al., 2025). Optimum/higher N application to soil has been shown to sustain/enhance grain and straw yields by maintaining availability of N that plays critical role in stimulating and maintaining vegetative & reproductive growth and grain-filling (Thakur et al., 2020; Sharma et al., 2021; Zhou et al., 2021). Thus, reducing the N to 50% of the recommended dose (even when supplemented with foliar applications of nano-urea) led to a notable decline in yield contributing attributes; shoot dry weight (Table 2), number of grains per plant (Table 4) and thereby the grain yield (Fig. 1). Indicated that 50% of recommended N dose with foliar supplementation of N was not adequate in achieving optimal performance of rice crop. In fact, it was already reported that an adequate supply of N regulates reproductive growth of crops and increases number of fertile spikes per panicle, number of grains per panicle and the yield, whereas N deficiency can lead to the degradation of photosynthetic pigments, yellowing of leaves and inhibition of the growth and yield of crops (Chen et al., 2022). Our results, in this study, are in agreement with Sikka et al. (2024), who also reported that application of two foliar sprays of nano-urea + 50% of recommended N (52.5 kg ha^{-1}) significantly reduced the grain yield of rice and wheat by 13.0% and 17.2%, respectively in comparison to control (100% of recommended dose of N i.e., 105.0 kg ha^{-1}, applied to the soil in split doses). Likewise, Reddy et al. (2025) also reported that application of 50% of recommended N dose (65.0 kg ha^{-1}) + two foliar applications of nano-urea formulation (1.250 L ha^{-1} per spray) recorded reduced grain yield by 9.4% in rice in comparison to the control with 130.0 kg of recommended N. These findings also align with previous work of Sarkar et al. (2023) on wheat and Reddy et al. (2024) on rice and wheat. In India, rice is cultivated over 47.6 million hectares (M ha) with an annual production of approximately 120 million tonnes (M t) (https://www.statista.com/statistics/765691/india-area-of-cultivation-for-rice/). Based on our results in this study, if one follows two foliar applications of nano-urea with only 50% of recommended N dose to the soil then yield get reduced by 27.9% (from control value of 4.79 t ha^{-1} to 3.45 t ha^{-1} in T_4). Based on this, if we presume that this practice is being adopted even in ¼ of the land area (11.9 M ha) out of total land that comes under cultivation of rice (47.6 M ha) then this would potentially result in reduction of rice production by 8.37 M t in India on annual basis. On the similar analogy, based on the data of

Sikka et al. (2024), reduction in rice production will be 5.16 M t.

Despite the claims made by IFFCO, some researchers have expressed serious doubts and genuine concerns with respect to the efficacy of nano-urea formulation (with a.i., 4% nano-N w/v) as used in this study as well. In most of the crops, N concentration in plant dry matter typically varies between 1 to 5% (De Bang et al., 2021). Based on this and with the presumption that 100% of applied N (as present in nano-urea formulation) is taken up by plants, then 20 g of nano-N (present in one bottle of 500 mL of nano-urea formulation) would only be sufficient to support the production of only 0.4 to 2.0 kg of plant dry matter. Further, based on well-known and basic understanding on rice crop, 25 kg of soil application of N is needed to produce one tonne of rice grains. If we assume that 50% of this soil applied N is utilized then rice grain yield of 500 kg can be obtained. Now, if we consider that nano-urea formulation (500 mL bottle) with 20 g of nano-N is applied and 100% of it is absorbed and utilized by plants (although, theoretically as well as practically, cent-percent uptake and efficiency are not possible) then also it would yield only 368 g of rice grains (Amrit, 2022). This thereby raises questions on the adequacy of nano-urea as a partial-substitute of N to get same level of crop performance and yield and that too in a sustainable manner. Key question is, how such a small quantity of nano-N in nano-urea formulation can compensate for much larger requirement of N for optimal crop growth and yield formation (Frank and Husted, 2024). Additionally, normal-urea being highly water-soluble is already available in its molecular form and thereby in its smallest size when applied to the soil. So, how nano-size of urea in nano-urea formulation can enhance the effectiveness and efficiency of N uptake and its use by the plant and that too when N serves as major macro-nutrient and it is used in assimilation i.e., formation of N-based macro- and micro-molecules and so the dry matter and yield-forming components rather than a catalytic element/factor/cofactor in plants.

Upadhyay et al. (2023) reported that application of 75% of recommended N (normal-urea to soil) through conventional way (split doses) in maize (three equal split doses), wheat (three equal split doses), pearl millet (two equal split doses) and mustard (two equal split) + full basal dose of recommended P_2O_5 and K_2O along with two foliar applications of nano-urea formulation (1.250 L ha^{-1} for each spray) resulted in grain yield statistically at par with control (recommended dose of fertilizers; 100% N + full dose of P_2O_5 and K_2O with no foliar application).

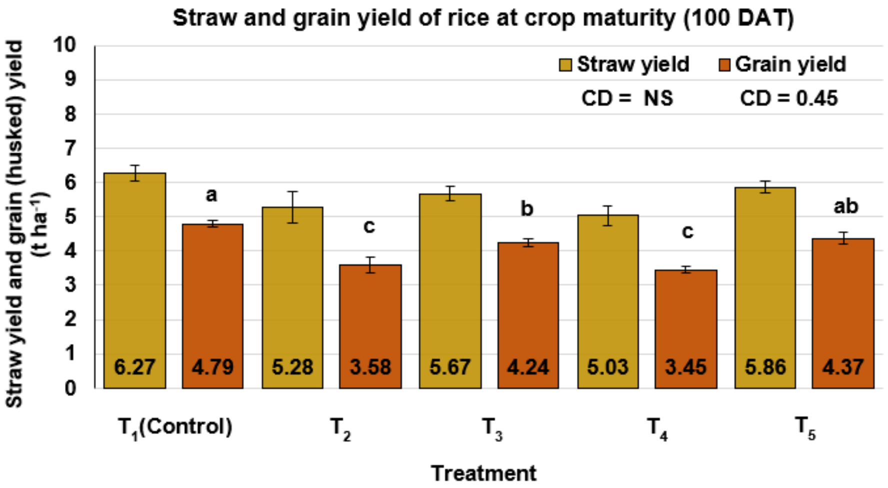

Fig. 1. Straw yield (t ha^{-1}) and grain (husked) yield (t ha^{-1}) of Basmati rice (Pusa Basmati 1692) at crop maturity (100 days after transplanting, DAT)

T_1 (Control): Recommended dose of fertilizers (RDFs) N:P:K::120:60:40 (kg ha^{-1}), T_2: 50% of recommended N dose + Two foliar sprays of normal-urea, T_3: 75% of recommended N dose + Two foliar sprays of normal-urea, T_4: 50% of recommended N dose + Two foliar sprays of nano-urea and T_5: 75% of recommended N dose + Two foliar sprays of nano-urea. For more and specific details of each treatment refer Supplementary Table 1; Each mean value is average of 6 replications. Mean value bar with different alphabetic letter/s indicate that given mean value is significant over other mean values across the treatments at CD (0.05). NS: Non-significant at CD (0.05) Vertical line at the top of each bar (representing mean value) is ± standard error of mean (± SEM)

Table 1. Effect of different treatments on growth-related parameters of Basmati rice (Pusa Basmati 1692) at three samplings

Parameter	Plant height (cm)			Stem cross sectional area (SCSA, mm^2) of plant			Circumference of stem cross section (CSCS, mm) of plant		
Sampling/ Treatment	**1st sampling (42 DAT)**	**2nd sampling (60 DAT)**	**3rd sampling (84 DAT)**	**1st sampling (42 DAT)**	**2nd sampling (60 DAT)**	**3rd sampling (84 DAT)**	**1st Sampling (42 DAT)**	**2nd sampling (60 DAT)**	**3rd sampling (84 DAT)**
T_1 (Control)	79.00 ± 2.16	97.00^{c} ± 1.41	98.75^{b} ± 1.00	1002.34^{a} ± 10.47	1037.92^{a} ± 25.92	1093.20^{a} ± 25.44	111.51^{a} ± 1.53	115.32^{a} ± 2.39	117.88^{a} ± 2.81
T_2	73.67 ± 0.96	98.50^{bc} ± 2.37	98.50^{b} ± 1.05	696.55^{c} ± 16.11	716.87^{b} ± 16.58	784.32^{b} ± 34.95	78.33^{d} ± 1.90	94.31^{b} ± 1.60	97.99^{b} ± 1.89
T_3	76.03 ± 1.15	106.40^{a} ± 2.69	104.88^{a} ± 0.35	995.42^{a} ± 17.43	1063.30^{a} ± 39.91	1028.93^{a} ± 31.21	104.31^{b} ± 1.77	112.90^{a} ± 1.46	112.38^{a} ± 2.18
T_4	75.20 ± 1.44	98.60^{bc} ± 2.03	99.75^{b} ± 0.62	643.48^{d} ± 14.98	677.74^{b} ± 21.07	770.67^{b} ± 29.40	75.19^{d} ± 2.01	92.57^{b} ± 1.91	100.49^{b} ± 2.00
T_5	72.40 ± 1.83	103.80^{ab} ± 1.72	102.75^{a} ± 0.70	937.95^{b} ± 12.85	1103.79^{a} ± 37.88	1105.74^{a} ± 38.50	98.25^{c} ± 1.58	114.26^{a} ± 2.24	116.52^{a} ± 2.11
CD (0.05)	NS	6.01	2.29	43.11	90.03	84.36	5.57	5.33	6.26

1st sampling: 10-12 days after 1st foliar application, active tillering stage, 42 days after transplanting (DAT); 2nd sampling: 10 days after 2nd foliar application, anthesis stage, 60 DAT; 3rd sampling: 33 days after 2nd foliar application, post-anthesis stage, 84 DAT; T1 (Control): Recommended dose of fertilizers (RDFs) N:P:K::120:60:40 (kg ha^{-1}), T2: 50% of recommended N dose + Two foliar sprays of normal-urea, T3: 75% of recommended N dose + Two foliar sprays of normal-urea, T4: 50% of recommended N dose + Two foliar sprays of nano-urea and T5: 75% of recommended N dose + Two foliar sprays of nano-urea. For more and specific details of each treatment refer Supplementary Table 1.; Each mean value is average of 6 replications. Mean value suffixed with different alphabetic letter/s indicate that given mean value is significant over other mean values within the column (across the treatments) at CD (0.05). NS: Non-significant at CD (0.05); Mean value followed by value prefixed with ± is standard error of mean (± SEM)

Table 2. Effect of different treatments on growth-related parameters of Basmati rice (Pusa Basmati 1692) at three samplings

Parameter	Number of tillers per plant			Fresh weight (g) of above ground parts per plant			Dry weight (g) of above ground parts per plant			Shoot dry weight (g) per plant		
Sampling/ Treatment	**1st sampling (42 DAT)**	**2nd sampling (60 DAT)**	**3rd sampling (84 DAT)**	**1st sampling (42 DAT)**	**2nd sampling (60 DAT)**	**3rd sampling (84 DAT)**	**1st sampling (42 DAT)**	**2nd sampling (60 DAT)**	**3rd sampling (84 DAT)**	**1st sampling (42 DAT)**	**2nd sampling (60 DAT)**	**3rd sampling (84 DAT)**
T_1 (Control)	20.50 ± 1.23	22.60^{a} ± 1.81	14.75^{b} ± 1.16	87.58^{a} ± 2.52	151.00^{a} ± 2.28	150.44^{a} ± 9.01	16.33 ± 1.69	38.22^{abc} ± 0.66	60.06^{a} ± 3.29	10.27 ± 1.55	16.54^{bc} ± 0.66	18.28^{a} ± 1.39
T_2	15.00 ± 1.46	14.40^{cd} ± 0.51	15.00^{ab} ± 0.89	69.50^{cd} ± 1.58	110.10^{b} ± 8.06	130.25^{a} ± 8.73	12.05 ± 0.82	29.69^{c} ± 2.69	42.58^{cd} ± 3.54	7.41 ± 0.78	15.20^{bc} ± 1.14	14.11^{b} ± 0.92
T_3	15.67 ± 1.61	19.80^{ab} ± 1.74	13.63^{b} ± 0.50	75.50^{b} ± 2.07	154.90^{a} ± 11.77	134.56^{a} ± 6.49	14.70 ± 0.39	38.92^{abc} ± 2.39	49.32^{bc} ± 2.94	8.97 ± 0.35	19.18^{ab} ± 1.32	14.37^{b} ± 0.68
T_4	19.67 ± 1.61	11.20^{d} ± 0.58	10.63^{c} ± 0.73	66.91^{d} ± 1.98	114.60^{b} ± 4.91	104.69^{b} ± 5.88	12.61 ± 0.96	31.74^{bc} ± 1.85	36.48^{d} ± 2.07	8.60 ± 0.88	13.25^{c} ± 0.88	11.06^{c} ± 1.17

Parameter	Number of tillers per plant			Fresh weight (g) of above ground parts per plant			Dry weight (g) of above ground parts per plant			Shoot dry weight (g) per plant		
Sampling/ Treatment	1st sampling (42 DAT)	2nd sampling (60 DAT)	3rd sampling (84 DAT)	1st sampling (42 DAT)	2nd sampling (60 DAT)	3rd sampling (84 DAT)	1st sampling (42 DAT)	2nd sampling (60 DAT)	3rd sampling (84 DAT)	1st sampling (42 DAT)	2nd sampling (60 DAT)	3rd sampling (84 DAT)
T_5	15.17 ± 2.60	18.00[bc] ± 1.58	17.38[a] ± 1.22	74.25[bc] ± 1.58	168.10[a] ± 16.09	147.44[a] ± 10.74	12.66 ± 1.68	42.69[a] ± 4.34	53.89[ab] ± 3.54	7.65 ± 1.49	21.13[a] ± 2.03	15.32[b] ± 1.13
CD (0.05)	NS	4.27	2.45	5.28	30.42	19.71	NS	7.98	7.70	NS	4.21	2.66

Details are same as given in foot notes of Table 1

Table 3. Effect of different treatments on growth-related parameters of Basmati rice (Pusa Basmati 1692) at three samplings

Treatments	Number of leaves per plant			Leaf dry weight (g) per plant			Leaf area (cm^2) per plant		
Sampling/ Treatment	1st sampling (42 DAT)	2nd sampling (60 DAT)	3rd sampling (84 DAT)	1st sampling (42 DAT)	2nd sampling (60 DAT)	3rd sampling (84 DAT)	1st sampling (42 DAT)	2nd sampling (60 DAT)	3rd sampling (84 DAT)
T_1 (Control)	82.83[a] ± 2.90	87.20[a] ± 5.86	39.25[ab] ± 4.84	6.06[a] ± 0.30	8.10[a] ± 0.30	9.31[a] ± 0.74	1378.23[a] ± 97.92	1742.84[a] ± 90.22	822.04[ab] ± 75.02
T_2	53.83[c] ± 1.80	59.80[cd] ± 2.89	44.88[a] ± 3.16	4.65[cd] ± 0.14	5.89[b] ± 0.70	7.41[b] ± 0.50	1023.24[b] ± 55.72	1076.36[b] ± 91.06	711.45[abc] ± 75.63
T_3	74.67[ab] ± 6.32	77.80[ab] ± 6.83	31.13[b] ± 1.81	5.72[ab] ± 0.17	8.43[a] ± 0.69	7.75[b] ± 0.52	1360.77[a] ± 99.73	1673.7[a] ± 195.12	660.40[bc] ± 48.98
T_4	41.50[d] ± 1.78	44.80[d] ± 1.53	30.75[b] ± 3.67	4.01[d] ± 0.16	5.45[b] ± 0.14	5.71[c] ± 0.40	856.50[b] ± 79.78	940.35[b] ± 45.56	566.15[c] ± 62.31
T_5	69.67[b] ± 4.02	69.40[bc] ± 6.38	37.00[ab] ± 2.78	5.01[bc] ± 0.40	8.36[a] ± 0.72	9.37[a] ± 0.66	1059.03[b] ± 119.53	1571.35[a] ± 114.94	875.51[a] ± 90.63
CD (0.05)	8.19	16.00	8.78	0.77	4.27	1.39	293.02	356.74	180.08

Details are same as given in foot notes of Table 1

Table 4. Effect of different treatments on reproductive growth and yield-related components of Basmati rice (Pusa Basmati 1692) at 2nd and 3rd sampling stages

Treatment	Number of panicles per plant		Dry weight (g) of panicle per plant		Number of grains per plant at 3rd sampling (84 DAT)	Grain (husked) weight (g) per plant at 3rd sampling (84 DAT)	1000-grain (husked) weight (g) at 3rd sampling (84 DAT)
	2nd sampling (60 DAT)	3rd sampling (84 DAT)	2nd sampling (60 DAT)	3rd sampling (84 DAT)			
T_1 Control)	10.80[ab] ± 0.58	14.00[ab] ± 1.15	13.59 ± 0.43	32.47[a] ± 1.56	903.13[a] ± 27.10	22.44[a] ± 0.68	25.77 ± 0.50
T_2	9.40[b] ± 0.68	14.00[ab] ± 1.25	8.60 ± 1.31	21.06[b] ± 2.82	857.97[a] ± 41.29	22.40[a] ± 1.28	24.62 ± 0.86

Treatment	Number of panicles per plant		Dry weight (g) of panicle per plant		Number of grains per plant at 3rd sampling (84 DAT)	Grain (husked) weight (g) per plant at 3rd sampling (84 DAT)	1000-grain (husked) weight (g) at 3rd sampling (84 DAT)
	2nd sampling (60 DAT)	3rd sampling (84 DAT)	2nd sampling (60 DAT)	3rd sampling (84 DAT)			
T_3	10.60[ab] ± 0.81	13.00[bc] ± 0.71	11.32 ± 1.18	27.21[a] ± 2.11	833.18[a] ± 14.91	21.60[a] ± 0.72	26.07 ± 0.35
T_4	10.20[b] ± 0.49	10.25[c] ± 0.45	13.04 ± 1.29	19.72[b] ± 1.26	717.14[b] ± 33.77	18.56[b] ± 0.69	24.97 ± 0.43
T_5	12.40[a] ± 0.51	16.25[a] ± 1.13	13.21 ± 2.49	29.20[a] ± 2.16	849.24[a] ± 28.75	21.31[a] ± 0.80	25.18 ± 0.42
CD (0.05)	1.74	2.75	NS	5.60	85.64	2.11	NS

2nd sampling: 10 days after 2nd foliar application, anthesis stage, 60 DAT; 3rd sampling: 33 days after 2nd foliar application, post-anthesis stage, 84 DAT; All other details are same as given in foot notes of Table 1

Table 5. Effect of different treatments on main panicle- and flag leaf-related parameters of Basmati rice (Pusa Basmati-1692) at crop maturity (100 days after transplanting, DAT)

Treatment	Length (cm) of main panicle	Dry weight (g) of main panicle	Dry weight (g) of spikelets on main panicle			Number of spikelets on main panicle			Length (cm) of main flag leaf
			Total	Filled	Unfilled	Total	Filled	Unfilled	
T_1 (Control)	26.37 ± 0.29	2.86 ± 0.14	2.39 ± 0.13	2.29 ± 0.13	0.10 ± 0.01	100.84 ± 4.08	87.74 ± 4.64	13.10 ± 0.70	25.38[bc] ± 0.12
T_2	26.73 ± 0.34	2.76 ± 0.10	2.30 ± 0.10	2.18 ± 0.10	0.12 ± 0.01	100.45 ± 3.97	84.55 ± 4.13	15.91 ± 1.05	25.24[c] ± 0.39
T_3	26.67 ± 0.19	2.76 ± 0.10	2.39 ± 0.07	2.29 ± 0.07	0.10 ± 0.01	98.50 ± 0.91	85.79 ± 1.55	12.72 ± 0.70	26.61[ab] ± 0.56
T_4	26.34 ± 0.36	2.64 ± 0.16	2.36 ± 0.14	2.24 ± 0.16	0.12 ± 0.01	96.98 ± 3.80	82.87 ± 4.81	14.11 ± 1.17	25.95[abc] ± 0.30
T_5	27.19 ± 0.12	3.00 ± 0.06	2.70 ± 0.07	2.59 ± 0.07	0.11 ± 0.00	108.78 ± 2.30	94.15 ± 1.97	14.63 ± 0.89	26.93[a] ± 0.41
CD (0.05)	NS	NS	NS	NS	NS	NS	NS	NS	1.22

Details, except for samplings, are same as given in foot notes of Table 1

Likewise, studies conducted by Kumar et al. (2020a; b); Kumar et al. (2021); Tiwari et al. (2021); Attri et al. (2022) and Kumar et al. (2024) also reported that foliar applications of nano-N in combination with 75% of recommended N dose (via soil application of normal-urea) was able to give yield comparable to control. In an important study by Sikka et al. (2024), it was clearly pointed out that even the above practice (75% of recommended N dose to soil along with two foliar applications of nano-urea) can reduce yield not only in rice but also in wheat. This finding for rice matched with our findings as we also recorded a tendency of reduction in yield by 8.7% in T5 in comparison to the control (Fig. 1). Besides this, more important point is that in flooded conditions of rice cultivation or in rice-wheat cropping system there is natural growth of blue-green algae (cyanobacteria). They are capable of biological fixation of atmospheric N2 up to 19 to 28 kg of N per hectare and thereby can reduce reliance on the use of external supply of nitrogenous fertilizer or normal-urea by about 25 to 35% (Hashem, 2001). Further, azolla–anabaena symbiotic system is also known to fix around 22 to 40 kg of N per hectare in flooded conditions, especially when N is deficient in soil (Koushal et al., 2024). Lush green growth was seen in our experimental plots during the period of rice cultivation. Thus, comparable results for yields of rice in T_5 with control (T_1) can be due to by and large compensation of N being made available by blue green algae and azolla–anabaena symbiotic association rather than totally by nano-urea. These organisms besides contributing for biological N fixation also add to the general health of the soil and towards the promotion of growth of crop plants as well (Mishra et al., 2021). Furthermore, supply of N to the soil *via* rain water, as the rice crop is being grown in monsoon season, is yet another aspect that also contribute for N to the soil.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

This study showed that in comparison to control (with 100% N applied to the soil), key growth-related parameters in Basmati rice exhibit more reductions in treatments where only 50% of recommended N was applied to the soil along with two foliar applications of either normal-urea (T_2) or nano-urea (T_4). While, less reductions were recorded in treatments where 75% of recommended N was applied to the soil with two foliar applications of either normal-urea (T_3) or nano-urea (T_5). Responses obtained with foliar applications of nano-urea were at par with responses obtained with foliar applications of normal-urea, separately at 50% of recommended N dose and at 75% of recommended N dose to the soil. Plant growth and yield in control (T_1) were either superior or comparable to the treatments T_5 and T_3. This indicated that at 75% of the recommended N dose to the soil along with partial substitution of left out N (25% of recommended N dose to the soil) by foliar application of nano-urea (T_5) was comparable to foliar application of normal-urea (T_3). Results, based on this short-term study, pointed out for the possibility of saving around 25% of N by two foliar applications of nano-urea in T_5 (Supplementary Table 1). Also, possibility of saving 17% of N by two foliar applications of normal-urea in T_3 (Supplementary Table 1). But, at the same time, there was tendency of reduction in yield by 8.7% in T_5 in comparison to control with the possibility of mining of N from the soil. Thus, the proposed practice of partial substitution of normal-urea to the soil with two foliar applications of nano-urea may lead to non-sustainable rice production in short- and long-term.

It is thereby suggested that future studies must monitor for long-term responses even with newer formulation of nano-urea (nano-urea plus with a.i., 20% nano-N w/v). This also holds valid for any other nutrient based nano-formulations as well. Further, due considerations need to be given not only to specific crop but also to cropping systems, agriculture, ecology, agri-ecology, ecosystem, soil health, soil flora & fauna and environment. Lastly, other but relevant issues like; safety, toxicity and impact on human health need to be answered with respect to nano-material and its carrier (in formulation) before arriving at any recommendation for large-scale and long-term use of nano-urea.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing this manuscript.

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COMPETING INTERESTS

The authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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SUPPLEMENTARY

Supplementary Table 1. Details of treatments

Treatment	Details
T_1: Treatment 1 (Control)	Recommended dose of fertilizers (RDFs) N:P:K::120:60:40 (kg/ha) Details: The recommended dose of fertilizers (RDFs) i.e., 120 kg N/ha (260.870 kg of normal-urea), 1/3rd (40 kg of N = 86.956 Kg of normal-urea) as basal, 1/3rd (40 kg of N = 86.956 kg of normal-urea) as top-dressing at the active tillering stage and 1/3rd (40 kg of N = 86.956 kg of normal-urea) as top dressing at before-flowering stage), 60 kg P_2O_5/ha (all as basal) and 40 kg K_2O/ha (all as basal).
T_2: Treatment 2	50 % of recommended N dose + Two foliar sprays of normal-urea Details: 50 % of recommended N i.e., 60 kg N/ha (130.435 kg of normal urea), 1/3rd (20 kg of N = 43.478 kg of normal-urea) as basal, 1/3rd (20 kg of N = 43.478 kg of normal-urea) as top-dressing at the active tillering stage and 1/3rd (20 kg of N = 43.478 kg of normal-urea) as top-dressing at before-flowering stage, 60 kg P_2O_5/ha (all as basal) and 40 kg K_2O/ha (all as basal). Foliar applications of normal-urea @ 2 % (1st at 30 and 2nd at 50 days after transplanting) were given to rice crop (D/T: 17/07). Each foliar application of normal-urea (2 % solution) means 10 kg of normal-urea (4.6 kg of N) of normal-urea dissolved in 500 L of water and applied to 1 hectare of area. So, two foliar sprays provided 20.00 kg of normal-urea (9.20 kg of N) to the crop instead of 130.435 kg of normal-urea (60.00 kg N) to the soil. In this way, 110.435 kg (130.435-20.000) of less normal-urea (which is equivalent to 50.800 kg N) was given to T_2. This was equivalent to 2.454 bags of normal-urea (@ 45 kg/bag) i.e., the net amount of normal-urea which is less applied.
T_3: Treatment 3	75 % of recommended N dose + Two foliar sprays of normal-urea Details: 75 % of recommended N i.e., 90 kg N/ha (195.652 Kg of normal-urea), 1/3rd (30 kg of N = 65.217 kg of normal-urea) as basal, 1/3rd (30 kg of N = 65.217 Kg of normal-urea) as top-dressing at the active tillering stage and 1/3rd (30 kg of N = 65.217 kg of normal-urea) as top-dressing at before-flowering stage, 60 kg P_2O_5/ha (all as basal) and 40 kg K_2O/ha (all as basal). Foliar applications of normal-urea @ 2 % (1st at 30 and 2nd at 50 days after transplanting) were given to rice crop (D/T: 17/07). Each foliar application of normal-urea (2 % solution) means 10 kg of normal-urea (4.6 kg of N) of normal-urea dissolved in 500 L of water and applied to 1 hectare of area. So, two foliar sprays provided 20 kg of normal-urea (9.20 kg of N) to the crop instead of 65.217 kg of normal-urea (30.0 kg N) to the soil. In this way, 45.217 kg (65.217-20.00) of less normal-urea (which is equivalent to 20.800 kg N) was given to T_3. This was equivalent to 1.005 bag of normal-urea (@ 45 kg/bag) i.e., the net amount of normal-urea which is less applied saved.
T_4: Treatment 4	50 % of recommended N dose + Two foliar sprays of nano-urea Details: 50 % of recommended N i.e., 60 kg N/ha (130.435 kg of normal-urea), 1/3rd (20 kg of N = 43.478 kg of normal-urea) as basal, 1/3rd (20 kg of N = 43.478 kg of normal-urea) as top-dressing at active tillering stage and 1/3rd (20 kg of N = 43.478 kg of normal-urea) as top-dressing at before-flowering stage, 60 kg P_2O_5/ha (all as basal) and 40 kg K_2O/ha (all as basal). Foliar application of nano-urea liquid formulation (1st at 30 and 2nd at 50 days after transplanting) were given to rice crop (D/T: 17/07). Each foliar application of nano-urea liquid formulation [with a.i. w/v of 4 % means 4.0 g of nano-N present in 100 ml of nano-urea liquid formulation] means 50 g of nano-N (as present in 1.250 L of nano-urea liquid formulation) was dissolved in 312.5 L of water (0.016 % W/V) and applied to 1 hectare of area. So, two foliar sprays provided 100 g of nano-N as present in 2.5 L of nano-urea liquid formulation (= 217.39 g of nano-urea) to the crop instead of 130.435 kg of normal-urea (60.000 kg N) to soil. In this way, 130.217 kg (130.435-0.21739) of less normal-urea (which is equivalent to 59.900 kg N) was given to T_4. This was equivalent to 2.894 bags of normal-urea (@ 45 kg/ha) i.e., the net amount of normal-urea which is less applied.

Treatment	Details
T_5: Treatment 5	75 % of recommended N dose + Two foliar sprays of nano-urea Details: 75 % of recommended N i.e., 90 kg N/ha (195.652 kg of normal-urea), 1/3rd (30 kg of N = 65.217 kg of normal-urea) as basal, 1/3rd (30 kg of N = 65.217 kg of normal-urea) as top-dressing at active tillering stage and 1/3rd (30 kg of N = 65.217 kg of normal-urea) as top-dressing at before-flowering stage, 60 kg P_2O_5/ha (all as basal) and 40 kg K_2O/ha (all as basal). Foliar application of nano-urea liquid formulation (1st at 30 and 2nd at 50 days after transplanting) were given to rice crop (D/T: 17/07). Each foliar application of nano-urea liquid formulation [with a.i. w/v of 4 % means 4.0 g of nano-N present in 100 ml of nano-urea liquid formulation] means 50 g of nano-N (as present in 1.250 L of nano-urea liquid formulation) was dissolved in 312.5 L of water (0.016 % w/v) and applied to 1 hectare of area. So, two foliar sprays provided 100 g of nano-N as present in 2.5 L of nano-urea liquid formulation (= 217.39 g of nano-urea) to the crop instead of 65.217 kg of normal-urea (30.000 kg N) to soil. In this way, 65.000 kg (65.217-0.21739) of less normal-urea (which is equivalent to 29.900 kg N) was given to T_5. This was equivalent to 1.444 bags of normal-urea (@ 45 Kg/ha) i.e., the net amount of normal-urea which is less applied.

Supplementary Table 2. Physicochemical properties of nano-urea formulation as compiled from available literature

Physicochemical property	Specification	Reference
N content (w/v)	4% (43 g urea or 20 g N)	Written on bottle (IFFCO, 2022)
Boiling point (ºC)	100	IFFCO (2022)
Density (g cm^{-3})	1.02-1.06	IFFCO (2022)
Viscosity (cP)	9.65	Kumar et al. (2022)
	5-30*	Frank and Husted (2023); IFFCO (2022)
pH	4.6	Kumar et al. (2022)
	4.5-6.0*	Frank and Husted (2023); IFFCO (2022)
Size (nm)	42.51 (TEM); 35.0 (DLS)	Kumar et al. (2022)
	20-50* (TEM)	Frank and Husted (2023); IFFCO (2022)
	56.79 (DLS)	Sikka et al. (2025)
Zeta potential in mV (+/- scale)	40.6	Frank and Husted (2023)
	42.4	Kumar et al. (2022)
	>30*	Frank and Husted (2023); IFFCO (2022)
	− 6.70	Sikka et al. (2025)
UV-Vis Spectroscopy (λ max i.e., nm)	203–234	Sikka et al. (2025)
Organic polymer content (%)	<1%	IFFCO (2022)

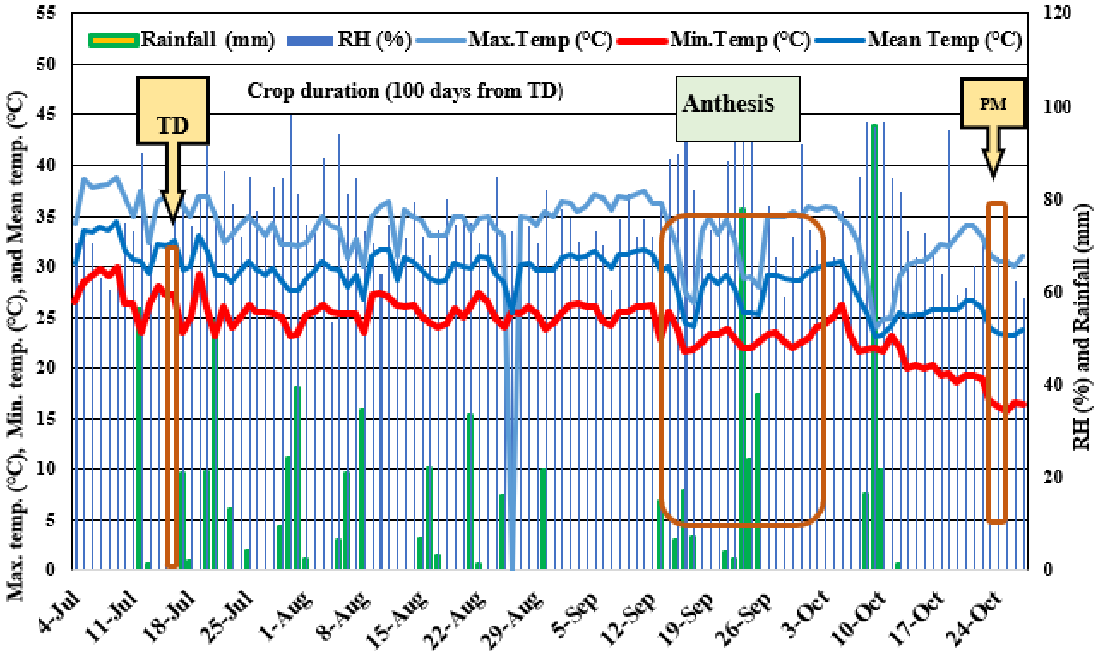
TEM: Physical size measured by transmission electron microscopy. DLS: Hydraulic particle size; measured by dynamic light scattering.; Stars (*) indicate product specifications from Indian Fertilizer Control Order and are not actual measurements.

Additional details: Nano-urea (liquid), developed by the India Farmers Fertilizer Cooperative Limited (IFFCO), contains 4% nano-N and has a shelf life of 2-year, with a zeta potential > 30 for stability. Nano-urea formulation is sprayed at 2-4 mL per litre during critical crop growth stages (first spray of nano-urea is undertaken 30 days after transplantation and second spray is done 1 week before anthesis/flowering (Kumar et al. 2021; Babu et al. 2022a; IFFCO 2022; Kantwa and Yadav, 2022).

Supplementary Table 3. Weekly weather data as prevailed during rice crop season (*kharif*) from 04/Jul to 30/Oct

MW	Period (stage)	Temperature (ºC)			Relative humidity (%)	Rainfall (mm)	Rainy days
		Maximum	Minimum	Mean			
27	Jul 04-10	37.50	28.44	32.97	68.14	0.00	0
28	Jul 11-17 (Transplanting)	36.04	26.03	31.04	73.43	11.17	3
29	Jul 18-24	34.77	25.49	30.13	80.14	12.83	4
30	Jul 25-31	33.23	24.89	29.06	83.00	11.00	4
31	Aug 01-07	33.23	25.51	29.37	78.43	4.26	3
32	Aug 08-14	34.16	26.21	30.9	71.64	4.94	1
33	Aug 15-21	33.87	24.96	29.41	74.07	9.30	4
34	Aug 22-28	34.40	25.67	29.40	74.00	2.44	2
35	Aug 29-Sep 04 (Active tillering stage)	35.49	25.39	30.44	72.93	3.09	1
36	Sep 05-11	36.87	25.43	31.15	72.50	0.00	0
37	Sep 12-18 (Anthesis stage)	32.30	23.46	27.88	82.07	6.56	4
38	Sep 19-25	31.59	22.89	27.24	84.21	20.79	5
39	Sep 26-Oct 02	35.29	22.99	29.14	73.07	0.00	0
40	Oct 03-09	32.29	23.46	27.87	80.29	16.03	2
41	Oct 10-16	28.76	21.03	24.89	77.86	3.24	2
42	Oct 17-23	32.77	18.77	25.77	69.00	0.00	0
43	Oct 23-30 (Crop maturity stage)	30.84	16.43	23.64	65.50	0.00	0
Overall average (summation)		33.73	23.94	28.84	75.31	(105.65)	(35)

MW: Meteorological week



Supplementary Fig. 1. Agro-meteorological data as recorded during cultivation period of experimental rice crop season (*kharif*)

TD: Transplanting date, PM: Physiological maturity, DAT: Days after transplanting, RH: Relative humidity, Max. temp.: Maximum temperature, Min. temp.: Minimum temperature, Mean temp.: Mean temperature

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