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RESEARCH ARTICLE

Impact of conventional urea and nano-urea with herbicide mixtures on wheat growth, weed suppression and nitrogen use efficiency

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Abstract

Conventional urea-based nitrogen management is often inefficient and promotes initial weed proliferation, yet the potential of nano urea to overcome these limitations under integrated weed management remains insufficiently explored. Therefore, the study hypothesises that integrating foliar-applied nano urea with reduced basal dose of conventional urea and herbicide mixtures may improve nitrogen allocation in favour of wheat rather than weeds, thereby enhancing productivity and nitrogen use efficiency compared to conventional urea-based management. Considering this, an experiment was undertaken during 2021–2022 at ICAR-Indian Agricultural Research Institute , New Delhi, using a split-plot design (SPD) on the impact of nano urea-based nitrogen management and new herbicide mixtures on wheat growth, productivity, profitability and nitrogen use efficiency. Four nitrogen management options in the main plots were tested: control (no nitrogen), 100 % recommended dose of nitrogen (RDN), 50 % RDN + 2 nano urea sprays (40 and 60 days after sowing – DAS) and 75 % RDN + 1 nano urea spray (60 DAS). Simultaneously, 4 weed management treatments in subplots included ready mix and tank mix herbicides, weed-free and un-weeded checks. Results revealed that 100 % RDN treatment significantly outperformed nano urea-based treatments in weed suppression, crop growth, profitability and nitrogen use efficiency, with achieving over 30 % higher productivity compared to 50 % RDN + 2 nano urea sprays along with herbicide mixtures. Various nitrogen use efficiency indicators showed that agronomic efficiency and apparent recovery efficiency both were highest in 100 % RDN through conventional urea-based treatment compared to nano urea-based treatments. However, partial factor productivity and partial nutrient balance were higher in nano urea-based treatments over conventional urea-based treatment.

Keywords: herbicide mixture; nano urea; nitrogen use efficiency; weed suppression; wheat productivity

Introduction

Wheat (*Triticum aestivum L.*; 2n = 6x = 42), being the cornerstone of global agriculture, serves as a primary source of sustenance for billions of people. Initially originated at South-West Asian region, later it became one of the most important staple crops of world. In India, it is grown in more than 30 million ha area with a production of 115.43 million tonnes (1). In the face of mounting population pressures and the necessity for increased food production, the imperative to augment wheat yields while upholding environmental sustainability becomes more pressing than ever before. Wheat, however, is besieged by a multitude of production challenges, including poor nutrient use efficiency (2), weeds (3), resource degradation (4), heat stress and climate induced yield variability (5–6), rising cost of cultivation (7), necessitating innovative strategies for sustaining its cultivation. Among these, poor nitrogen use efficiency and weed infestations pose a persistent and detrimental challenge. Weeds have a competitive advantage over crops in nitrogen absorption and the excessive application of basal nitrogen via conventional urea in the soil often inadvertently promotes initial weed growth and results in poor nutrient use efficiency (8). This understanding highlights the importance of supplying nitrogen exclusively to crops in a targeted manner, potentially enabling crops to outcompete weeds through their robust and healthy growth. To achieve this objective while preserving environmental sustainability, efficient nutrient management and weed control are imperative (9).

Traditional approaches to nitrogen management involve soil application of conventional urea, the most widely used nitrogen fertiliser. However, conventional urea applications are associated with several problems, including poor nutrient use efficiency and environmental pollution due to nitrogen leaching, volatilisation and denitrification losses (10). As a consequence, it has become increasingly important to explore alternative nutrient management strategies that can enhance wheat production while mitigating the environmental consequences of conventional urea use. Given these concerns, there is a growing focus on nano-formulated nitrogenous fertiliser materials as a solution to enhance nitrogen use efficiency (NUE) and reduce losses, ultimately promoting environmental and economic sustainability (11, 12). Nano fertilisers, characterised by their smaller particle size and improved efficiency are required in smaller quantities compared to conventional fertilisers, which reduces waste and supports environmental and economic sustainability (13). They have the potential to enhance productivity and overcome yield limitations, offering a promising path toward agricultural progress. In this direction, nano urea, can be a potential option to address the limitations of conventional urea. By leveraging nanoscale technologies, nano urea aims to provide a more efficient and targeted approach of nutrient delivery. Foliar application of nano urea can potentially reduce nitrogen losses, enhance nutrient use efficiency and lower the environmental impact associated with conventional urea applications (14). While this innovation holds great promise for a ground breaking development in future, its performance in terms of wheat growth, yield, nutrient content and nutrient use efficiency remains an important subject of investigation.

Additionally, as the importance of herbicide mixture application is increasing day by day, how it can be complemented with optimised nitrogen management, particularly encompassing new generation fertilisers like nano urea, is a matter of investigation. The unique proposition in this research emerges from the confluence of these thoughts. The potential benefits of nano urea in optimizing nutrient management strategies and its role in complementing herbicide mixtures in wheat are yet to be fully understood, particularly in terms of their effects on growth, yield, nutrient content and nutrient use efficiency of wheat. Building on these considerations, we hypothesised that substituting 25 % of recommended dose of nitrogen (RDN) with foliar nano urea spray combined with herbicide mixtures would maintain wheat yield and NUE while reducing weed competition. To test this hypothesis, we conducted an experiment to evaluate whether the integration of nano urea based nitrogen management and herbicide mixtures effectively manage weeds and improves the productivity, profitability and nitrogen use efficiency of wheat.

Materials and Methods

Experimental site and climate

The experimental study was undertaken during 2021–2022 at the ICAR–Indian Agricultural Research Institute (IARI), New Delhi (28°38′ N, 77°10′ E; 228.6 m amsl).This semi-arid, sub-tropical region experiences an annual rainfall of 650 to 710 mm and an average annual temperature of 24.2 °C. During the growing season, total rainfall was 181.5 mm, peaking in the second week of January. The average temperature during the growing season was 18.6 °C, with the highest and lowest temperatures recorded at harvest and the last week of January respectively (Fig. 1). The soil, classified as Inceptisol, has a sandy loam texture with 58.6 % sand, 22.8 % silt and 18.6 % clay. The upper 0–15 cm layer has a bulk density of 1.52 g cm^{-3}, 0.41 % oxidizable organic carbon and this layer contains 0.41 % of oxidizable organic carbon, along with 221.38 kg ha^{-1} of available nitrogen (N), 12.61 kg ha^{-1} of available phosphorus (P) and 241.11 kg ha^{-1} of available potassium (K).

Experimental details

The experiment followed a split-plot design (SPD) and comprised 4 main plots for nitrogen management treatments and 4 subplots for weed management treatments, replicated thrice (Supplementary Fig. 1). The primary plot (18 × 4 m) treatments were-N_1: control (no nitrogen application); N_2: 100 % RDN (120 kg N ha^{-1}, with half applied at the basal stage, one-fourth at crown root initiation (CRI) and the remaining one-fourth at maximum tillering); N_3: 50 % RDN (half at the basal stage and half at CRI) with 2 applications of nano urea spray (NUS) at 40 and 60 Days after sowing (DAS) and N_4: 75 % RDN (half at basal and half at CRI) with one NUS application at 60 DAS. Simultaneously, in sub plot (4 x 4 m) the weed management treatments included -W_1: application of a premixed combination of sulfosulfuron and metsulfuron methyl at 30 + 2 g active ingredient (a.i.) ha^{-1} (equivalent to 40 g ha^{-1}product basis) at 30 DAS;, W_2: tank mix of clodinafop-propargyl at 60 g a.i. ha^{-1} and carfentrazone-ethyl at 20 g a.i. ha^{-1}at 30 DAS; W_3: weed-free control group and W_4: unweeded control group.

Product details

In this research, we employed a liquid nano urea formulation developed by the Indian Farmers Fertilizer Cooperative Limited (IFFCO). This formulation comprised 4 % nitrogen per unit volume and is recommended to be applied at a rate of 4.0 mL L^{-1} of water (15–17). To cover or spray an area of one hectare, it is necessary to mix 1250 mL of nano urea with 312 L of water. This nano urea boasts particle sizes ranging from 20–50 nm, offering a remarkably larger surface area (over 10000 times greater than a 1 mm urea prill) and a higher particle count (55000 nitrogen particles compared to a 1 mm urea prill) per unit area compared to conventional urea (15–17). For

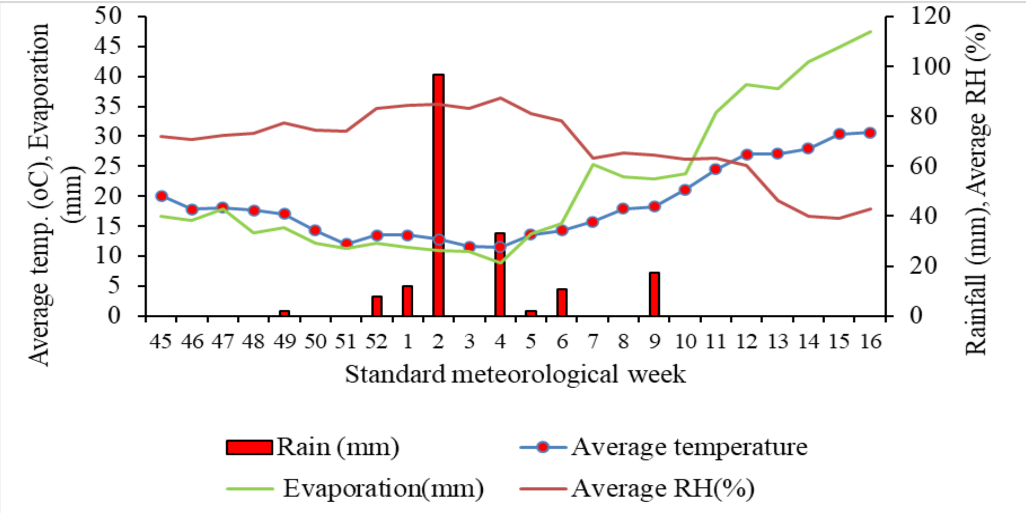

Fig. 1. Average weather during the experimental period.

more detailed information, please consult IFFCO's official website at nanourea.in.

Agronomic management

The wheat variety used in the experiment was 'HD 2967' (duration of 140–145 days). Six irrigations were administered and phosphorus (60 kg P_2O_5) and potassium (60 kg K_2O) were applied uniformly before sowing as single super phosphate and muriate of potash respectively. Nitrogen application varied based on treatments. Similarly, herbicide mixtures were applied at 30 DAS, as per the treatments. The agronomic practices were consistent across treatments, ensuring uniformity. For the weed-free check treatment (W_3), repeated manual weeding was performed to maintain a completely weed-free condition throughout the crop growth period. In contrast, for the unweeded check (W_4), no measures were taken to control weed growth.

Weed sampling, measurement and calculation of various Indices

Weed data was collected at three time points (40, 80 DAS and at harvest). To collect weed data, a 50 x 50 cm quadrat was randomly positioned in 3 locations within each subplot. Weed samples were first air-dried and then oven-dried and expressed in g/m^2 (18). To ascertain the actual dominance of weed species, the summed dominance ratio (SDR) was computed (19).

Biometric observations

Plant height was systematically measured at designated intervals (40 DAS, 80 DAS and harvest). Five plants randomly chosen from the middle row of each plot were marked for height assessment and their average height, calculated from ground level to the tip of the highest part was expressed in centimetres (cm) (20). For evaluating dry matter accumulation, destructive sampling was executed on the third row of each plot. Two random spots within this row were selected for collecting plant samples, air-dried and followed by oven drying at 65 °C for 5–7 days. The resulting dry weight was then quantified and expressed in grams per square meter (g m^{-2}) (20). Tiller count, performed at 40 DAS, 80 DAS and harvest, involved counting tillers from 2 spots (1 m row length) within the middle rows of each plot, expressed as the number of tillers per square metre (m^2) (20). In determining the leaf area index (LAI), the third row from each plot facilitated leaf area measurement. Leaf blades were isolated from the leaf sheath and leaf area was assessed at 40 DAS and 80 DAS using a leaf area meter (LI COR-3100) (20). For flag leaf, randomly selected 2 spot from the middle of each plot. The flag leaves from 5 consecutive tillers were collected and their leaf area, dry weight and SPAD value observations were taken.

Analysis of nutrient concentration in wheat

Nitrogen, phosphorus and potassium concentrations in wheat straw and grain at harvest were determined using standard methods (21).

Nitrogen use efficiency indices in wheat

Various nitrogen use efficiency were calculated, viz., agronomic efficiency, apparent recovery efficiency, partial nutrient balance and partial factor productivity of nitrogen using the standard formulas (22, 23).

Economic analysis

The cost of each input and the price of the outputs are detailed in Supplementary Table 1. Based on this, the net benefit: cost was calculated.

Statistical analysis

Statistical analyses were conducted using the general linear model (GLM) approach with SAS 9.3 software. The split-plot experimental design was verified through an analysis of variance (ANOVA). Standard error of means (SEm±) and Fisher's least significant difference (LSD) at a 5 % level of significance were calculated for each treatment. Square root transformations were applied to improve homoscedasticity in weed density and dry weight data.

Results

Effect on weeds

According to the SDR (Fig. 2) calculated from the naturally occurring weed species in the unweeded nitrogen control plot, it was observed that broad-leaved weeds (BLW) exhibited higher dominance compared to grasses and sedges throughout the experimental period. *Melilotus indica* (L.) All. stood out as the most dominant weed, consistently showing the highest SDR values at 40 DAS, 80 DAS and during harvest. Following closely was *Cyperus rotundus* L., while *Spergula arvensis* L. exhibited the least dominance among all the weeds studied.

Regarding the weed density and weed dry weight in main plot treatments, 100 % RDN application (N_2) exhibited stronger weed suppression with significantly lower weed density and dry weight ($p < 0.05$) than both the nano urea-based treatment and the nitrogen

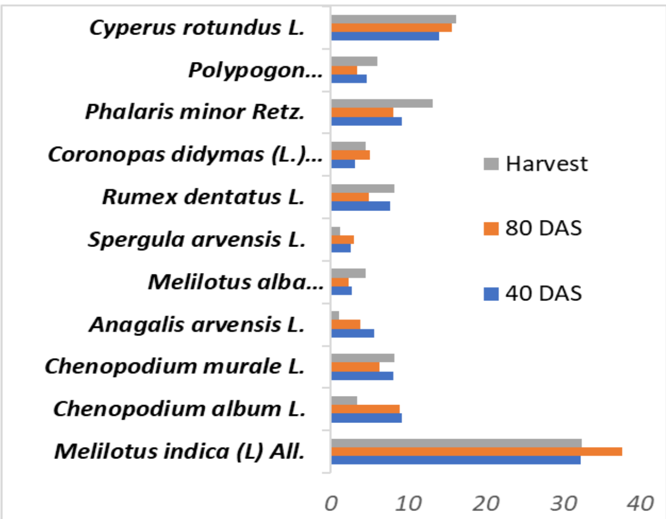

Fig. 2. SDR of naturally infested weed species in the experiment.

control across all observation intervals (Table 1). At 80 DAS, 100 % RDN reduced weed density and dry weight by 25.0 % and 28.5 % respectively, compared to 50 % RDN + 2 nano urea sprays. At harvest, the reductions further increased to 37.5 % for weed density and 22.7 % for weed dry weight. Furthermore, the tank mix of clodinafop + carfentrazone-ethyl exhibited significantly superior weed control ($p < 0.05$), reducing weed density and dry weight at harvest by 25 % and 7.3 % respectively, compared to the ready-mix formulation of sulfosulfuron + metsulfuron-methyl.

Effect on plant growth parameters

Plant height was maximum in 100 % RDN (N_2) treatment at 40, 80 DAS and harvest (35.92 cm, 88.49 cm and 120.58 cm respectively). Although 75 % RDN + 1 nano urea spray (N_4) was statistically at par with 100 % RDN (N_2) treatment at all 3 intervals (34.11 cm, 79.95 cm and 115.42 cm respectively), 50 % RDN + 2 spray of nano urea (N_3) had 11.3 %, 14.7 % and 12.7 % lower plant height than N_2 and 5.7 %, 3.6 % and 7.9 % lower plant height than N_4 at 40, 80 DAS and at harvest respectively. However, in case of tiller number per square metre and dry matter accumulation per square metre at 40, 80 DAS and harvest, 100 % RDN (N_2) was significantly superior at all three intervals than others ($p < 0.05$). It had 9.4 %,11.2 % and 18.9 % higher tiller m^{-2} and 19.5 %, 6.3 % and 31.8 % higher dry matter accumulation per square metre than N_3 at 40, 80 DAS and at harvest. Similarly, it resulted 3.3 %, 4.6 % and 8.7 % higher tiller per square metre and 9.4 %, 3.2 % and 14 % higher dry matter accumulation per square metre than N_4 at 40, 80 DAS and at harvest. Furthermore, LAI at 40 and 80 DAS also showed similar trend i.e. 11.1 % and 16.9 % higher than N_4 and 28.4 % and 33.7 % higher than N_3 at 40 and 80 DAS respectively (Fig . 3).

Among sub plot treatments, all the growth parameters viz., plant height, tiller number per square metre, dry matter accumulation per square metre and LAI was statistically at par among all 4 treatments at 40 DAS. However, at 80 DAS and harvest, there was significant variation among treatments. Plant height was significantly superior in weed-free check at both the time (79.83 and 117.25 cm at 80 DAS and harvest respectively) ($p < 0.05$). In comparison between 2 herbicide mixtures, tank mixed clodinafop + carfentrazone resulted 5.6 % and 13.2 % higher plant height than unweeded check at 80 DAS and at harvest, whereas ready mixed sulfosulfuron + metsulfuron methyl resulted 4 % and 8.9 % higher plant height than unweeded check at 80 DAS and at harvest respectively. Furthermore, in case of tiller number per square metre and dry matter accumulation m^{-2}, weed-free check was significantly higher (tiller numbers of 382 and 321 per square metre, dry matter accumulation of 660.02 and 1179.51 g m^{-2} respectively at 80 DAS and harvest) ($p < 0.05$). However, in between two herbicide mixture based treatments, tank mixed clodinafop + carfentrazone resulted 4.2 % and 17.8 % higher tiller per square metre, 4.3 % and 18.9 % higher dry matter accumulation per square metre than unweeded control at 80 DAS and harvest, whereas ready mixed sulfosulfuron + metsulfuron methyl had 2.5 %, 14.7 % higher tiller m^{-2} and 2.9 %, 13.4 % higher dry matter accumulation m^{-2} than unweeded control at 80 DAS and harvest respectively. Interestingly LAI at 80 DAS was statistically at par among all 3 sub plot treatments (4.42 in W_1, 4.51 in W_2 and 4.64 in W_3) except unweeded check (4.13) (Fig. 3).

Effect on flag leaf

Flag leaf status was evaluated at maximum flowering stage of wheat. Significant difference was observed in flag leaf area, flag leaf dry weight (g), flag leaf N %, flag leaf SPAD value. Flag leaf area was 17.2 % higher in 100 % RDN (N_2) than 50 % RDN + 2 spray of nano urea (N_3) and 13.3 % higher than 75 % RDN + 1 spray of nano urea. Both the nano urea-based treatments were statistically at par with each other. In case of flag leaf nitrogen content, it was also 10.6 % higher than 50 % RDN + two spray of nano urea (N_3) and 3.42 % higher than 75 % RDN + one spray of nano urea. Furthermore, SPAD value of the flag leaf followed the same trend, being significantly higher in 100 % RDN ($p < 0.05$) followed by 75 % RDN + one spray of nano urea and 50 % RDN + two spray of nano urea. All these parameters were significantly lower in nitrogen control (N_1) (Table 2).

In terms of weed management practices, flag leaf area was significantly higher in weed-free check (W_3) ($p < 0.05$). It was statistically at par between 2 herbicide mixture-based treatments. In case of flag leaf dry weight, weed-free check (W_3) was significantly 5.3 % higher than ready mixed sulfosulfuron + metsulfuron methyl and 2.8 % higher than tank mixed clodinafop + carfentrazone ($p < 0.05$). However, flag leaf N % was statistically at par between all three of them. Similar trend was observed in case of SPAD value of flag leaf as well. All these parameters were significantly lower in unweeded control treatment (W_4).

Interaction effect of yield attributing characters, grain yield and net B:C

Table 1. Effect of different treatments on weed density and dry weight

Treatments	Weed density (no. m^{-2})			Weed dry weight (g m^{-2})		
	40 DAS	80 DAS	Harvest	40 DAS	80 DAS	Harvest
			Nitrogen management			
N_1 (Control)	5.07^{A*} (25)	5.8^{A} (34)	3.83^{A} (14)	3.36^{A} (10.7)	5.11^{A} (25.6)	4.77^{A} (22.2)
N_2 (100 % RDN)	4.38^{D} (18)	4.77^{D} (24)	2.9^{D} (8)	2.66^{C} (6.5)	4.25^{D} (17.5)	4.15^{C} (16.7)
N_3 (50 % RDN + 2 NUS)	4.88^{B} (24)	5.42^{B} (30)	3.41^{B} (11)	3.09^{B} (9.0)	4.8^{B} (22.5)	4.59^{AB} (20.5)
N_4 (75 % RDN + 1 NUS)	4.65^{C} (22)	5.15^{C} (26)	3.19^{C} (11)	3^{B} (8.5)	4.51^{C} (19.8)	4.44^{B} (19.2)
			Herbicide mixtures			
W_1 (SS + MSM)	4.36^{B} (18)	4.82^{B} (23)	3.07^{B} (10)	2.9^{B} (7.9)	4.22^{B} (17.3)	4.91^{B} (23.6)
W_2 (CP + CAR)	4.02^{C} (16)	4.25^{C} (17)	2.84^{B} (8)	2.31^{C} (4.8)	3.94^{B} (15)	4.75^{C} (22)

*Data were subjected to square-root transformation (√(x+0.5)); original values are mentioned in parentheses. Means with different letters in each column are statistically different at LSD 0.05 and means with same letter are statistically at per at LSD 0.05.

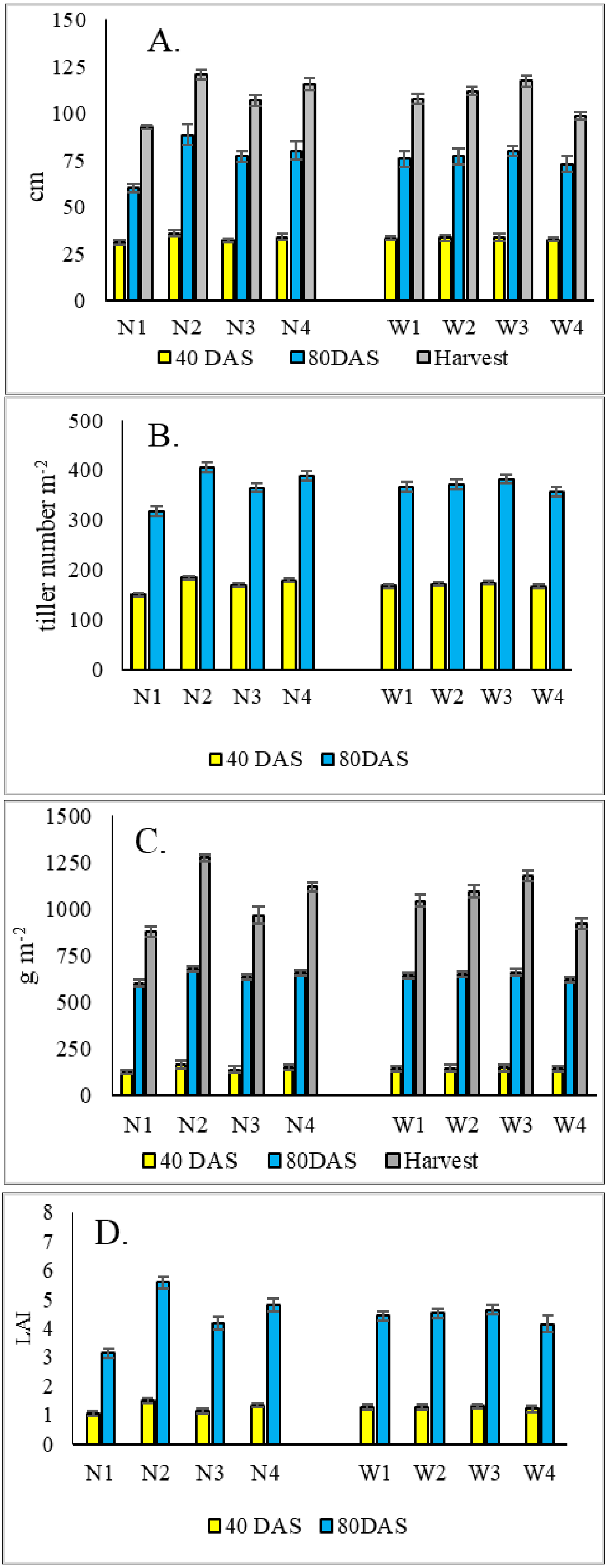

Fig. 3. Effect of different treatment on plant growth parameters (A: plant height; B: Tiller number; C: Dry matter accumulation; D: LAI).

Table 2. Flag leaf status affected by nitrogen management and weed management treatment

Treatments	Flag leaf area (cm^2)	Flag leaf dry weight (g)	Flag leaf N %	SPAD value of flag leaf
		Nitrogen management		
N_1 (Control)	16.93^C	1.83^C	2.35^D	36.92^D
N_2 (100 % RDN)	33.92^A	2.39^A	3.02^A	45.45^A
N_3 (50 % RDN + 2 NUS)	28.92^B	2.04^B	2.73^C	41.65^C
N_4 (75 % RDN + 1 NUS)	29.93^B	2.05^B	2.92^B	43.57^B
		Weed management		
W_1 (SS + MSM)	26.84^B	2.07^C	2.76^A	41.82^A
W_2 (CP + CAR)	27.71^B	2.12^B	2.80^A	42.15^A
W_3 (WFC)	29.53^A	2.18^A	2.81^A	42.6^A
W_4 (UWC)	25.62^C	1.95^D	2.64^B	41.02^B

Significant interaction effect was observed in yield attributing characters, grain yield and net B: C (Fig. 4). Considering ear bearing tiller per square metre, it was 5.1 % and 8.1% higher in 100 % RDN + weed-free check treatment compared to 100 % RDN + tank mixed clodinafop and carfentrazone ($N_2 W_2$) and 100 % RDN + ready mixed sulfosulfuron and metsulfuron methyl ($N_2 W_1$) respectively. Grain per spike was also significantly higher in 100% RDN + weed-free check treatment ($N_2 W_2$) (40.26) ($p < 0.05$), however unlike ear bearing tiller, it was at par with 75 % RDN + 1 nano urea spray with weed-free check ($N_4 W_3$) (38.67) treatment followed by 100 % RDN with tank mixed clodinafop + carfentrazone treatment ($N_2 W_2$) (38.15). Both these factors ultimately lead to significantly higher grain yield in 100 % RDN with weed-free check treatment ($N_2 W_3$) (5.73 t ha^{-1}) ($p < 0.05$). The treatment combination N_2W_3 had 6.5 % higher grain yield than $N_2W_2$and 9.5 % higher grain yield than N_2W_1. However, net B:C was significantly higher in 100 % RDN with tank mixed clodinafop + carfentrazone ($N_2 W_2$) (2.79, i.e., 8.1 % higher than $N_2 W_3$) ($p < 0.05$) followed by 100 % RDN with ready mixed sulfosulfuron + metsulfuron methyl (N2 W_1) (2.67, i.e. 3.4 % higher than $N_2 W_3$).

Nitrogen, phosphorus and potassium content in grain and straw

The nitrogen, phosphorus and potassium content was accessed after harvest of wheat in grain and straw (Table 3). It was found that N % in grain was significantly higher in 100 % RDN (N_2) ($p < 0.05$) followed by 75 % RDN + 1 spray of nano urea (N_4) and 50 % RDN + 2 spray of nano urea (N_3). The N % in straw was also higher in 100 % RDN (N_2), however in this case both the nano urea-based treatments (N_3 and N_4) were statistically at par with each other. Considering phosphorus, there was non-significant difference across four nitrogen treatments in terms of grain P %. But in case of P % of straw, 100 % RDN (N_2) was statistically at par with 75 % RDN + 1 spray of nano urea (N_4). It was followed by 50 % RDN + 2 spray of nano urea (N_3). For K % in grain, 100 % RDN (N_2) was statistically at par with 75 % RDN + 1 spray of nano urea (N_4) and the later 1 was at par with 50 % RDN + 2 spray of nano urea (N_3). However, for K % in straw, there was non-significant difference across treatments.

In case of weed management treatments, N % in grain was significantly higher in weed-free check (W_3) ($p < 0.05$) followed by tank mix of clodinafop + carfentrazone (W_2). However, N % in straw was statistically at par between these two treatments, followed by ready mix of sulfosulfuron + metsulfuron methyl (W_1). For P % and K % in grain as well as in straw, there was non-significant difference across treatments.

Nutrient use efficiency

Different nutrient use efficiency indices of nitrogen management treatments were calculated like agronomic efficiency, apparent recovery efficiency, partial factor productivity and partial nutrient balance. Agronomic efficiency and apparent recovery efficiency were 67 % and 87 % higher in 100 % RDN (N_2) treatment over N_3. However, partial factor productivity and partial nutrient balance were maximum in 50 % RDN + two sprays of nano urea treatment (N_3) (62.04 kg kg^{-1}; 0.88 kg N kg^{-1}) followed by 75 % RDN + 1 spray of nano urea (N_4) (48.9 kg kg^{-1}N applied; 0.75 kg N/kg of N applied) and 100% RDN (N_2) (43.39 kg kg^{-1}; 0.74 kg N kg^{-1}) (Fig. 5).

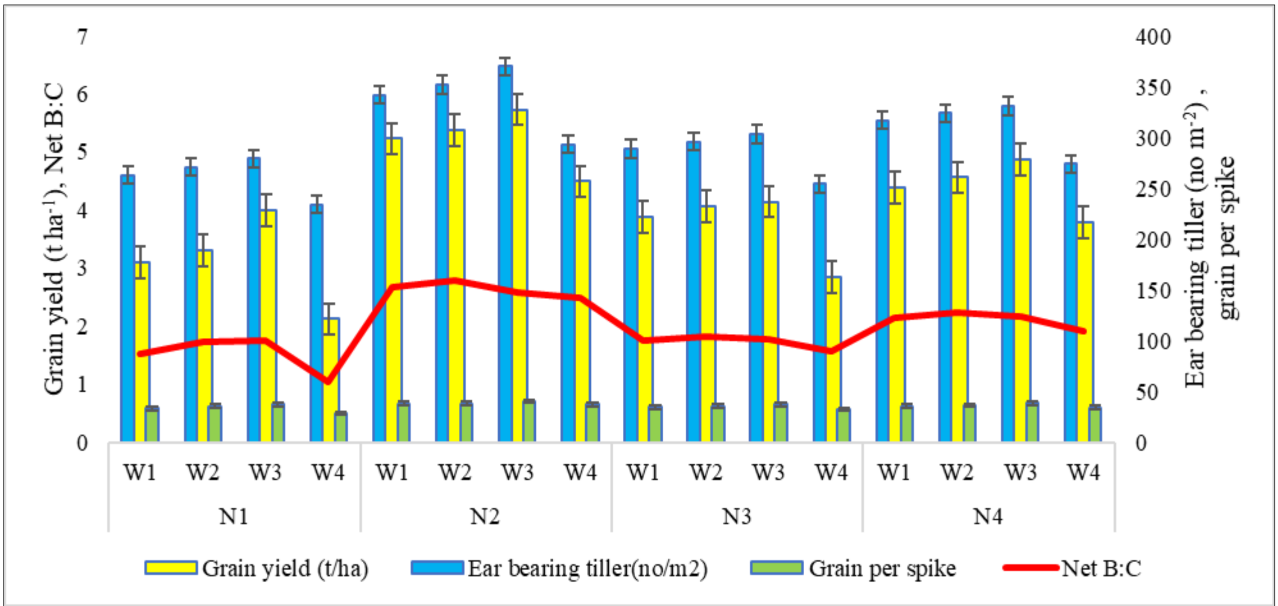

Fig. 4. Interaction effect on yield attributing characters, grain yield and net B:C.

Table 3. Effect of different treatments on N, P and K content in grain and straw

Treatment	N content in grain (%)	N content in straw (%)	P content in grain (%)	P content in straw (%)	K content in grain (%)	K content in straw (%)
			Nitrogen management			
N_1 (Control)	1.32^D	0.34^D	0.20	0.095^C	0.41^C	1.54
N_2 (100 % RDN)	1.70^A	0.46^A	0.22	0.103^A	0.48^A	1.78
N_3 (50 % RDN + 2 NUS)	1.41^C	0.42^B	0.21	0.100^B	0.44^{BC}	1.65
N_4 (75 % RDN + 1 NUS)	1.53^B	0.43^B	0.21	0.101^{AB}	0.46^{AB}	1.70
			Weed management			
W_1 (SS + MSM)	1.46^C	0.41^{BC}	0.21	0.100	0.45	1.66
W_2 (CP + CAR)	1.51^B	0.43^{AB}	0.21	0.100	0.45	1.68
W_3 (WFC)	1.60^A	0.43^A	0.21	0.101	0.46	1.70
W_4 (UWC)	1.38^D	0.40^C	0.21	0.099	0.44	1.63

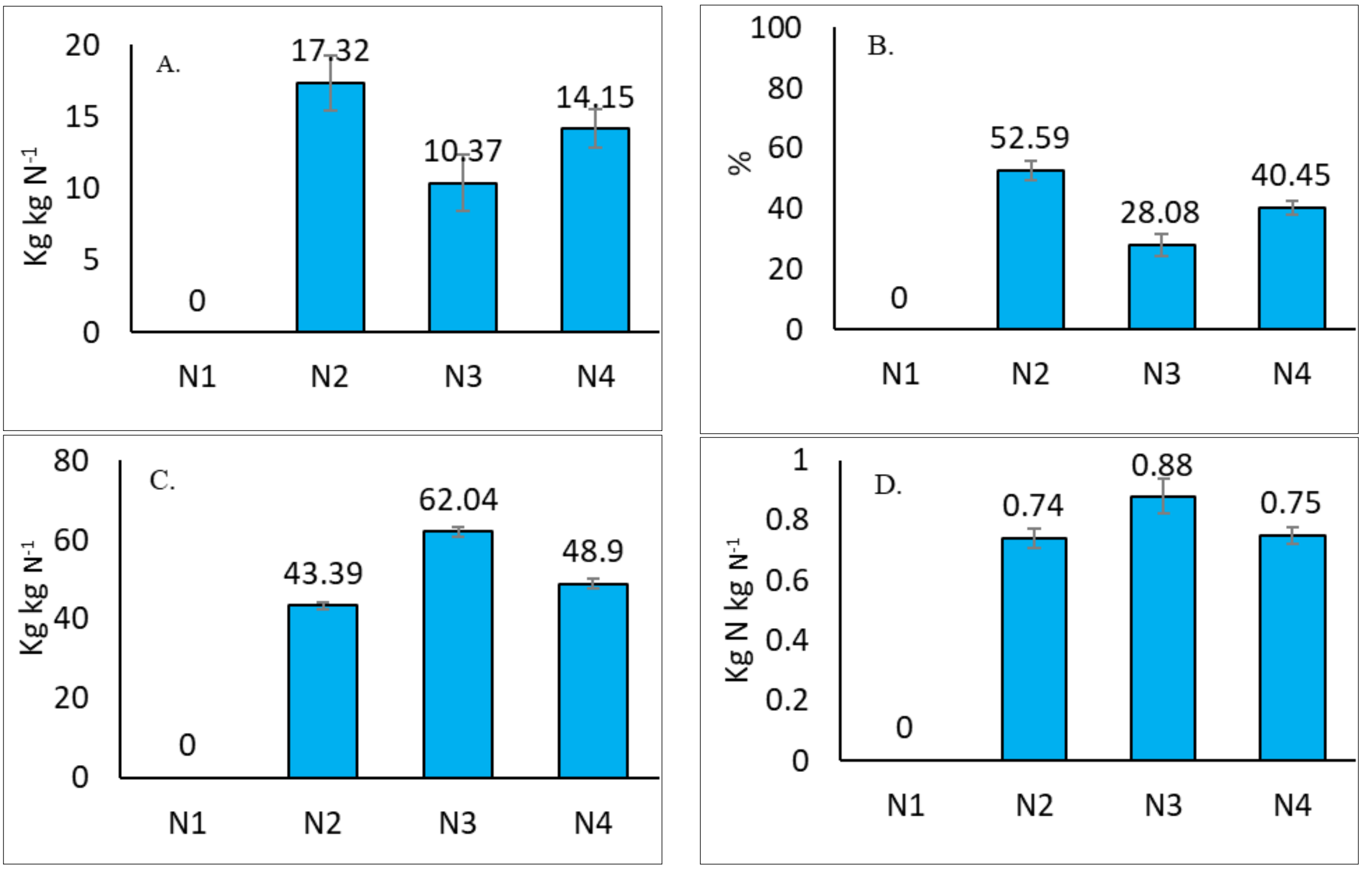

Fig. 5. Different nitrogen use efficiency indices of main plot treatments (A: Agronomic efficiency of nitrogen management treatments, B: Apparent recovery efficiency of nitrogen management treatments, C: Partial factor productivity of nitrogen management treatments, D: Partial nutrient balance of nitrogen management treatments).

Discussion

Effect on weeds

In the experiment, broad-leaved weeds, particularly *M. indica* dominated may be due to an existing weed seed bank in the experimental field. The 100 % RDN treatment showed higher weed suppression, attributed to vigorous crop growth from a higher initial basal nitrogen application. Along with this, during the initial 20–25 days of crop growth period, the average temperature was comparatively higher, which delayed the germination of winter season annual weeds like *Melilotus sp*., requiring a lower average temperature (<15 °C) for germination (24). After the first irrigation at 25–30 DAS, the temperature got decreased and weeds started to emerge. However, by this time, because of initial higher basal nitrogen dose, the crop growth was higher in this treatment, resulting better smothering action by wheat in 100 % RDN. Moreover, at later stage also, this 100 % RDN treatment enjoyed better crop growth. One spray of nano urea over 1 ha of land supplies only 50 g of nano N, which in spite of having higher efficiency, not equivalent to 25 % RDN of wheat i.e., 30 kg N ha^{-1}. So, foliar spray of nano urea in 75 % RDN + one nano urea spray and 50 % RDN + two nano urea spray treatments were not good enough to trigger vigorous crop growth in later stages also and did not compensate for RDN reduction, resulting poor weed suppression at 80 DAS as well until harvest.

In the sub-plot weed management treatments, the tank mix of clodinafop-propargyl + carfentrazone demonstrated superior weed suppression compared to the ready mix of metsulfuron + sulfosulfuron at 40 DAS, 80 DAS and harvest. Three potential reasons contribute to this observation. Firstly, both active ingredients in the tank mix were applied at their recommended rates, while the ready mix had metsulfuron methyl below the recommended rate (2 g a.i. ha^{-1} instead of 4 g a.i. ha^{-1}), resulting in poor control of broad-leaved weeds, the dominating weed flora of the experiment. Secondly, better compatibility among tank mix components compared to the ready mix. Thirdly, the reduced efficacy of sulfonylurea herbicides (components of the ready mix) compared to the tank mix. The application of SSP as a phosphorus source led to increased sulfur (S) availability in soil. This S might have resulted increased synthesis of leucine, isoleucine and valine amino acid through increased synthesis of biotin (25, 26), resulting lower efficacy of sulfonylurea herbicide. This aligns with findings from previous studies (27–29).

Effect on plant growth parameters

Plant growth parameters, including plant height, tiller number per square metre, dry matter accumulation and LAI responded significantly to nitrogen and weed management treatments. While plant height remained statistically similar between 100 % RDN and 75 % RDN + 1 nano urea sprays, other parameters were notably higher in the 100 % RDN treatment, followed by 75 % RDN + 1 nano urea spray and 50 % RDN + 2 nano urea sprays. Enhanced nitrogen availability in the 100 % RDN treatment, coupled with effective weed control, led to superior plant growth, consistent with previous studies (30, 31).

Weed management treatments showed no significant differences in plant growth parameters until 40 DAS, which aligns with previous observations (32). However, by 80 DAS and at harvest, the weed-free check exhibited superior tiller number and dry matter accumulation due to weed absence. In comparing herbicide mixtures, tank-mixed clodinafop + carfentrazone outperformed the ready mix of metsulfuron + sulfosulfuron in tiller number and dry matter accumulation, indicating superior weed suppression by the tank mix. Leaf area index was similar between the weed-free check and herbicide mixtures at 40 and 80 DAS, consistent with earlier studies (32, 33).

Flag leaf evaluation is crucial due to its significant contribution to grain photosynthates. The trend in flag leaf status aligns with overall plant growth parameters. Flag leaf area, dry weight and N % were highest in the 100 % RDN treatment, followed by 75 % RDN + 1 nano urea spray and 50 % RDN + 2 nano urea sprays. This again suggests that one nano urea spray did not match the impact of 25 % RDN in wheat, despite its higher use efficiency. In case of flag leaf area in sub plot treatments, weed-free treatment was significantly higher followed by statistically at par 2 herbicide mixture treatment. However, with respect to flag leaf N % and SPAD value, both the herbicide mixture-based treatments were statistically at par with weed-free treatment, indicating superiority of N content in flag leaf by both the herbicidal treatments.

Interaction effect of yield attributing characters, grain yield and net B:C

Higher availability of nitrogen and better crop growth parameters along with better flag leaf status has led to significantly higher ear bearing tillers, grains per spike and ultimately grain yield in the treatment combination of 100 % RDN along with weed-free check. Similar findings have also been documented by several other researchers (34–36). But interestingly, 100 % RDN along with tank mix of clodinafop + carfentrazone resulted statistically at par yield with the previous treatment. This is mainly because of statistically at par grain per spike between two treatments. Apart from these, 100 % RDN along with tank mix of clodinafop + carfentrazone combination had the highest net B:C, signifying superiority of the treatment over others. Additionally, the poor performance of nano urea based treatments along with its interactions with other inputs like irrigation or different fertilisers has also been reported (37, 38).

Nutrient content in grain and straw

Nitrogen content in grain and straw both were significantly higher in 100 % RDN because of more availability of nitrogen. This will favour higher protein % in this treatment, improving the quality of grain. It was found that, foliage application of nano urea did not resulted higher or at par nitrogen %, neither in grain nor in straw, because of unavailability of sufficient nitrogen, unlike 100 % RDN. However, for K content in grain, it seems that it has some synergistic effect as evident from statistically at par K % in grain between 100 % RDN along with 75 % RDN + 1 spray of nano urea and 75 % RDN + 1 spray of nano urea with 50 % RDN + 2 spray of nano urea. Similar synergism has also been reported by other studies (37–39). Higher potassium content in grain will result in better nutritional value as well as baking quality (40). In case weed management treatments, weed-free check had the highest N % due to absence of weed competition, followed by tank mixed clodinafop + carfentrazone. However, both were statistically at par in terms of N % in straw, indicating superiority of tank mix treatment over ready-mix treatment.

Nutrient use efficiency

Agronomic efficiency was highest in 100 % RDN treatment, indicating highest yield increase per kg nitrogen application compared to control, it was followed by 75 % RDN + 1 spray of nano urea. This signifies highest nitrogen responsiveness in 100 % RDN. Similarly apparent recovery efficiency was also highest in 100 % RDN, which means maximum nitrogen uptake per kilogram nitrogen application compared to control, indicating maximum recovery of applied nitrogen. However, in case of partial factor productivity, it was highest in 50 % RDN + 2 spray of nano urea indicating highest yield per kilogram nutrient applied. It was followed by 75 % RDN + 1 spray of nano urea. Similar type of result also reported by others (37, 38). Similarly, higher partial nutrient balance in nano urea-based treatments, indicating highest nitrogen uptake in grain per kilogram nitrogen applied. But both these indices do not involve nitrogen control in calculation, thus they cannot eliminate the contribution from soil inherent supply of nitrogen. Considering this view along with higher value of partial factor productivity and partial nutrient balance, there is potential threat of nitrogen mining from soil, questioning the sustainability of these treatments in long run as yield and nitrogen uptake was highest per kg nutrient applied.

Conclusion

This study delves into the impact of nano urea-based nitrogen management and herbicide mixtures on wheat growth, weed suppression, productivity, profitability, nutrient content and nitrogen use efficiency. The 100 % RDN treatment exhibited superior wheat growth, productivity and profitability with better nutrient uptake. In contrast, partial replacement of basal nitrogen with foliar nano urea spray did not sustain crop performance, indicating that nano urea cannot substitute conventional nitrogen sources. Moreover, higher partial factor productivity and partial nutrient balance in nano urea-based treatments indicating the threat of nitrogen mining from soil, questioning its sustainability in long run. However, it may be used as a complementary foliar supplement to fine-tune nitrogen delivery rather than as a replacement for reducing recommended nitrogen rates. This underscores the need for further research to unlock the full potential benefits of nano fertilisers, particularly focusing on evaluating more precise combinations of urea-nano urea application, optimization of application rate through multi-year, multi-location trials, its synergism with other nutrient management practices etc., which hold promise for selectively nourishing crops and increase the nitrogen use efficiency.

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Authors' contributions

AS carried out the investigation, data analysis and writing of the original manuscript. TS, TKD, CMP, KP participated in drafting of objectives and designing the research. AD, AM, KSR, AS, RS participated in editing of draft and statistical analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical issues: None

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