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Optimising nitrogen management through conjoint application of conventional and nano-urea in wheat (*Triticum aestivum*)

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ABSTRACT

The study was carried out during the winter (*rabi*) seasons of 2019–20, 2020–21 and 2021–22 at Rajasthan Agricultural Research Institute (Sri Karan Narendra Agriculture University, Jobner), Durgapura, Jaipur, Rajasthan evaluate the effect of nitrogen management through combined application of nano-urea and different levels of conventional urea on growth indices, productivity and economics of wheat (*Triticum aestivum* L.) (var. Raj 4238). The experiment was laid out in a randomised block design (RBD) with 10 treatments [T_1, Control (100% recommended doses of PKSZn + 0% RDN); T_2, T_1 + 120 kg N/ha (100% RDN); T_3, T_1 + one nano-urea spray; T_4, T_1 + two nano-urea sprays; T_5, T_1 + 50% RDN (60 kg N/ha) + one nano-urea spray; T_6, T_1 + 50% RDN (60 kg N/ha) + two nano-urea sprays; T_7, T_1 + 75% RDN (90 kg N/ha) + one spray of nano-urea; T_8, T_1 + 75% RDN (90 kg N/ha) + two sprays with nano-urea; T_9, T_1 + 100% RDN (120 kg N/ha) + one spray with nano-urea; T_{10}, T_1 + 100% RDN (120 kg N/ha) + two sprays with nano-urea] replicated three times. Over three years of experiment, it was observed that 100% RDN (120 kg N/ha) and 75% RDN (90 kg N/ha) alongwith one or two sprays of nano-urea @2.5 mL/L water significantly improved growth parameters, yield attributes and grain yield than100% RDN alone. The application of 50% RDN alongwith two sprays of nano-urea performed at par with 100% RDN alone. However, the combination of 75% RDN with two sprays of nano-urea recorded the highest benefit-cost ratio and net returns. Hence, applying 75% RDN along with two foliar sprays of nano-urea may be considered an efficient strategy to enhance wheat productivity while economising urea consumption.

Keywords: Chlorophyll content, Economics, Leaf area index, Nano-urea, Wheat yield

In the present agricultural scenario, the use of agrochemicals is steadily increasing to enhance the crop yields, although, existing agricultural practices have not proven effective in enhancing productivity of crop (Seleiman *et al.* 2019, Adnan *et al.* (2024) due to low nutrient use efficiencies and limited food supply (Guo *et al.* 2018). According to the FAI survey report (2023), the production of synthetic fertilizers on global basis accounted 213.46 Mt, while the pesticides consumption in agricultural fields is about 4 Mt (Kah *et al.* 2019). During the upcoming years, the quantity of agrochemicals is expected to increase an amount that could feed 9.6 billion people by 2050 (FAO 2017, Diatta *et al.* 2020). The previous work done indicates that the nutrient use efficiencies of three basic macronutrients, i.e. nitrogen (N), phosphorus (P), and potassium (K) are nearly 30–35%, 15–20%, and 35–40%, respectively (Husen and Iqbal 2019, Singh and Singh 2021). This indicates that even less than half of the fertilisers that are applied actually get used by crop. The other half is lost through processes like photolysis, hydrolysis, leaching, and microbial immobilisation and degradation. This might lead to many environmental problems such as air pollution, soil deterioration, water eutrophication, and groundwater contamination as well long-term agricultural sustainability (Czymmek *et al.* 2020, Eid *et al.* 2020). In addition, indiscriminate use of chemical fertilisers increases production costs and reduces returns. Judicious use of micronutrients, water soluble fertilisers, biofertilisers and biostimulants in crop production system may provide an effective solution to overcome these problems. Micronutrients also play pivotal role in increasing nutrient use efficiencies and crop yield. Application of zinc fertilisers, pre-treated with organics, increased the zinc use efficiency and reduced the fertilisers' consumption (Sahai

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et al. 2006) and positive response of boron fertilisation has also been reported in various studies (Singh *et al.* 2020). Foliar application of water-soluble nutrients was found effective in supplementing high nutrient demand at some crucial crop growth stages, correcting nutrient deficiencies in field crops and increase crop production (Singh *et al.* 2021). Application of plant growth promoting rhizobacteria as seed treatment increased yield and nutrient uptake (Sahai and Chandra 2010; 2011). Singh *et al.* (2025) reviewed and reported that biostimulants application enhanced growth parameters, yield attributing characters, yield and quality of different crops.

Wheat (*Triticum aestivum* L.), being one of the major important cereal crops, significantly contributes in fulfilling the worldwide demand of food forever increasing population, mainly in underdeveloped countries. In the year 2023-24, wheat production during the *rabi* season in India was over 113.2 mt from 31.8 mha and contributed around 37% of total food grain production (FAI 2024). Wheat productivity has increased dramatically after the green revolution, owing to the increasing use of fertilisers, particularly urea in irrigated areas. However, the indiscriminate use of chemical fertilisers had a negative impact on soil health, human health, and factor production (Spiegal *et al.* 2020, Jatav *et al.* 2022). Nutrient management is presently one of the most challenging tasks under the field management. Even though mineral fertilisers are necessary for the growth of plants, their prolonged usage poses environmental and health risks, such as surface and groundwater pollution. Nitrogen (N) plays an important role in determining crop yield. The efficient use of nitrogen in agriculture is of great importance in terms of enhancing crop yield, quality, and soil health. The efficiency of N application by plants is a major problem because 50–70% of nitrogen is wasted and causes environmental pollution (Ladha *et al.* 2005, Pujarula *et al.* 2021). Nitrogen has been identified as the most deficient critical nutrient in most of the soils and its deficiency limits growth in various plant organs, including roots, stems, leaves, flowers, and fruits (Huq *et al.* 2025). Therefore, new and innovative technologies are required to cope with the challenges of sustainable agriculture, increasing food security and conserving soil health. Nanotechnology offers the possibility of using nanoscale or nanostructured materials as controlled-release carriers to prepare 'smart fertilisers' to protect the environment and agricultural biodiversity (Singh *et al.* 2022). Novel nano-fertilisers application has an edge over conventional fertilisers as these fertilisers slowly release required nutrients as per need of plant (Sekhon 2014). In light of these points, the present study was proposed to assess the effect of the combined application of nano-urea and conventional urea on wheat growth, yield attributing characters, yield, and economics.

MATERIALS AND METHODS

The study was carried out during the winter (*rabi*) seasons of 2019–20, 2020–21 and 2021–22 at Rajasthan Agricultural Research Institute (Sri Karan Narendra Agriculture University, Jobner) (26°51′ N, 75°47′ E; at an elevation of 390 m amsl), Durgapura, Jaipur, Rajasthan. During the growing season, maximum temperatures ranged from 19.8–36.1°C, minimum temperatures from 5.8–19.0°C, with an average humidity of 66% and total rainfall of 16.6 mm. The soil at the experimental site was classified as loamy sand with good drainage. Initial soil *p*H was 8.09, electrical conductivity (0.29 dS/m), oxidisable organic carbon content was 2.40 g/kg, available N, P and K contents were 155, 25.4 and 233.0 kg/ha, respectively. Additionally, the DTPA-extractable micronutrient contents were 0.56 mg/kg zinc, 4.30 mg/kg iron, 2.12 mg/kg maganese, and 0.22 mg/kg copper. The experiments were laid out in a randomised block design (RBD) with ten treatments and three replications.

The treatments taken for the experiment were, T_1, Control (100% recommended doses of PKSZn + 0% RDN); T_2, T_1 + 120 kg N/ha (100% RDN); T_3, T_1 + one nano-urea spray; T_4, T_1 + two nano-urea sprays; T_5, T_1 + 50% RDN (60 kg N/ha) + one nano-urea spray; T_6, T_1 + 50% RDN (60 kg N/ha) + two nano-urea sprays; T_7, T_1 + 75% RDN (90 kg N/ha) + one spray of nano-urea; T_8, T_1 + 75% RDN (90 kg N/ha) + two sprays with nano-urea; T_9, T_1 + 100% RDN (120 kg N/ha) + one spray with nano-urea; and T_{10}, T_1 + 100% RDN (120 kg N/ha) + two sprays with nano-urea. Field preparation included one deep ploughing by mouldboard plough followed by two cross harrowing and planking. The wheat variety RAJ-4238 was sown during 3rd week of November with seed rate of 100 kg/ha. A uniform recommended dose of 20 kg P_2O_5/ha, 30 kg K_2O/ha, 20 kg S/ha and 5 kg Zn/ha were applied as basal by using di-ammonium phosphate (18% N and 46% P_2O_5), muriate of potash (60% K_2O), bentonite sulphur (90% S) and zinc sulphate monohydrate (33% Zn), respectively in all treatments whereas nitrogen through conventional urea (46% N) was applied as per treatments. Nitrogen fertiliser was applied in three splits: 50% at sowing, 25% at 25–30 days after sowing (DAS) and the remaining 25% at 50–55 DAS. Nano-urea was applied at 2.5 mL/L of water using a knapsack sprayer to ensure uniform foliar coverage during the tillering stage (35–40 DAS) and the jointing stage (55–60 DAS). The first foliar spray was applied with 300 L of water/ha, while during the second spray 400 L water/ha was used. The crops were cultivated following standard agronomic practices and protocols prevailing in the location.

Plant measurements and analysis: Plant height was measured by standard meter scale from the base to the tip of the plant at 45, 60, and 90 DAS and averaging the height of 10 randomly selected plants from each plot. Leaf area was measured by separating leaves of five randomly selected plants from the stem and cleaned them with deionized water and then dried with tissue paper. The area of fresh green leaves for each treatment was measured by using a leaf area meter (Systronics-India) and was expressed in cm^2/plant. Leaf area index (LAI) was calculated at 45, 60, and 90 DAS using the formula as suggested by Evans (1972).

Chlorophyll and carotenoid analysis was done at 45, 60 and 90 DAS in fresh matter of leaves determined spectrophotometrically in dimetylsulphoxide extract. Fifty mg fresh leaf sample with dimetylsulphoxide was taken in a glass tube and kept for 4 h at 65ºC and cooled at room temperature (Hiscox and Israelstam 1979). Absorbance was recorded at three wavelengths 480 nm, 645 nm and 663 nm using Spectrophotometer (Systronics-India). Chlorophyll a, chlorophyll b, Total chlorophyll and carotenoids were calculated by using following equations:

$$\text{Chlorophyll a (mg/g)}=(12.7 \times A663–2.69 \times A645) \times V/(W \times 1000)$$

$$\text{Chlorophyll b (mg/g)}=(22.9 \times A645-4.68\times A663) \times V/(W\times 1000)$$

$$\text{Total chlorophyll (mg/g)}=(20.2 \times A645+8.02 \times A663) \times V/(W \times 1000)$$

$$\text{Carotenoid } (\mu g/g)=(A480+0.114 \times A663-0.638 \times A645)\times V/W$$

Yield attributing characters and yield: At the time of maturity after leaving two border rows on either side of the plots, crop was harvested manually with sickle and sun dried for three days in the field and then biological yield was recorded. After threshing, the grain yield was recorded. The straw yield was calculated by subtracting the grain yield from biological yield of individual plots.

Economics and crop production efficiency: The net return of wheat cultivation under various treatments was calculated by subtracting the cost of cultivation from gross returns of respective treatments and benefit-cost ratio was calculated. The cost of cultivation for each treatment was calculated as a sum of expenditures incurred on sowing to threshing of crop. For computation of cash inputs, market prices for inputs were considered. Gross Monetary Return (GMR) was estimated by using minimum support prices (MSP) announced by the Government of India for each year.

$$\text{Gross monetory return, GMR (₹/ha)} = \text{Grain yield (kg/ha)} \times \text{Selling price (₹/kg)}$$

$$\text{Net monetory return, NMR (₹/ha)} = \text{GMR (₹/ha)} - \text{Cost of Cultivation (₹/ha)}$$

$$\text{B:C Ratio} = \frac{\text{NMR (₹/ha)}}{\text{Cost of cultivation (₹/ha)}}$$

The data collected for different variables were analysed using OPSTAT statistical software (Sheoran *et al.* 1998) followed by ANOVA procedure. Treatment significance was tested using the variance ratio (‘F’ test). The standard error of mean (SEM ±) was determined for each parameter. Where the ‘F’ test indicated significant differences among treatment means, the least significant difference (LSD) test at p=0.05 was used for comparison. The economic benefits of all treatments were calculated by including input and output costs across the study years.

RESULTS AND DISCUSSION

Plant growth parameters: Pooled analysis over three consecutive years indicated that foliar application of nano-urea exerted a statistically significant effect on wheat growth attributes, particularly plant height and leaf area index (LAI) (Table 1). Application of 100% recommended dose of nitrogen (RDN) in conjunction with two nano-urea sprays (T_{10}) consistently recorded the greatest plant height, followed by T_9, at all observed growth stages (45, 60, and 90 DAS), indicating enhanced vegetative growth under combined nitrogen management. A similar trend was observed for LAI, with T_{10} registering the highest values, closely followed by T_9. At 60 and 90 DAS, two foliar applications of nano-urea produced significantly higher LAI than a single spray, even when conjoint application with reduced rates of conventional urea, suggesting improved canopy development and sustained leaf expansion. The decline in LAI observed at 90 DAS across treatments compared to 60 DAS can be attributed to progressive leaf senescence, reduced assimilatory surface area, and remobilisation of nutrients toward reproductive sinks during later phenophases.

With respect to photosynthetic pigments, application of 100% RDN in conjunction with two nano-urea sprays resulted in the highest chlorophyll a, chlorophyll b, total chlorophyll, and carotenoid contents at 45 DAS. However, at 60 and 90 DAS, treatment T_8 exhibited superior pigment concentrations (Table 2, Fig. 1), indicating a sustained physiological advantage during mid and late growth stages. The enhanced pigment content under nano-urea treatments may be attributed to its controlled and prolonged nitrogen release pattern (approximately 40–50 days), which contrasts with the rapid hydrolysis and transient availability of nitrogen from conventional urea, often associated with lower nitrogen use efficiency (NUE) due to volatilisation and leaching losses (Upadhyay *et al.* 2023). Sustained nitrogen availability likely promoted continuous chlorophyll biosynthesis, delayed leaf senescence, and maintained higher photosynthetic efficiency, thereby improving overall

Table 1 Combined effect of conventional and nano-urea on plant height and leaf area index at different growth stages of wheat (Pooled data of 3 years)

Treatments	Plant height (cm)			Leaf area index		
	45 DAS	60 DAS	90 DAS	45 DAS	60 DAS	90 DAS
T_1	23.3	42.5	64.2	0.83	1.23	1.17
T_2	34.6	57.5	86.7	2.50	3.63	3.00
T_3	25.8	45.9	69.2	1.03	1.67	1.60
T_4	27.2	47.7	72.0	1.27	2.03	2.00
T_5	31.5	53.4	80.6	2.13	2.77	2.87
T_6	32.2	54.3	81.9	2.93	3.77	4.10
T_7	34.1	57.1	85.7	2.77	4.60	3.63
T_8	34.6	57.8	86.7	3.50	4.83	4.53
T_9	35.6	59.1	88.7	3.53	4.67	3.77
T_{10}	35.9	59.6	89.5	3.77	4.83	4.50
CD (p=0.05)	3.7	4.9	7.4	0.59	0.47	0.46

Treatment details are given under Materials and Methods. DAS, Days after sowing.

Table 2 Combined effect of conventional and nano-urea on chlorophyll a and b content and carotenoids at various growth stages of wheat (Pooled data of 3 years)

Treatments	Chlorophyll a (mg/g fresh weight)			Chlorophyll b (mg/g fresh weight)			Carotenoids (µg/g fresh weight)		
	45 DAS	60 DAS	90 DAS	45 DAS	60 DAS	90 DAS	45 DAS	60 DAS	90 DAS
T_1	2.04	3.18	1.25	0.34	0.55	0.17	151	261	123
T_2	2.55	4.44	1.64	0.62	1.07	0.30	189	353	145
T_3	2.07	3.43	1.28	0.40	0.66	0.29	154	292	129
T_4	2.07	3.59	1.39	0.41	0.72	0.29	155	305	135
T_5	2.21	3.98	1.60	0.48	0.86	0.33	166	323	143
T_6	2.22	4.16	1.69	0.47	0.90	0.34	165	342	152
T_7	2.28	4.52	1.81	0.53	0.96	0.37	174	366	163
T_8	2.29	4.64	1.95	0.52	0.97	0.34	176	389	173
T_9	2.58	4.57	1.86	0.62	0.93	0.35	193	375	166
T_{10}	2.61	4.36	1.86	0.63	0.89	0.34	192	354	162
CD (p=0.05)	0.25	0.48	0.31	0.18	NS	NS	20	NS	NS

DAS, Days after sowing. Treatment details are given under Materials and Methods.

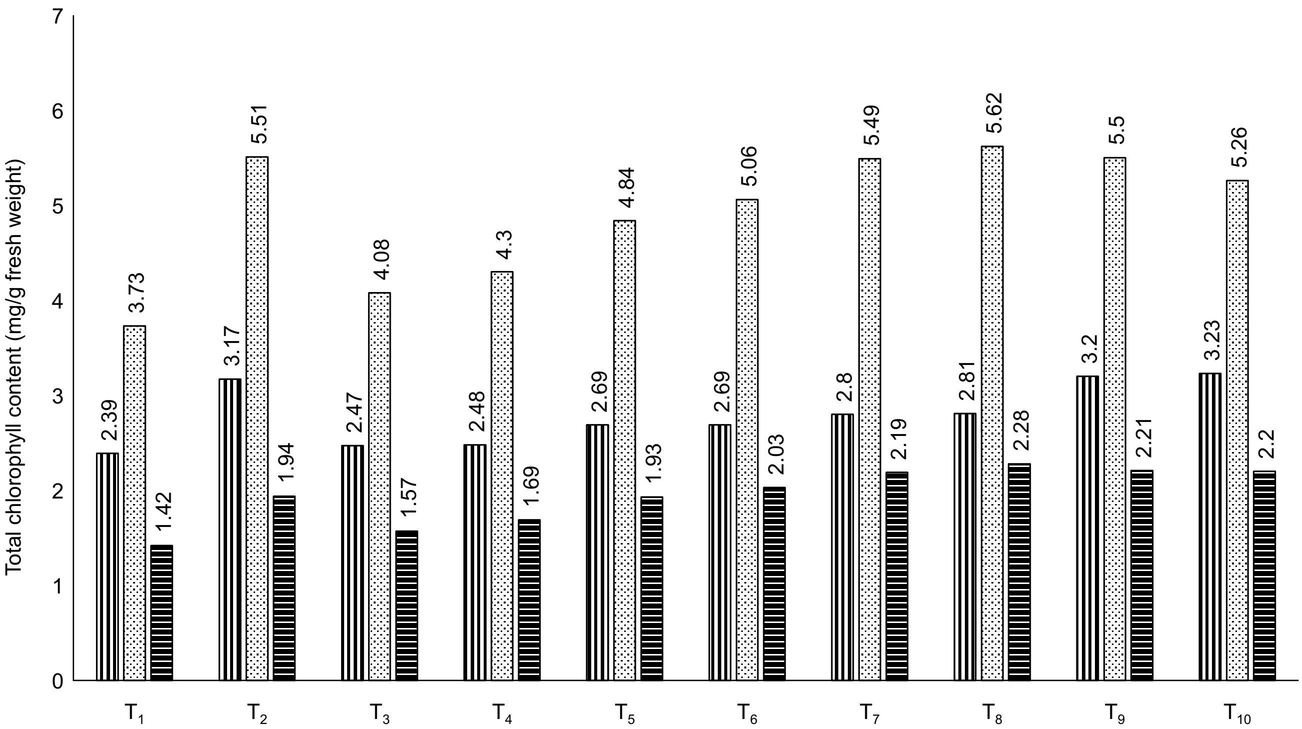

Fig. 1 Combined effect of conventional and nano-urea on total chlorophyll content at different stages (Pooled data of 3 years). Treatment details are given under Materials and Methods.

NUE (Huq *et al.* 2025). Comparable results were reported by Sharma *et al.* (2022), who documented increased dry matter accumulation and chlorophyll concentration in pearl millet following foliar nano-urea application integrated with varying levels of soil-applied nitrogen.

Yield attributing characters: Based on pooled data from three consecutive years, the combined application of conventional urea with foliar nano-urea significantly improved yield-attributing characters of wheat (Table 3). Treatment T_8 recorded the highest number of tillers/m, grains/spike, spike length, and test weight, followed by T_9. All yield-attributing parameters under T_8 were significantly superior to T_2, indicating the advantage of conjoint application of nano-urea with conventional nitrogen fertilisation.

Kumar *et al.* (2024) also reported that nano-urea sustains wheat growth even under reduced rates of conventional urea. The enhanced performance may be attributed to the

Table 3 Combined effect of conventional and nano-urea on yield attributing characters of wheat (Pooled data of 3 years)

Treatments	Total tillers /m^2	Spike /m^2	Spike length (cm)	Grains/ spike	1000-seed weight (g)
T_1	255	249	8.35	37.4	39.2
T_2	374	368	8.82	42.4	42.2
T_3	283	277	8.50	39.3	38.9
T_4	295	292	8.61	40.2	40.4
T_5	361	353	8.89	41.7	41.8
T_6	382	380	8.98	42.1	41.9
T_7	405	403	9.00	43.1	44.0
T_8	419	417	9.13	44.0	44.9
T_9	420	408	9.02	42.4	43.8
T_{10}	406	391	8.98	42.2	42.5
CD (p=0.05)	15	15	0.33	2.4	1.5

Treatment details are given under Materials and Methods.

nano-scale particle size and controlled-release behaviour of nano-urea, which ensure a sustained nitrogen supply over a longer duration. Prolonged nitrogen availability likely promotes continuous vegetative growth and enhances the formation of effective tillers.

Treatments T_5 and T_6 were statistically at par ($p<0.05$) with T_2 for all yield-attributing characters, suggesting that partial substitution with nano-urea maintained yield components comparable to recommended conventional nitrogen application. In contrast, T_1 (no nitrogen application) consistently recorded the lowest values across all years, highlighting the essential role of nitrogen in determining wheat productivity.

Nano-urea is characterised by controlled nutrient release, enhanced target specificity, and improved nutrient use efficiency, which collectively contribute to higher grain yield (Kumar *et al.* 2023). According to Gastal and Lemaire (2002), the critical nitrogen concentration required to achieve maximum growth rate depends on plant metabolic activity. Nanofertilisers have been reported to enhance metabolic processes (Kalwani *et al.* 2022), potentially improving nitrogen assimilation and biomass accumulation.

At lower concentrations, nano fertilisers have been shown to improve wheat growth and yield parameters. Due to their nano-scale size, these particles can be readily absorbed through leaf epidermal structures and translocated via the phloem to actively growing tissues (Abdel-Aziz *et al.* 2016). In nano-urea formulations, nitrogen molecules are polymer-coated and dispersed as nano-sized particles, preventing agglomeration in aqueous solution. In contrast, conventional urea molecules tend to aggregate when dissolved. The non-agglomerated nano particles can penetrate through stomata and cuticular pathways and are gradually released within plant tissues as the polymer coating degrades (Lv *et al.* 2019). This stepwise release ensures sustained nitrogen availability for chlorophyll synthesis, amino acid formation, and other metabolic functions, thereby enhancing yield attributes.

Yield: Foliar application of nano-urea significantly influenced wheat yield (Table 4). Based on pooled analysis, treatment T_8 produced the highest grain yield (5397 kg/ha), which was significantly greater ($p<0.05$) than T_2, indicating superior nitrogen use efficiency under integrated nano and conventional fertilisation. The highest straw yield (7,844 kg/ha) was recorded under T_{10}. Grain yield in T_8 was 14.7% higher than T_2, whereas straw yield in T_{10} increased by 3.3% over T_2.

The enhanced grain yield under T_8 may be attributed to synchronised nitrogen supply through foliar nano-urea, improving nitrogen assimilation during critical growth stages. Nano-urea particles, owing to their high surface area-to-volume ratio and controlled-release behaviour, facilitate gradual NH_4^+ availability and improved leaf

Table 4 Combined effect of conventional and nano-urea on yields and harvest index of wheat

Treatments	Biological yield (kg /ha)			Grain yield (kg/ha)			Straw yield (kg/ha)			Harvest index (%)		
	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22
T_1	9,343	9,092	8,727	3,575	3,455	3,368	5,768	5,637	5,359	38.3	38.0	38.6
T_2	12,046	11,365	10,988	4,817	4,544	4,610	7,229	6,821	6,378	40.0	40.0	42.0
T_3	9,849	9,481	8,990	3,793	3,615	3,567	6,056	5,867	5,423	38.5	38.1	39.7
T_4	9,931	9,735	9,281	3,901	3,787	3,782	6,030	5,948	5,499	39.2	38.8	40.7
T_5	11,898	11,467	10,367	4,761	4,539	4,321	7,137	6,928	6,046	40.0	39.6	41.7
T_6	12,004	11,524	10,686	4,834	4,574	4,572	7,171	6,950	6,114	40.3	39.7	43.0
T_7	12,657	11,973	11,657	5,191	4,921	4,882	7,466	7,052	6,775	41.0	41.1	41.8
T_8	13,189	12,417	12,159	5,545	5,249	5,231	7,644	7,168	6,928	42.0	42.3	43.0
T_9	13,100	12,666	12,403	5,253	4,972	5,000	7,847	7,695	7,403	40.1	39.3	40.3
T_{10}	12,982	12,597	12,438	5,050	4,776	4,894	7,932	7,821	7,544	38.9	37.9	39.3
CD (p=0.05)				287	344	350	367	405	660	1.4	2.4	NS

Treatment details are given under Materials and Methods.

absorption efficiency (Millan *et al.* 2008). This sustained nitrogen availability likely enhanced chlorophyll content, photosynthetic rate, and assimilate partitioning toward reproductive organs, resulting in greater dry matter accumulation and grain formation. Similar synergistic effects of nano fertilisers with conventional fertilisers have been reported in wheat, maize, and rice, where improved nutrient uptake and translocation enhanced productivity (Jyothi and Hebsur 2017, Khalil *et al.* 2019).

Although T_{10} recorded the highest straw yield, its comparatively lower grain yield than T_8 suggests a shift toward excessive vegetative growth under higher nitrogen availability. Elevated nitrogen levels stimulate tillering and canopy expansion, which may increase biomass but reduce harvest index due to suboptimal assimilate partitioning toward grains. Gastal and Lemaire (2002) reported that excessive nitrogen promotes leaf area development more than photosynthetic efficiency per unit area. Similarly, higher nitrogen doses can induce luxuriant vegetative growth, reduced light penetration within the canopy, and increased lodging susceptibility, ultimately limiting grain yield (Tripathi *et al.* 2004). Therefore, balanced nitrogen supply through nano supplementation appears critical for optimising source-sink relationships.

Treatments T_5 and T_6 were statistically at par with T_2, indicating that partial substitution of recommended nitrogen with nano-urea can maintain yield without significant reduction. Previous studies have demonstrated that reducing RDN by 50% and supplementing with nano-urea sprays sustains or improves grain yield by enhancing nitrogen use efficiency and minimising losses through volatilisation and leaching (Kumar *et al.* 2023, Kumar *et al.* 2024). The improved performance under nano supplementation may also be linked to enhanced enzymatic activity involved in nitrogen metabolism, promoting better protein synthesis and grain filling.

Application of nano-urea alone (T_4) significantly increased grain and biological yield compared to the absolute control (T_1), confirming its effectiveness as a foliar nitrogen source. However, yields under T_3 and T_4 remained lower than T_2, suggesting that nano-urea acts more effectively as a supplement rather than a complete substitute for basal nitrogen application. Foliar nutrition improves leaf nutrient status, carbon balance, and photosynthetic capacity (Gosavi *et al.* 2017), but adequate soil nitrogen remains essential to sustain early vegetative growth and root development.

Overall, the findings demonstrate that integrating nano-urea with conventional nitrogen fertilisation enhances nitrogen use efficiency, optimizes source–sink dynamics, and improves grain yield. Excess nitrogen, however, favours vegetative biomass accumulation over reproductive output, emphasising the importance of balanced nutrient management. These results corroborate earlier reports showing increased wheat yield when 50% RDN was supplemented with nano-urea (Gangwar *et al.* 2022, Midde *et al.* 2022, Samanta *et al.* 2022).

Economics: Foliar application of nano-urea significantly influenced the economic returns of wheat cultivation (Table 5). Treatment T_8 (75% RDN + two foliar sprays of nano-urea) recorded the highest net return (₹63,998/ha) and benefit–cost (B:C) ratio (1.15), which were significantly higher than T_2 (100% RDN). Compared to T_2, T_8 increased net return by 25.6% and B:C ratio by 23.0%, indicating improved economic efficiency through partial substitution of conventional nitrogen with nano-urea.

Net return and B:C ratio under T_5 and T_6 were statistically at par with T_2, suggesting that reduced nitrogen levels supplemented with nano-urea can sustain profitability comparable to full recommended nitrogen application. Treatment T_4 (nano-urea sprays without basal nitrogen) recorded significantly higher net return and B:C ratio than the absolute control (T_1), confirming the positive economic contribution of foliar nano nitrogen. The higher profitability in nano-urea-treated plots can be attributed to enhanced grain yield coupled with reduced input cost due to lower conventional urea usage. Similar improvements in economic returns with nano nitrogen supplementation have been reported by Kumar *et al.* (2020) and Choudhary *et al.* (2022).

Based on three years of experimentation, it can be concluded that application of two foliar sprays of nano-urea at tillering and jointing stages combined with 75% recommended dose of nitrogen (RDN) increased grain yield by 14.7% and net returns by 25.6% over 100% RDN alone. The results indicated that nano-urea improves nitrogen use efficiency and economic returns by optimising nutrient supply during critical growth stages while reducing dependency on conventional nitrogen fertilisers. However, nano-urea alone was not sufficient to achieve maximum productivity, highlighting that it functions more effectively as a supplement rather than a complete replacement for soil-applied nitrogen. Therefore, conjoint application nano-

Table 5 Combined effect of conventional and nano-urea on economics of wheat (Pooled data of 3 years)

Treatments	Net return (₹/ha)	B:C ratio	Economic efficiency (₹/ha/day)	Productivity efficiency (kg/ha/day)
T_1	26,885	0.51	215	26.7
T_2	51,197	0.95	374	33.9
T_3	30,325	0.57	236	27.7
T_4	32,836	0.61	251	28.8
T_5	48,631	0.90	376	34.1
T_6	50,378	0.91	376	34.4
T_7	57,966	1.06	429	36.2
T_8	63,998	1.15	470	39.0
T_9	60,079	1.09	436	36.8
T_{10}	56,306	1.01	402	34.9
CD (p=0.05)	5,111	0.10	46	1.1

Treatment details are given under Materials and Methods.

urea with reduced doses of conventional urea presents a promising strategy for enhancing crop productivity, improving farmers' income, reducing fertiliser input costs, and promoting sustainable nutrient management under semi-arid conditions.

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