



Integration of nano-nitrogen in rice-wheat fertilizer management for improving nitrogen use efficiency

Manu Rani^{1,2,3}, Kapil Malik², Vishal Goyal², Ashwani Kumar², Parvender Sheoran⁴, Rakesh Mehra³ and Ajay Kumar Bhardwaj^{2,*}

¹Haryana Space Applications Center, Hisar, Haryana, India

²ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana, India

³Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana, India

⁴ICAR-Agriculture Technology Application Research Institute, Ludhiana, Punjab, India

*Corresponding author email: ak.bhardwaj@icar.org.in, ajaykbhardwaj@gmail.com

Received : April 02, 2026

Revised : May 16, 2026

Accepted : May 17, 2026

Published : August 31, 2026

ABSTRACT

Nitrogen (N) losses from conventional fertilizer systems reduce nitrogen-use efficiency (NUE), increase fertilizer requirements, and may adversely affect environmental quality. Nano-nitrogen (nano-N), applied as a foliar source, offers an opportunity to reduce soil-applied N while maintaining crop productivity. However, complete replacement of conventional urea may not adequately meet the N requirements of high-yielding cereal crops. Therefore, a two-year field experiment was conducted at the ICAR-Central Soil Salinity Research Institute (ICAR-CSSRI), Karnal, Haryana, India, under a rice-wheat cropping system to evaluate different levels of prilled urea substitution with nano-N and crop-based N management approaches. The treatments included 0, 33, 50, 66 and 100% replacement of prilled urea with nano-N, along with GreenSeeker- and Leaf Colour Chart (LCC)-based N management. Soil bulk density, air-filled porosity, soil pH and electrical conductivity were not significantly affected by the treatments. Grain yield of rice and wheat remained comparable with 100% prilled urea (R0) up to 33% replacement, whereas higher replacement levels, particularly complete replacement, resulted in reduced crop performance. Apparent N recovery efficiency increased substantially with nano-N substitution, with higher recovery observed under R66 and sensor-based N management treatments. The 33% replacement treatment (R33), equivalent to replacing the final one of three recommended urea splits with nano-N, maintained crop productivity while improving N recovery efficiency. Overall, partial substitution of prilled urea with foliar-applied nano-N provides a promising soil-foliar hybrid strategy for improving NUE and reducing dependence on conventional soil-applied N in the rice-wheat system.

Keywords: Nano-nitrogen, prilled urea, nitrogen-use efficiency, apparent N recovery, rice-wheat system

INTRODUCTION

Nitrogen (N) is essential for crop growth because it contributes to cellular constituents and regulates numerous biochemical and physiological processes (Marschner, 2012; Hirel *et al.*, 2011). Although atmospheric N₂ is abundant, it is largely unavailable to crops without conversion into reactive forms (Barbieri *et al.*, 2000). Consequently, N deficiency remains a major constraint to crop productivity,

while intensive agriculture increasingly depends on synthetic N fertilizers (Mosier *et al.*, 2002; Mohan *et al.*, 2015). Global agriculture currently consumes more than 118-120 million tonnes of N fertilizer annually, with demand expected to increase further to meet food requirements (FAO, 2014; FAO, 2020; Good and Beatty, 2011).

Despite high fertilizer inputs, crop recovery of applied N commonly remains only 30-50%, with

substantial N transferred to the environment when application exceeds or is poorly synchronized with crop demand (Fageria, 2002; Anas *et al.*, 2020; Tilman *et al.*, 2002; Kopittke *et al.*, 2021). Soil N transformations following urea application include hydrolysis, volatilization, nitrification, leaching, and denitrification, resulting in losses of NH_4^+ , nitrate, N, O, and N, (Galloway *et al.*, 2008; Sutton *et al.*, 2013). These losses reduce fertilizer-use efficiency and contribute to groundwater contamination, eutrophication, atmospheric pollution, and climate change (Zhang *et al.*, 2015). Agricultural N, O emissions are also strongly associated with microbial nitrification and denitrification (Kopittke *et al.*, 2021).

Fixed fertilizer rates and schedules often fail to match variation in indigenous soil N supply, crop growth, and crop N demand (Timsina and Connor, 2001). Precision N management, using tools such as SPAD, GreenSeeker, and leaf colour chart (LCC), can improve synchronization between fertilizer supply and crop demand (Dobermann *et al.*, 1998). Fertilizer technologies, including enhanced-efficiency and foliar fertilizers, offer another approach for improving N-use efficiency (NUE) and reducing soil-mediated N losses (Bhardwaj *et al.*, 2021; Kumar *et al.*, 2021).

Nanotechnology has introduced nano-nitrogen as a potential alternative N source. Liquid nano urea, developed by the Indian Farmers Fertiliser Cooperative Limited (IFFCO), contains approximately 4% N compared with 46% N in prilled urea, with N-containing particles reportedly ranging from 20-50 nm (Kumar *et al.*, 2020). Foliar application may facilitate direct N absorption and reduce exposure to leaching, volatilization, and gaseous losses. Nano-nitrogen has also been associated with improved crop performance and changes in rhizosphere biological activity (Upadhyay *et al.*, 2023). However, its low N concentration limits its ability to completely replace conventional fertilizer in high-N-demand crops. For example, 500 mL nano urea contains approximately 20 g N compared with about 20 kg N in a conventional urea bag, while rice and wheat yielding approximately 4 t ha^{-1} may remove 60-100 kg N ha^{-1} (Kumar *et al.*, 2021).

Therefore, complete replacement of soil-applied N may increase dependence on indigenous soil N and potentially cause soil N mining (Fageria and Barbosa Filho, 2001; Ladha *et al.*, 2003; Bhardwaj *et*

al., 2021). A soil-foliar hybrid strategy, combining basal soil-applied N with foliar nano-nitrogen and precision-based application, may provide a better balance between crop N supply, NUE, and environmental protection (Ladha and Reddy, 2003; Bhardwaj *et al.*, 2021).

However, information remains limited on how different nano-N substitution levels influence soil N availability, nitrate dynamics, N_2O emissions, overall N balance, and crop productivity, particularly when combined with precision N management (Bhardwaj *et al.*, 2021). This knowledge gap is particularly important in rice-wheat systems, where high N demand and contrasting water regimes strongly influence N transformations and losses (Ladha *et al.*, 2003).

Accordingly, field experiments were conducted at ICAR-Central Soil Salinity Research Institute, Karnal, India, to evaluate nano-nitrogen as a partial substitute for soil-applied prilled urea under rice-wheat cropping. Different substitution levels and precision-based N management approaches were assessed for their effects on crop productivity, NUE, soil N dynamics, and environmental N losses, with the aim of developing a sustainable soil-foliar hybrid N management strategy.

MATERIALS AND METHODS

Study site and experimental layout

A field trial on the integrated use of nano-nitrogen with prilled urea in a rice-wheat system was initiated in 2020 at ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, India (29.43°N, 76.58°E). The experiment was conducted during 2021-22 and 2022-23. Treatments were imposed in 10.75 × 6 m plots with three replications in a randomized complete block design. The site has a semi-arid subtropical climate with hot summers and cool winters and receives approximately 750 mm annual precipitation. Weather data during the study period are presented in Fig. 1.

Eight treatments were evaluated: four levels of prilled urea replacement with nano-nitrogen, i.e., 33% (R33), 50% (R50), 66% (R66), and 100% (R100); two precision-scheduling treatments, namely nano-nitrogen application based on leaf colour chart (LCC) values after one basal dose of prilled urea (M-LCC) and GreenSeeker (GS) values after one basal dose (M-GS); and two controls, 100% recommended

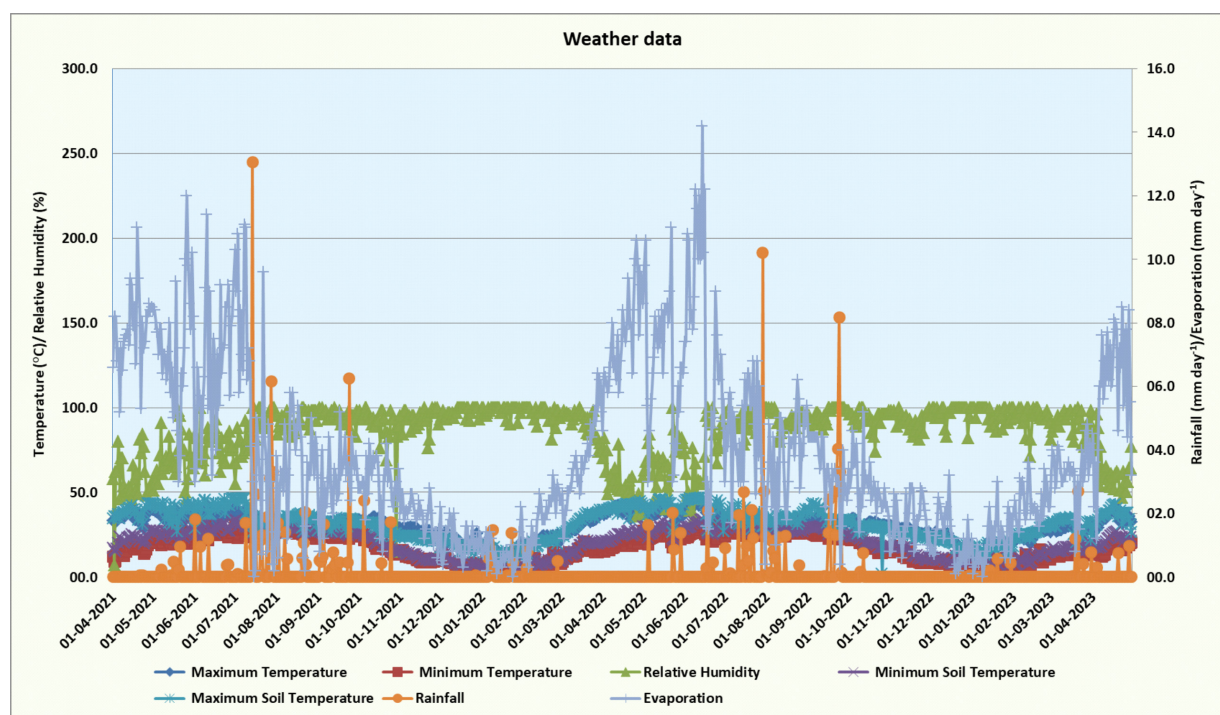


Fig. 1. Weather data during the study period (01-04-2021 to 30-04-2023)

N through prilled urea (R0; no replacement) and no N fertilizer (No-N). The annual cropping system comprised aromatic (*basmati*) rice (*Oryza sativa* L.) during summer and wheat (*Triticum aestivum* L.) during winter. Recommended prilled urea N rates were 90 and 150 kg N ha⁻¹ for rice and wheat, respectively, applied in three equal splits at T=0, 21, and 42 days after transplanting (rice)/sowing (wheat).

During rice, all plots were puddled using a power tiller, and one-month-old nursery-raised Pusa Basmati 1121 seedlings were transplanted at 20 × 15 cm spacing. Wheat soils were dry-tilled using a power tiller before sowing KRL 210 at 22.5 × 10 cm spacing. Rice was planted in July and harvested in the last week of October, while wheat was planted in the first week of November and harvested in the first

week of April. At rice transplanting/wheat sowing, one-third of the urea N dose, the full dose of single superphosphate (SSP), and muriate of potash (MOP) were applied. Recommended N, P, and K rates were 90, 30, and 30 kg ha⁻¹ for rice and 150, 60, and 60 kg ha⁻¹ for wheat, respectively.

During rice, fields were flooded for puddling, followed by 10 cm standing water for the first two months with irrigation every 2-3 days. During the third month, irrigation was applied weekly to maintain saturated soil without standing water, and irrigation was stopped two weeks before harvest. Wheat received four surface-flood irrigations at approximately one-month intervals. Treatment-specific management schedules are presented in Table 1.

Table 1. Treatments details of soil-foliar hybrid application of nitrogen fertilizers

S.No.	Treatment	Details
1	No- N	Control
2	R0	Recommended dose of nitrogen by Urea
3	R33	Basal and 1 st split dose of urea + 2 nd split dose of Nano-N
4	R50	Basal and half of 1 st split dose of urea + half of 1 st split dose and 2 nd split dose of Nano-N
5	R66	Basal dose of urea + 1 st and 2 nd split dose of Nano-N
6	R100	Recommended dose of nitrogen by Nano-N
7	M-GS	Application of nitrogen based on GreenSeeker (GS) values by Nano-N, basal dose by urea
8	M-LCC	Application of nitrogen based on Leaf colour chart (LCC) values by Nano-N, basal dose by urea

- i. **No-N:** Rice-wheat grown without inorganic or organic N inputs.
- ii. **R0:** 100% recommended N supplied through prilled urea.
- iii. **R33:** 33% N replaced with nano-N; prilled urea applied in the first two splits and nano-N in the third split.
- iv. **R50:** 50% N replaced with nano-N; prilled urea applied in the first split and half of the second split, with nano-N in the remaining second and third splits.
- v. **R66:** 66% N replaced with nano-N; prilled urea applied in the first split and nano-N in the second and third splits.
- vi. **R100:** 100% recommended N replaced with nano-N.
- vii. **M-LCC:** Nano-N application guided by Leaf Colour Chart (LCC) after one basal prilled urea application.
- viii. **M-GS:** Nano-N application guided by GreenSeeker (GS) after one basal prilled urea application.

Characteristics of fertilizer materials

The nano-nitrogen fertilizer used in the study was developed at the Nano Biotechnology Center of Indian Farmers Fertilizer Cooperative (IFFCO), Kalol, Gujarat, India. It contained 4% N (w/v), with urea particles ranging from 20-50 nm.

Leaf colour chart (M-LCC) and GreenSeeker (M-GS) based scheduling

Leaf greenness was assessed using a Leaf Colour Chart (LCC; Punjab Agricultural University, Ludhiana) with values from 1 (very light green) to 6 (extremely dark green). Ten fully expanded leaves were assessed at 7-day intervals from 42 days after transplanting (DAT) until anthesis. In rice, nano-N was applied at 625 mL ha⁻¹ when more than six leaves recorded an LCC value <4. In wheat, nano-N was applied according to LCC readings: 375 mL ha⁻¹ at >5, 750 mL ha⁻¹ at 4.5–5, 1000 mL ha⁻¹ at 4–4.5, and 1375 mL ha⁻¹ at <4, when more than six leaves showed the respective reading.

GreenSeeker (Trimble, Westminster, Colorado, USA) is an optical sensor that measures crop vigour using the normalized difference vegetation index (NDVI), based on reflected red and near-infrared radiation. Higher NDVI generally indicates greater crop vigour. Before fertilizer application, NDVI

readings were recorded from both an N-rich strip and treatment plots by holding the sensor 60-120 cm above the crop canopy. The sensor was directed towards the canopy with the trigger pressed, and the NDVI value (0.00-0.99) was displayed on the LCD after measurement. Readings from the N-rich strip and treatment plots were used in an algorithm to estimate potential yield response to N and determine the recommended N application rate. NDVI was calculated as:

$$NDVI = \frac{(NIR_{ref} - Red_{ref})}{(NIR_{ref} + Red_{ref})} \quad (i)$$

where NIR_ref and Red_ref represent reflectance in the near-infrared and red bands, respectively. An Android-based N Calculator application was used to determine the optimum N fertilizer dose from the NDVI values recorded using the GreenSeeker.

Soil physical parameters

Soil Bulk Density and Air filled porosity (%)

At each gas sampling event, we measured soil temperature, soil bulk density (BD), and gravimetric water content (GWC). Soil bulk density (BD) was measured using a fixed-volume soil core for each treatment plot. Water-filled pore space (% WFPS) was calculated as

$$\% \text{ WFPS} = 100\% \times \frac{\text{GWC (g g}^{-1}) \times \text{BD (g cm}^{-3})}{\text{soil porosity}}$$

$$\text{Soil porosity (\%)} = 100 - \frac{\text{Soil bulk density (g cm}^{-3}) \times 100}{\text{Soil particle density (g cm}^{-3})}$$

The density of soil particles was considered to equal the normal 2.65 g cm⁻³. As a result, the air-filled porosity was determined using the following formula:

$$\text{Air-filled porosity (\%)} = 100 - \text{WFPS (\%)}$$

Soil sampling

Soil samples were collected after rice and wheat harvest, air-dried, and passed through a 2-mm sieve. For organic carbon analysis, samples were further sieved through a 0.5-mm sieve.

Soil pH and electrical conductivity

Soil pH and EC were determined in a 1:2 soil-to-water suspension by mixing 20 g oven-dried soil with 40 mL distilled water. The suspension was intermittently stirred for 30 min and allowed to settle. The conductivity meter was calibrated with 0.01 M

KCl, while the pH meter was calibrated using pH 7.0 and 9.2 buffer solutions. EC was measured in the clear supernatant, followed by pH measurement after thoroughly mixing the suspension.

Apparent recovery efficiency

Nitrogen-use efficiency (NUE) is an important indicator of crop production performance. Apparent N recovery efficiency was calculated as:

$$\text{Apparent recovery efficiency (AR)} = \frac{U - U_0}{F}$$

where F is the amount of N fertilizer applied, U is the total N uptake in aboveground biomass of fertilized crops, and U_0 is the N uptake in aboveground biomass without N fertilization.

Grain and Straw yield

Grain and straw yield of rice and wheat crop were calculated by measuring the yield of the full plot of each treatment.

Statistical Analysis

Data were analysed by ANOVA, with means separated using Tukey's HSD test at $P \leq 0.05$ in JMP (2009; SAS Inc., Cary, NC, USA). Weighted least-squares linear regression and graphical analyses were performed using Origin v8.5 (OriginLab, Northampton, MA, USA).

RESULTS

Bulk Density

The season-wise average soil bulk density (Mg m^{-3}) under different treatments in the rice-wheat system is presented in Table 2. The values represent the two-year mean across the respective seasons. During the rice season, soil bulk density ranged from 1.43 to 1.49 Mg m^{-3} , while during the wheat season it varied from 1.36 to 1.42 Mg m^{-3} . During the fallow period, soil bulk density ranged from 1.34 to 1.40 Mg m^{-3} . Overall, soil bulk density was comparatively higher during the rice season than during the wheat and fallow periods. However, the differences among treatments were statistically non-significant, indicating that the applied treatments did not appreciably alter soil bulk density.

Air filled porosity

The daily air-filled porosity (%) under different treatments in the rice-wheat system is presented in Fig. 2. Air-filled porosity was generally lower during the rice season than during the wheat and fallow periods. During the initial stage of the rice season, air-filled porosity remained very low due to saturated or flooded soil conditions and gradually increased as the crop season progressed. During the rice season, air-filled porosity ranged from 0 to 75%, whereas it varied from 25 to 100% during the wheat and fallow periods. A similar seasonal pattern was observed

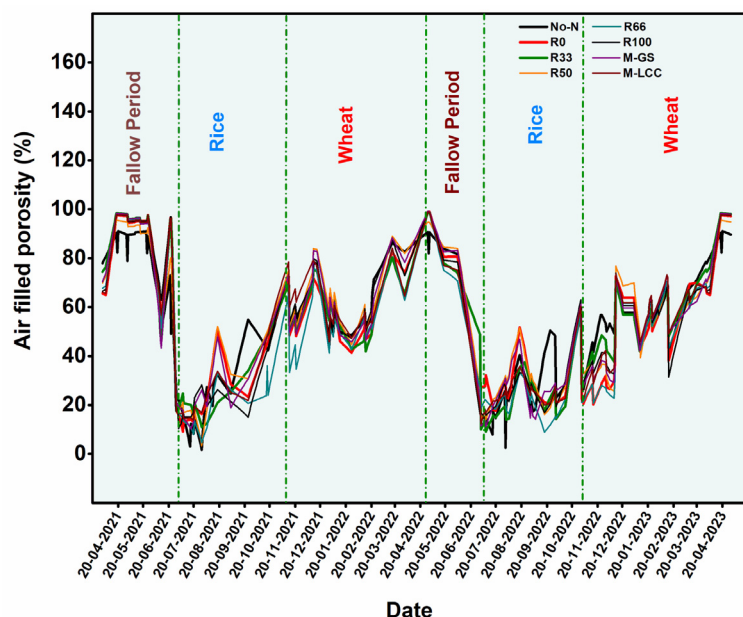


Fig. 2. Daily air-filled porosity under different treatments in the rice-wheat system

Table 2. Season-wise average soil bulk density (Mg m^{-3}) under different treatments in rice-wheat system

Treatments	Rice	Wheat	Fallow
No-N	1.46 ± 0.06^A	1.37 ± 0.07^A	1.37 ± 0.07^A
R0	1.45 ± 0.05^A	1.42 ± 0.06^A	1.38 ± 0.06^A
R33	1.48 ± 0.06^A	1.42 ± 0.07^A	1.40 ± 0.07^A
R50	1.43 ± 0.07^A	1.39 ± 0.06^A	1.34 ± 0.07^A
R66	1.48 ± 0.07^A	1.40 ± 0.07^A	1.35 ± 0.07^A
R100	1.47 ± 0.05^A	1.36 ± 0.07^A	1.36 ± 0.07^A
M-GS	1.44 ± 0.07^A	1.38 ± 0.07^A	1.36 ± 0.05^A
M-LCC	1.49 ± 0.07^A	1.39 ± 0.06^A	1.37 ± 0.06^A

in both years across all treatments, broadly corresponding to the variation in soil bulk density.

Soil electrical conductivity (EC)

The daily soil electrical conductivity (EC) at 0-15 cm depth and EC measured before and after each crop season at 15-30 cm depth under different treatments are presented in Figs. 3 and 4, respectively. Soil EC remained statistically similar among all treatments, including the No-N control, at both soil depths throughout the experiment. The surface soil generally exhibited higher EC than the sub-surface soil. At 0-15 cm depth, EC fluctuated between 0.12 and 0.59 dS m^{-1} , whereas at 15-30 cm depth it ranged from 0.12 to 0.20 dS m^{-1} . Although temporal fluctuations in surface-soil EC were observed during the experimental period, these variations were not associated with significant treatment effects.

Soil pH

The daily soil pH at 0-15 cm depth and pH measured before and after each crop season at 15-30 cm depth are presented in Figs. 5 and 6, respectively. Soil pH remained statistically at par among all treatments, including the No-N control, at both depths throughout the experiment. Surface-soil pH varied from 7.5 to 8.3, whereas sub-surface soil pH ranged from 7.7 to 8.1. Thus, neither nano-N substitution nor precision-based N management resulted in a significant alteration of soil pH during the study period.

Grain and straw yield

Grain and straw yields of rice and wheat under different treatments during both years are presented in Fig. 7. In rice, R33 recorded the highest grain yield, whereas No-N recorded the lowest in both years. During 2021, grain yield under R33 was significantly higher than that under No-N and R100 but remained statistically at par with R0, R50, R66, M-GS, and M-LCC. In 2022, R33 remained statistically at par with R0 and significantly outperformed the remaining treatments. Rice straw yield did not differ significantly among treatments during 2021. In 2022, R0 recorded the highest straw yield and was statistically at par with R33, R50, R66, M-GS, and M-LCC, while significantly exceeding R100 and No-N.

In wheat, R33 and No-N consistently recorded the highest and lowest grain yields, respectively, in

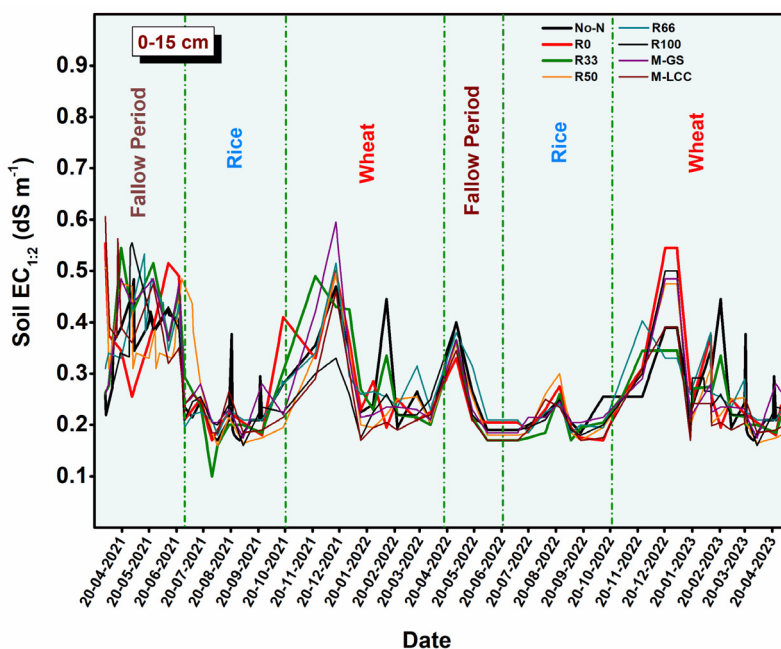


Fig. 3. Soil EC under different treatments in the rice-wheat system (0-15 cm)

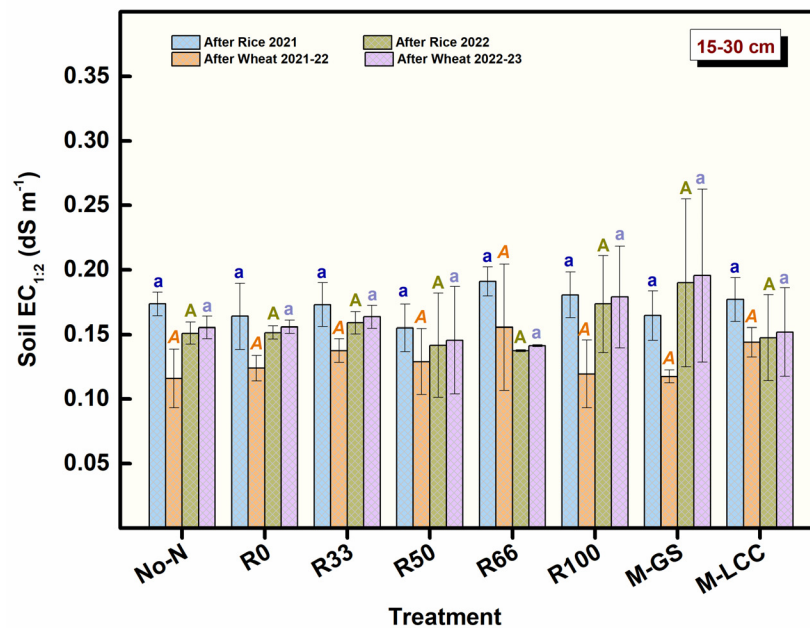


Fig. 4. Soil EC under different treatments in the rice-wheat system (15-30 cm)

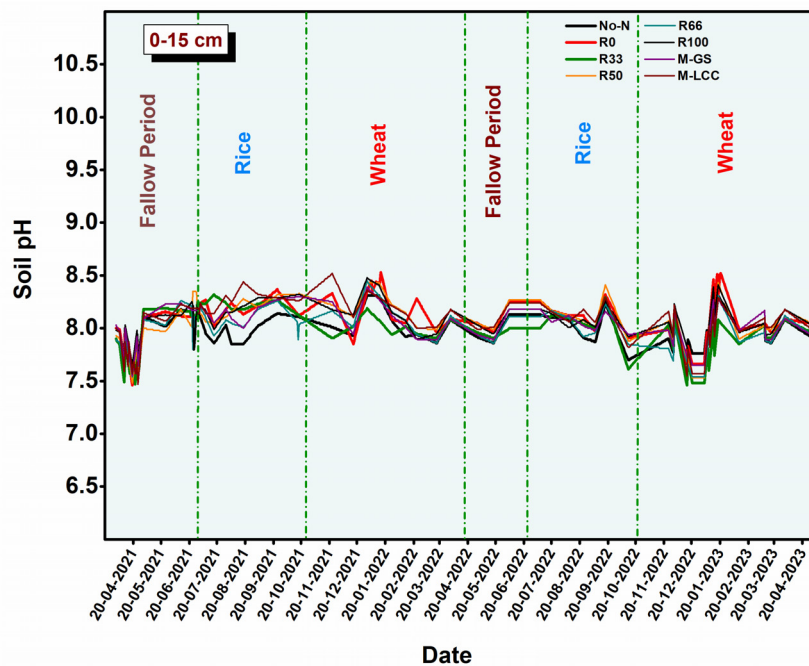


Fig. 5. Soil pH under different treatments in the rice-wheat system (0-15 cm)

both years. Grain yield under R33 was significantly higher than No-N and R100 but remained statistically comparable with R0, R50, R66, M-GS, and M-LCC in both years. For straw yield, R0 recorded the highest value and No-N the lowest in both years. During 2021, straw yield under R0 was significantly higher than No-N and M-GS but remained at par with the other treatments. During

2022, R0 was statistically at par with R50, R66, M-GS, and M-LCC and significantly higher than R33, R100, and No-N.

Apparent recovery efficiency

The apparent recovery efficiency (ARE) of rice and wheat under different treatments is presented in Fig. 8. In rice, ARE was highest under R66, which

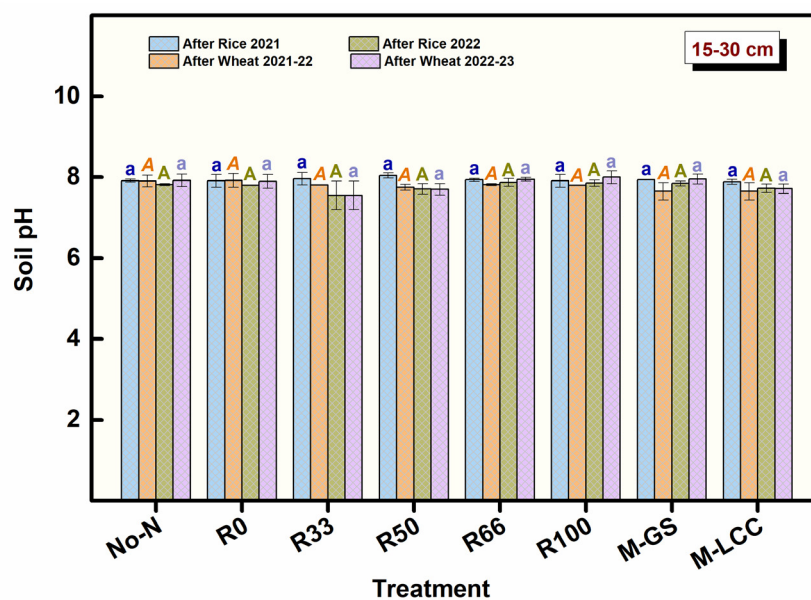


Fig. 6. Soil pH under different treatments in the rice-wheat system (15-30 cm)

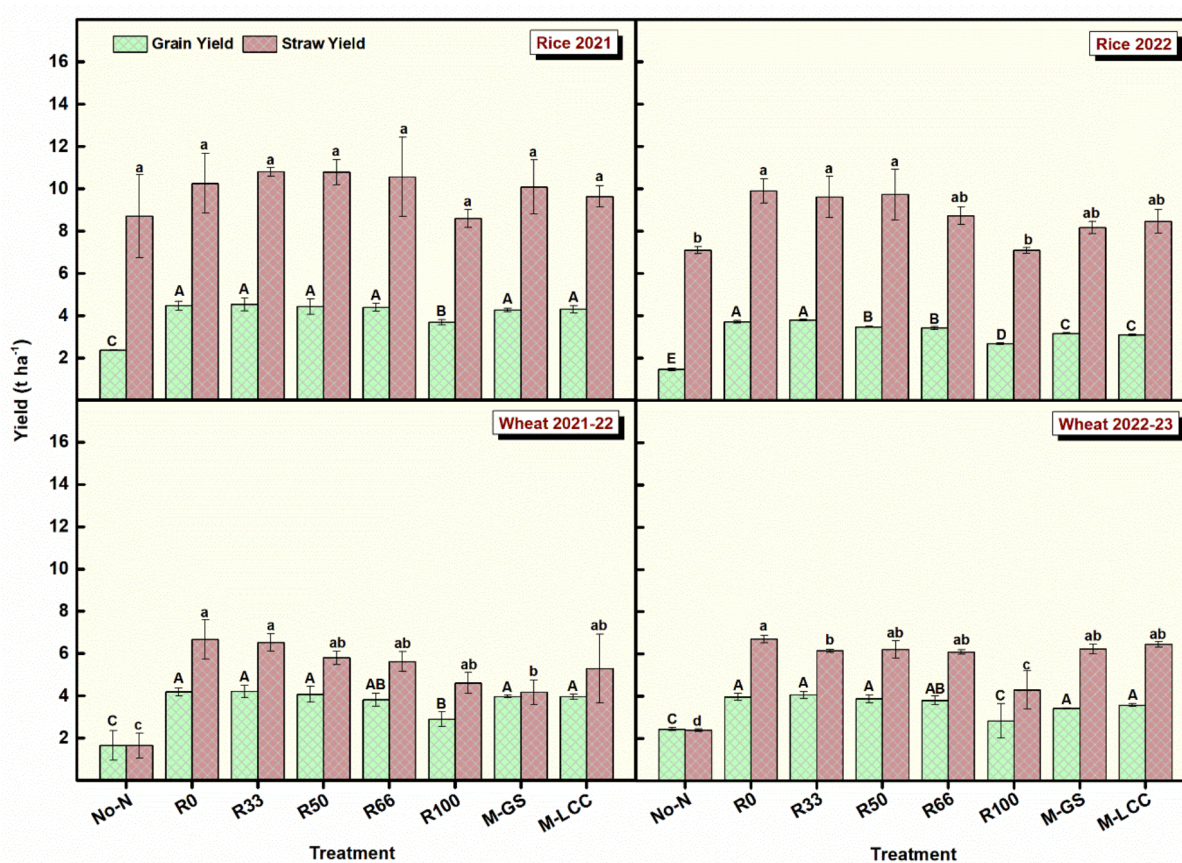


Fig. 7. Grain and Straw yield under different treatments in the rice-wheat system

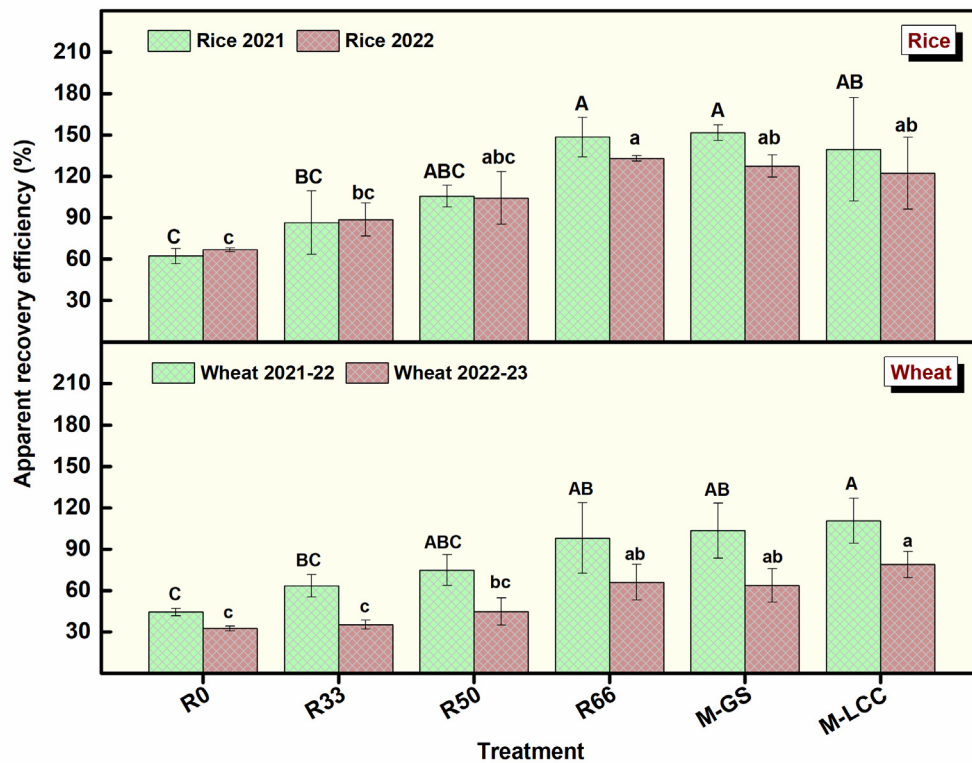


Fig. 8. Apparent recovery efficiency under different treatments in the rice-wheat system

remained statistically at par with M-GS and M-LCC, followed by R50 and R33, while R0 recorded the lowest value. Relative to R0, ARE increased by 39, 70, 139, 144, and 125% under R33, R50, R66, M-GS, and M-LCC, respectively, during the first season. Corresponding increases during the second season were 33, 56, 99, 91, and 83%, respectively.

In wheat, the highest ARE was observed under M-LCC, which was statistically at par with M-GS and R66, followed by R50 and R33, whereas R0 recorded the lowest ARE. Compared with R0, ARE increased by 43, 68, 121, 133, and 149% under R33, R50, R66, M-GS, and M-LCC, respectively, during the first season. During the second season, the corresponding increases were 8, 37, 103, 96, and 143%, respectively. Overall, partial substitution of conventional urea with nano-N and precision-based N management substantially improved apparent N recovery compared with conventional urea alone.

DISCUSSION

Soil physical properties remained largely unaffected by N management, indicating that partial replacement of prilled urea with nano-N did not measurably alter soil compaction during the study period. Bulk density was comparatively higher

during rice than wheat and fallow periods, likely due to flooding and soil settling, whereas drier conditions resulted in lower bulk density during wheat and fallow. Air-filled porosity showed the opposite trend, with very low values during the initial flooded rice period and increasing values following drainage. The absence of significant treatment effects suggests that N source and replacement level did not substantially modify soil physical conditions over the experimental period, consistent with earlier observations under fertilizer and integrated nutrient management practices (Bhardwaj *et al.*, 2021; Bhardwaj *et al.*, 2022a).

Soil EC and pH remained statistically comparable among treatments in both surface and sub-surface layers. The relatively higher surface EC may reflect greater concentration and cycling of soluble ions in the upper soil, while the narrow sub-surface range indicates limited redistribution of soluble salts. The unchanged pH and EC suggest that replacing soil-applied urea with foliar nano-N did not substantially alter the soil chemical environment, possibly because foliar nano-N largely bypasses direct soil interactions (Bhardwaj *et al.*, 2022b). Maintaining soil quality while improving fertilizer-use efficiency is important for sustainable

intensive cropping systems (Fageria, 2002; Tilman *et al.*, 2002).

Partial replacement of prilled urea with nano-N maintained crop productivity. R33 consistently produced the highest grain yield, whereas No-N recorded the lowest. Grain yield under R33 remained comparable with R0, R50, R66, M-GS and M-LCC, indicating that replacing the final one of three recommended urea splits with nano-N was sufficient to maintain grain production. In contrast, higher replacement, particularly complete replacement (R100), reduced yield, suggesting that nano-N alone could not meet the total N requirement of the crops. Similar evidence indicates that nanofertilizers are more effective when integrated with conventional N rather than used as complete replacements (Kumar *et al.*, 2022; Upadhyay *et al.*, 2024).

The lower yield at higher replacement levels was associated with reduced soil N availability. R0 and R33 maintained comparable soil available N, indicating that substantial soil N depletion was avoided at 33% replacement. Adequate N availability supports chlorophyll formation, photosynthesis, biomass accumulation and assimilate partitioning towards grain production (Tiwari *et al.*, 2020). Synchronization between N supply and crop demand is also critical for productivity and NUE under integrated nutrient management (Bhardwaj *et al.*, 2020, 2021). Thus, retaining two soil-applied urea splits while replacing the final split with nano-N provided a suitable balance between soil N supply and foliar supplementation.

Straw yield showed a similar response, with R0 generally recording the highest values but remaining comparable with several partial-replacement treatments. Lower straw production under No-N and higher nano-N replacement further demonstrates the importance of adequate N for vegetative growth and biomass production. These results agree with findings that nano-N performs effectively as a partial rather than complete substitute for conventional N (Kumar *et al.*, 2021), supporting the need to improve fertilizer-use efficiency without compromising biomass and yield (Hirel *et al.*, 2011).

Apparent N recovery efficiency increased substantially with nano-N substitution. In rice, R66 recorded the highest recovery efficiency, whereas M-LCC showed the highest value in wheat, with M-GS and R66 remaining statistically comparable. Greater recovery may be attributed to foliar

application, which reduces direct exposure of N to soil-mediated losses. In contrast, soil-applied urea is susceptible to volatilization, nitrification, leaching and denitrification, while foliar nano-N can supply N directly to plant tissues (Kumar *et al.*, 2021; Bhardwaj *et al.*, 2022a; Galloway *et al.*, 2008; Kopittke *et al.*, 2021). However, greater recovery at high substitution levels does not indicate agronomic sustainability because excessive reduction in soil-applied N reduced soil N availability and crop performance. NUE should therefore be interpreted together with yield, soil N status and overall N balance (Bhardwaj *et al.*, 2023a, 2023b).

Overall, R33, equivalent to replacing one of three conventional N splits with nano-N, provided the most balanced response by maintaining grain yield while improving N recovery efficiency without adversely affecting measured soil properties. Higher replacement progressively reduced soil N availability and crop performance. These findings support a soil–foliar hybrid strategy in which conventional urea supplies the major N requirement and nano-N supplements crop demand during later growth stages, improving NUE while reducing unnecessary soil-applied N and associated losses (Bhardwaj *et al.*, 2021; Kumar *et al.*, 2021; Bhardwaj *et al.*, 2022a; Bhardwaj *et al.*, 2022b; Upadhyay *et al.*, 2024). Synchronizing N supply with crop demand remains essential for reducing reactive N losses while sustaining productivity (Galloway *et al.*, 2008; Zhang *et al.*, 2015).

CONCLUSION

The two-year study demonstrated that partial replacement of prilled urea with foliar-applied nano-N can improve nitrogen-use efficiency without adversely affecting crop productivity or soil properties. Replacing 33% of prilled urea with nano-N (R33), equivalent to substituting the final one of three recommended urea splits, maintained rice and wheat grain yields comparable to 100% prilled urea (R0) while improving apparent N recovery. In contrast, higher replacement levels, particularly complete replacement (R100), reduced crop performance, indicating that nano-N alone could not meet crop N requirements. Thus, 33% substitution offers a promising soil-foliar hybrid N management strategy for maintaining productivity, improving N-use efficiency, and reducing dependence on soil-applied urea in the rice-wheat system.

FUNDING

This work was supported by the NICRA (National Innovation in Climate Resilient Agriculture) project through grant no. ICAR-DARE-NICRA-03 (CSSRI Project No. 1006538).

REFERENCES

- Anas, M., Liao, F., Verma, K.K., Sarwar, M.A., Mahmood, A., Chen, Z.L. and Li, Y.R., (2020). Fate of nitrogen in agriculture and environment: agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. *Biological Research*, 53, 1-20. doi:10.1186/s40659-020-00312-4.
- Barbieri, P.A., Rozas, H.N.R.S., Andrade, F.H. and Echeverria, H.N.E., (2000). Row spacing effects at different levels of nitrogen availability in maize. *Agronomy Journal*, 92, 283-288. doi:10.2134/agronj2000.922283x.
- Bhardwaj, A.K., Rajwar, D., Basak, N., Bhardwaj, N., Chaudhari, S.K., Bhaskar, S. and Sharma, P.C., (2020). Plant available nitrogen at critical stages of rice (*Oryza sativa*) crop and its relation to soil biological activity and crop productivity under major nutrient management systems. *Journal of Soil Science and Plant Nutrition*, 20, 1238-1248. doi:10.1007/s42729-020-00208-y.
- Bhardwaj, A.K., Rajwar, D., Yadav, R.K., Chaudhari, S.K. and Sharma, D.K., (2021). Nitrogen availability and use efficiency in wheat crop as influenced by the organic-input quality under major integrated nutrient management systems. *Frontiers in Plant Science*, 12, 752-764. doi:10.3389/fpls.2021.634448.
- Bhardwaj, A.K., Arya, G., Kumar, R., Hamed, L., Pirasteh-Anosheh, H., Jasrotia, P., Kashyap, P.L. and Singh, G.P., (2022a). Switching to nanonutrients for sustaining agroecosystems and environment: the challenges and benefits in moving up from ionic to particle feeding. *Journal of Nanobiotechnology*, 20, 19. doi:10.1186/s12951-021-01177-9.
- Bhardwaj, A.K., Malik, K., Chejara, S., Rajwar, D., Narjary, B. and Chandra, P., (2022b). Integration of organics in nutrient management for rice-wheat system improves nitrogen use efficiency via favorable soil biological and electrochemical responses. *Frontiers in Plant Science*, 13, 1075011. doi:10.3389/fpls.2022.1075011.
- Bhardwaj, A.K., Malik, K., Chejara, S., Basak, N., Narjary, B., Chandra, P., Mandal, U.K., Sharma, D.K. and Chaudhari, S.K., (2023a). Integrated nutrient management modules for utilization of crop residues to enhance the productivity of rice-wheat systems in the north-western Indo-Gangetic plain. *Journal of the Indian Society of Soil Science*, 71, 58-69. doi:10.5958/0974-0228.2023.00001.4.
- Bhardwaj, A.K., Malik, K., Rani, M., Mandal, U.K., Basak, N., Singh, A., Yadav, R.K., Chaudhari, S.K. and Sharma, D.K., (2023b). Residue recycling options and their implications for sustainable nitrogen management in rice-wheat agroecosystems. *Ecological Processes*, 12, 53. doi:10.1186/s13717-023-00464-7.
- Dobermann, A., Cassman, K.G., Mamaril, C.P. and Sheehy, J.E., (1998). Management of phosphorus, potassium, and sulfur in intensive, irrigated lowland rice. *Field Crops Research*, 56, 113-138. doi:10.1016/S0378-4290(97)00124-X.
- Fageria, N.K., (2002). Soil quality vs. environmentally-based agricultural management practices. *Communications in Soil Science and Plant Analysis*, 33, 2301-2329. doi:10.1081/CSS-120005764.
- Fageria, N.K. and Barbosa Filho, M.P., (2001). Nitrogen use efficiency in lowland rice genotypes. *Communications in Soil Science and Plant Analysis*, 32, 2079-2089. doi:10.1081/CSS-120000270.
- FAO, (2014). FAOSTAT. Available at: <http://faostat.fao.org/>.
- FAO, (2020). *World Fertilizer Trends and Outlook to 2020*. FAO. Available at: <https://www.fao.org/3/i6895e/i6895e.pdf>.
- Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R. and Sutton, M.A., (2008). Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science*, 320, 889-892. doi:10.1126/science.1136674.
- Good, A.G. and Beatty, P.H., (2011). Biotechnological approaches to improving nitrogen use efficiency in plants: alanine aminotransferase as a case study. In *The Molecular and Physiological Basis of Nutrient Use Efficiency in Crops*, 165-191. doi:10.1002/9780470960707.ch9.
- Hirel, B., Tétu, T., Lea, P.J. and Dubois, F., (2011). Improving nitrogen use efficiency in crops for sustainable agriculture. *Sustainability*, 3, 1452-1485. doi:10.3390/su3091452.
- Kopittke, P.M., Menzies, N.W., Dalal, R.C., McKenna, B.A., Husted, S., Wang, P. and Lombi, E., (2021). The role of soil in defining planetary boundaries and the safe operating space for humanity. *Environment International*, 146, 106245. doi:10.1016/j.envint.2020.106245.
- Kumar, A., Singh, K., Verma, P., Singh, O., Panwar, A., Singh, T. and Raliya, R., (2022). Effect of nitrogen and zinc nanofertilizer with the organic farming practices on cereal and oil seed crops. *Scientific Reports*, 12, 6938. doi:10.1038/s41598-022-10843-3.

- Kumar, Y., Tiwari, K.N., Nayak, R.K., Rai, A., Singh, S.P., Singh, A.N. and Raliya, R., (2020). Nanofertilizers for increasing nutrient use efficiency, yield and economic returns in important winter season crops of Uttar Pradesh. *Indian Journal of Fertilisers*, 16, 772-786.
- Kumar, Y., Tiwari, K.N., Singh, T. and Raliya, R., (2021). Nanofertilizers and their role in sustainable agriculture. *Annals of Plant and Soil Research*, 23, 238-255. doi:10.47815/apr.2021.10067.
- Ladha, J.K. and Reddy, P.M., (2003). Nitrogen fixation in rice systems: state of knowledge and future prospects. *Plant and Soil*, 252, 151-167. doi:10.1023/A:1024175307238.
- Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B. and Hobbs, P.R., (2003). How extensive are yield declines in long-term rice-wheat experiments in Asia? *Field Crops Research*, 81, 159-180. doi:10.1016/S0378-4290(02)00219-8.
- Marschner, P., (2012). *Marschner's Mineral Nutrition of Higher Plants*. 3rd edn. Academic Press, Elsevier, UK. doi:10.1016/C2009-0-63043-9.
- Mohan, S., Singh, M. and Kumar, R., (2015). Effect of nitrogen, phosphorus and zinc fertilization on yield and quality of kharif fodder—a review. *Agricultural Reviews*, 36, 218-226. doi:10.5958/0976-0741.2015.00025.2.
- Mosier, A.R., Bleken, M.A., Chaiwanakupt, P., Ellis, E.C., Freney, J.R., Howarth, R.B. and Zhu, Z.L., (2002). Policy implications of human-accelerated nitrogen cycling. In *The Nitrogen Cycle at Regional to Global Scales*, 477-516. Springer, Dordrecht. doi:10.1007/978-94-017-3405-9_15.
- Sutton, M. et al., (2013). *Our Nutrient World: The Challenge to Produce More Food and Energy with Less Pollution*. Centre for Ecology and Hydrology, Edinburgh.
- Tiwari, S., Patel, A., Pandey, N., Raju, A., Singh, M. and Prasad, S.M., (2020). Sustainable solutions for elemental deficiency and excess in crop plants: deficiency of essential elements in crop plants. Springer, Singapore. doi:10.1007/978-981-15-8636-1_2.
- Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R. and Polasky, S., (2002). Agricultural sustainability and intensive production practices. *Nature*, 418, 671-677. doi:10.1038/nature01014.
- Timsina, J. and Connor, D.J., (2001). Productivity and management of rice-wheat cropping systems: issues and challenges. *Field Crops Research*, 69, 93-132. doi:10.1016/S0378-4290(00)00143-X.
- Upadhyay, P.K., Dey, A., Singh, V.K., Dwivedi, B.S., Singh, T., GA, R. and Shukla, G., (2023). Conjoint application of nano-urea with conventional fertilizers: an energy efficient and environmentally robust approach for sustainable crop production. *PLOS ONE*, 18, e0284009. doi:10.1371/journal.pone.0284009.
- Upadhyay, P.K., Dey, A., Singh, V.K. et al., (2024). Changes in microbial community structure and yield responses with the use of nano-fertilizers of nitrogen and zinc in wheat-maize system. *Scientific Reports*, 14, 1100. doi:10.1038/s41598-023-48951-3.
- Zhang, Q., Sun, J., Liu, J., Huang, G., Lu, C. and Zhang, Y., (2015). Driving mechanism and sources of groundwater nitrate contamination in the rapidly urbanized region of south China. *Journal of Contaminant Hydrology*, 182, 221-230. doi:10.1016/j.jconhyd.2015.09.009.