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Effect of nano-urea and fertilizer deep placement on nutrient uptake and nitrogen use efficiency in wet direct seeded rice (*Oryza sativa* L.)

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Abstract
Efficient nitrogen management is essential for improving nutrient uptake and nitrogen use efficiency in rice cultivation, particularly under wet cultivation systems where nutrient losses are high. A field experiment was conducted during the *kharif* seasons of 2022 and 2023 at the Instructional-cum-Research Farm, Assam Agricultural University, Jorhat, to evaluate the effect of different nitrogen management practices on nutrient uptake (N, P and K) and nitrogen use efficiency indices in rice. The experiment was laid out in a randomized block design with three replications and thirteen treatments, comprising different levels of recommended dose of nitrogen (RDN), nano-urea application and fertilizer deep placement (FDP). Grain and straw samples collected at harvest were analyzed for nitrogen, phosphorus and potassium content, and nutrient uptake was calculated. Partial factor productivity of nitrogen (PFPN) and agronomic efficiency of nitrogen (AE) were computed to assess nitrogen use efficiency. Nutrient uptake showed numerical variation among treatments. The highest total nitrogen uptake (68.57 kg ha^{-1}) was recorded under 125% RDN + nano-urea, followed by 100% RDN as FDP (63.70 kg ha^{-1}), whereas the lowest uptake (22.09 kg ha^{-1}) was observed under the control. Similarly, total phosphorus uptake ranged from 6.12 kg ha^{-1} in the control to 16.89 kg ha^{-1} under 100% RDN as FDP, while total potassium uptake varied from 27.53 to 61.79 kg ha^{-1} across treatments. Nitrogen use efficiency indices responded distinctly to nitrogen management practices. Higher PFPN was observed under reduced nitrogen doses combined with nano-urea, with a maximum PFPN of 181.42 kg grain kg^{-1} N under 50% RDN + nano-urea. Agronomic efficiency was highest under 125% RDN + nano-urea, recording 75.20 kg grain kg^{-1} N, indicating better yield response to applied nitrogen. Overall, the results suggest that nano-urea application and fertilizer deep placement improved nutrient uptake and nitrogen use efficiency compared to conventional surface application. The study highlights that optimizing nitrogen application methods and timing is more effective than increasing nitrogen dose for achieving sustainable rice production.

Keywords: Rice, nitrogen use efficiency, nano-urea, fertilizer deep placement, nutrient uptake

Introduction
Rice (*Oryza sativa* L.) is one of the most important cereal crops in the world and serves as the staple food for more than half of the global population, particularly in Asia. In India, rice occupies a major share of cultivated area and plays a crucial role in ensuring food and nutritional security. Sustaining rice productivity is therefore essential to meet the food demand of an increasing population (FAO, 2017; IRRI, 2020) [9, 12]. Rice is a nutrient-exhaustive crop with a high requirement for nitrogen, which is the most limiting nutrient for growth and yield. However, nitrogen use efficiency in rice is generally low, often ranging between 30-40 per cent, due to losses through volatilization, leaching, runoff and denitrification, especially under wet cultivation conditions (Ladha *et al.*, 2005; Fageria and Baligar, 2005) [10, 13]. Along with nitrogen, adequate uptake of phosphorus and potassium is equally important, as these nutrients play vital roles in root development, energy transfer, enzyme activation and assimilate translocation. Imbalanced or inefficient nutrient management leads to poor nutrient uptake, reduced yield and increased fertilizer losses (Dobermann and Fairhurst, 2000) [8]. Conventional surface application of nitrogen fertilizers in rice fields often results in substantial nutrient losses

and poor synchronization between nitrogen supply and crop demand. This problem is more pronounced in wet direct seeded rice systems, where fluctuating soil moisture conditions enhance nitrogen losses and reduce nutrient recovery by the crop (Choudhury and Kennedy, 2005; Pan *et al.*, 2016) [5, 15]. Although recommended nitrogen doses are widely followed, their effectiveness varies across establishment methods and soil conditions, highlighting the need for improved nitrogen management strategies. Fertilizer deep placement is an efficient nitrogen management practice that places nitrogen fertilizers in the reduced soil zone, thereby minimizing nitrogen losses and ensuring sustained nitrogen availability to rice roots. Several studies have reported improved nutrient uptake and nitrogen use efficiency with fertilizer deep placement compared to surface broadcasting (Bandaogo *et al.*, 2015; Chen *et al.*, 2021) [2, 4]. Similarly, nano-urea has emerged as a novel nitrogen source that enhances nitrogen absorption efficiency due to its small particle size and high surface area. Foliar application of nano-urea improves synchronization between nitrogen supply and crop demand and reduces fertilizer requirement (De Rosa *et al.*, 2010; Rahale, 2010) [6, 16]. Nutrient uptake of nitrogen, phosphorus and potassium is a direct indicator of nutrient absorption and utilization by the crop. In addition, nitrogen use efficiency indices such as partial factor productivity of nitrogen (PFPN) and agronomic efficiency of nitrogen (AE) are widely used to evaluate the effectiveness of nitrogen management practices. PFPN reflects the grain yield obtained per unit of nitrogen applied, while AE indicates the yield response to applied nitrogen, making these indices important tools for assessing sustainable nutrient management (Dobermann, 2007; Fageria *et al.*, 2011) [7, 11]. Despite the availability of improved nitrogen management practices, limited information is available on their comparative effects on nutrient uptake and nitrogen use efficiency indices under rice cultivation. Therefore, the present investigation was undertaken to evaluate the effect of different nitrogen management practices involving varying nitrogen levels, nano-urea application and fertilizer deep placement on N, P and K uptake and nitrogen use efficiency indices in rice. The results of this study are expected to contribute to the development of efficient and sustainable nitrogen management strategies for rice production.

Materials and Methods

Experimental site and crop

The field experiment was conducted during the kharif seasons of 2022 and 2023 at the Instructional-cum-Research Farm, Assam Agricultural University, Jorhat, Assam. Rice (*Oryza sativa* L.) was grown under wet direct seeded and transplanted conditions following recommended agronomic practices. The soil of the experimental field was sandy loam, acidic in reaction, medium in organic carbon and available nitrogen, medium in available phosphorus and low in available potassium.

Experimental design and treatments

The experiment was laid out in a Randomized Block Design (RBD) with three replications. Thirteen nitrogen management treatments comprising different nitrogen levels, nano-urea application and fertilizer deep placement were evaluated. Nitrogen was applied at 50, 75, 100 and 125 per cent of the recommended dose of nitrogen (RDN) through urea as surface application, fertilizer deep placement or in combination with foliar sprays of nano-urea. Nano-urea was applied as two foliar sprays at active tillering and panicle initiation stages. Phosphorus and potassium were applied uniformly to all treatments as per the recommended dose.

Sampling and analysis of nutrient uptake

At harvest, grain and straw samples were collected separately from each treatment plot. The plant samples were oven-dried, ground and analysed for nitrogen, phosphorus and potassium content using standard laboratory procedures. Nitrogen content was estimated by the Kjeldahl method, phosphorus by vanado-molybdate yellow colour method and potassium by flame photometry. Nutrient uptake by grain and straw was calculated by multiplying nutrient concentration with corresponding dry matter yield and expressed as kg ha^{-1}. Total nutrient uptake was obtained by summing grain and straw uptake.

Nitrogen use efficiency indices

Partial factor productivity of nitrogen (PFPN) was calculated as the ratio of grain yield to the amount of nitrogen applied. Agronomic efficiency of nitrogen (AE) was calculated as the increase in grain yield due to nitrogen application divided by the quantity of nitrogen applied.

Statistical analysis

Data on nutrient uptake and nitrogen use efficiency indices were subjected to analysis of variance (ANOVA) following the procedure appropriate for the randomized block design. Treatment means were compared using critical difference at 5 per cent probability level wherever applicable.

Results

A. Nutrient uptake

The uptake of nitrogen, phosphorus and potassium by grain, straw and total uptake showed non-significant variation among treatments, though distinct numerical trends were evident across nitrogen management practices (Table 1).

- **Nitrogen uptake**

Nitrogen uptake in grain did not differ significantly among the treatments, though clear numerical variation was observed. The highest grain nitrogen uptake was recorded under 125% RDN + nano-urea (T_9) with 41.41 kg ha^{-1}, followed by 100% RDN as FDP (T_{12}) (38.32 kg ha^{-1}) and 125% RDN as FDP (T_{13}) (37.56 kg ha^{-1}). The lowest grain nitrogen uptake was observed in the control treatment (T_1) with 13.21 kg ha^{-1}. Treatments receiving nano-urea or fertilizer deep placement recorded higher numerical values compared to sole RDN application; however, these differences remained statistically non-significant. Straw nitrogen uptake also showed non-significant variation among treatments. Numerically, T_9 (125% RDN + nano- urea) recorded the highest straw nitrogen uptake (27.17 kg ha^{-1}), followed by T_{12} (100% RDN as FDP) (25.38 kg ha^{-1}) and T_{13} (125% RDN as FDP) (24.42 kg ha^{-1}). The minimum uptake was recorded under T_1 (control) (8.88 kg ha^{-1}). The graphical trend indicated increased straw nitrogen uptake under higher nitrogen levels and improved nitrogen placement methods. Total nitrogen uptake did not vary significantly, but exhibited a consistent numerical trend. The maximum total nitrogen uptake was recorded in T_9 (68.57 kg ha^{-1}), followed by T_{12} (63.70 kg ha^{-1}) and T_{13} (61.99 kg ha^{-1}). The lowest total uptake was observed under the control (22.09 kg ha^{-1}). The numerical increase in total nitrogen uptake reflects the cumulative effect of higher grain and straw uptake under improved nitrogen management practices.

- **Phosphorus uptake**

Phosphorus uptake in grain did not show significant differences among treatments. Numerically, the highest grain phosphorus uptake was observed under 100% RDN as FDP (T_{12}) with 8.99 kg ha^{-1}, followed by 125% RDN as FDP (T_{13}) (8.82 kg ha^{-1}) and 125% RDN + nano-urea (T_9) (7.61 kg ha^{-1}). The lowest uptake was recorded in the control (T_1) (2.67 kg ha^{-1}). Although FDP and nano-urea treatments recorded higher numerical values, the differences were statistically non-significant. Straw phosphorus uptake remained statistically non-significant across treatments. The highest numerical uptake was recorded under T_{12} (7.89 kg ha^{-1}), closely followed by T_{13} (7.83 kg ha^{-1}), whereas the lowest uptake was observed in T_1 (3.46 kg ha^{-1}). The numerical trend suggests improved phosphorus uptake under fertilizer deep placement treatments. Total phosphorus uptake did not differ significantly, but varied numerically among treatments. The highest total phosphorus uptake was recorded under T_{12} (16.89 kg ha^{-1}), followed by T_{13} (16.65 kg ha^{-1}) and T_9 (14.87 kg ha^{-1}). The lowest total uptake was observed under T_1 (6.12 kg ha^{-1}). The graphical representation corroborates the gradual increase in phosphorus uptake under FDP and nano-urea integrated treatments.

- **Potassium uptake**

Potassium uptake in grain showed non-significant differences among treatments, with noticeable numerical variation. The highest grain potassium uptake was recorded under 100% RDN as FDP (T_{12}) with 12.98 kg ha^{-1}, followed by 125% RDN as FDP (T_{13}) (12.85 kg ha^{-1}) and 125% RDN + nano-urea (T_9) (12.45 kg ha^{-1}). The lowest uptake was recorded in the control (T_1) (4.53 kg ha^{-1}). Straw potassium uptake did not differ significantly, though higher numerical values were recorded under FDP treatments. T_{13} recorded the highest straw potassium uptake (49.03 kg ha^{-1}), followed by T_{12} (48.78 kg ha^{-1}), whereas the lowest uptake was recorded under T_1 (22.92 kg ha^{-1}). The figure illustrates a consistent numerical advantage of fertilizer deep placement. Total potassium uptake remained statistically non-significant among treatments. Numerically, the maximum total potassium uptake was observed under T_{12} (61.79 kg ha^{-1}) and T_{13} (61.73 kg ha^{-1}), followed by T_9 (56.43 kg ha^{-1}). The lowest total uptake was recorded in the control (27.53 kg ha^{-1}). The cumulative uptake trend mirrors the individual grain and straw uptake patterns.

B. Nitrogen use efficiency indices (PFPN and AE)

The partial factor productivity of nitrogen (PFPN) and agronomic efficiency (AE) exhibited distinct numerical variation among treatments, as depicted in Fig. 1.

- **Partial factor productivity of nitrogen (PFPN)**

PFPN values showed wide numerical variation across treatments. The highest PFPN was recorded under T_6 (50% RDN + nano-urea) with a value of 181.42 kg grain kg^{-1} N, indicating superior nitrogen use efficiency at reduced nitrogen application. This was followed by T_7 (75% RDN + nano-urea) (142.27 kg kg^{-1}) and T_8 (100% RDN + nano-urea) (141.35 kg kg^{-1}). Moderate PFPN values were observed under T_9 (125% RDN + nano-urea) (129.61 kg kg^{-1}) and T_{10} (50% RDN as FDP) (98.18 kg kg^{-1}). In contrast, lower PFPN values were recorded under higher nitrogen doses applied through FDP and conventional methods, with T_{13} (125% RDN as FDP) recording 59.67 kg kg^{-1}, and T_5 (125% RDN) showing 55.89 kg kg^{-1}. The control (T_1) recorded zero PFPN due to the absence of nitrogen application. Overall, PFPN exhibited a declining trend with increasing nitrogen levels, particularly under conventional and FDP-based higher nitrogen doses.

- **Agronomic efficiency (AE)**

The highest AE was recorded under T_9 (125% RDN + nano-urea) with 75.20 kg grain kg^{-1} N, followed closely by T_8 (100% RDN + nano-urea) (73.36 kg kg^{-1}) and T_7 (75% RDN + nano-urea) (51.67 kg kg^{-1}). Treatments receiving FDP recorded intermediate AE values, with T_{12} (100% RDN as FDP) showing 41.44 kg kg^{-1}, while T_{10} (50% RDN as FDP) recorded 30.08 kg kg^{-1}. Lower AE values were observed under sole RDN treatments, with T_4 (100% RDN) (26.71 kg kg^{-1}) and T_5 (125% RDN) (28.65 kg kg^{-1}). As expected, T_1 (control) recorded zero AE. The trend indicates that integration of nano-urea with reduced or recommended nitrogen doses enhanced agronomic efficiency, whereas higher nitrogen application rates resulted in reduced AE.

Discussion

The uptake of nitrogen, phosphorus and potassium in wet direct seeded rice under different nitrogen management practices can be explained by variations in nutrient availability, retention in the root zone, and plant physiological responses induced by nano-urea application and fertilizer deep placement. Improved nitrogen uptake under nano-urea-based treatments may be attributed to the unique physicochemical properties of nano-urea particles, which possess extremely small size and high surface area, facilitating rapid absorption through stomatal openings and cuticular pathways. Foliar-applied nano-urea ensures direct delivery of nitrogen to metabolically active plant tissues, thereby improving synchronization between nitrogen supply and crop demand. This enhanced nitrogen availability supports increased chlorophyll synthesis, photosynthetic efficiency and assimilate production, ultimately promoting greater biomass accumulation and nitrogen uptake in wet direct seeded rice (De Rosa *et al.*, 2010; Rahale, 2010) [6, 16]. In treatments involving fertilizer deep placement, higher nutrient uptake can be explained by the placement of nitrogenous fertilizers in the reduced soil zone, where ammoniacal nitrogen remains stable and available for a longer duration. Deep placement minimizes nitrogen losses through ammonia volatilization, leaching and denitrification, which are common in surface-applied fertilizers under wet direct seeded rice conditions. Sustained nitrogen availability in the root zone enhances root growth and activity, leading to improved nutrient absorption throughout the crop growth period (Pan *et al.*, 2016; Chen *et al.*, 2021) [4, 15].

Enhanced phosphorus uptake under improved nitrogen management practices may be attributed to indirect effects of nitrogen on root morphology and metabolic activity. Adequate nitrogen supply stimulates root proliferation and increases root surface area, enabling greater exploration of soil phosphorus pools. In acidic soils, such as those of the experimental site, phosphorus availability is often constrained due to fixation; however, improved root growth and rhizosphere activity under better nitrogen nutrition can enhance phosphorus solubilization and uptake. Similar synergistic interactions between nitrogen availability and phosphorus uptake in rice have been reported earlier (Sahu *et al.*, 2022; Namasharma *et al.*, 2023) [14, 17].

Potassium uptake in wet direct seeded rice appears to be closely associated with biomass production, particularly straw yield. Potassium plays a vital role in enzyme activation, stomatal regulation and translocation of photosynthates. Improved nitrogen nutrition under nano-urea and fertilizer deep placement treatments enhances vegetative growth and dry matter accumulation, thereby increasing potassium demand and uptake.

Deep placement of fertilizers may further support potassium uptake by maintaining a favorable nutrient environment in the root zone and reducing nutrient losses, leading to sustained potassium availability during critical growth stages (Bandaogo *et al.*, 2015; Sharna *et al.*, 2021) [2, 18]. Lower nutrient uptake observed under conventional surface application and control treatments can be attributed to inefficient nitrogen utilization, restricted root development and reduced biomass production. In wet direct seeded rice, where nutrient losses are often pronounced due to fluctuating soil moisture regimes, inefficient fertilizer placement limits nutrient recovery by the crop, thereby reducing overall N, P and K uptake (Chatterjee *et al.*, 2018; Akter *et al.*, 2022) [1, 3].

Higher partial factor productivity and agronomic efficiency of nitrogen under nano- urea-based treatments can be attributed to improved nitrogen absorption and reduced nitrogen losses. Foliar application of nano-urea supplies nitrogen directly to plant leaves during critical growth stages, resulting in better synchronization between nitrogen availability and crop demand. This improves nitrogen recovery and yield per unit of applied nitrogen. Fertilizer deep placement also enhances nitrogen use efficiency by retaining ammoniacal nitrogen in the reduced soil zone, thereby reducing volatilization and leaching losses. Sustained nitrogen availability under deep placement supports continuous nitrogen uptake and yield formation. Lower efficiency at higher nitrogen doses may be due to diminishing yield response to excess nitrogen. These findings indicate that efficient nitrogen application methods are more important than higher nitrogen doses for improving nitrogen use efficiency in wet direct seeded rice (De Rosa *et al.*, 2010; Rahale, 2010; Pan *et al.*, 2016; Sahu *et al.*, 2022) [6, 15, 16, 17].

Table 1: Effect of nano-urea and fertilizer deep placement on nutrient Effect of nano-urea and fertilizer deep placement on partial factor productivity and agronomic efficiency under wet direct seeded and transplanted kharif riceuptake in grain, straw and total uptake of wet direct seeded kharif rice.

Treatment	N uptake (kg/ha)			P uptake (kg/ha)			K uptake (kg/ha)		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T_1 - Control	13.21	8.88	22.09	2.67	3.46	6.12	4.53	22.92	27.53
T_2 - 50% RDN	18.99	11.75	30.73	3.67	4.39	8.07	6.28	27.95	34.13
T_3 - 75% RDN	26.90	16.05	42.95	4.84	5.34	10.18	8.25	33.33	41.44
T_4 - 100% RDN	30.03	18.56	48.59	5.39	5.75	11.14	9.12	35.51	44.56
T_5 - 125% RDN	34.73	21.91	56.63	6.46	6.68	13.13	10.63	40.98	51.71
T_6 - 50% RDN + Nano-urea	20.98	13.33	34.31	3.95	4.57	8.52	6.67	28.85	35.59
T_7 - 75% RDN + Nano-urea	25.68	15.75	41.43	4.70	5.33	10.02	7.98	32.98	40.89
T_8 - 100% RDN + Nano-urea	35.55	22.90	58.44	6.37	6.52	12.89	10.73	40.26	51.17
T_9 - 125% RDN + Nano-urea	41.41	27.17	68.57	7.61	7.26	14.87	12.45	44.13	56.43
T_{10} - 50% RDN as FDP	22.74	14.33	37.06	5.71	5.70	11.41	8.33	36.05	44.23
T_{11} - 75% RDN as FDP	28.85	17.79	46.63	6.90	6.61	13.50	10.09	41.53	51.59
T_{12}- 100% RDN as FDP	38.32	25.38	63.70	8.9	7.89	16.89	12.98	48.78	61.79
T_{13}- 125% RDN as FDP	37.56	24.42	61.99	8.82	7.83	16.65	12.85	49.03	61.73
S.Em (±)	-	-	-	-	-	-	-	-	-
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS

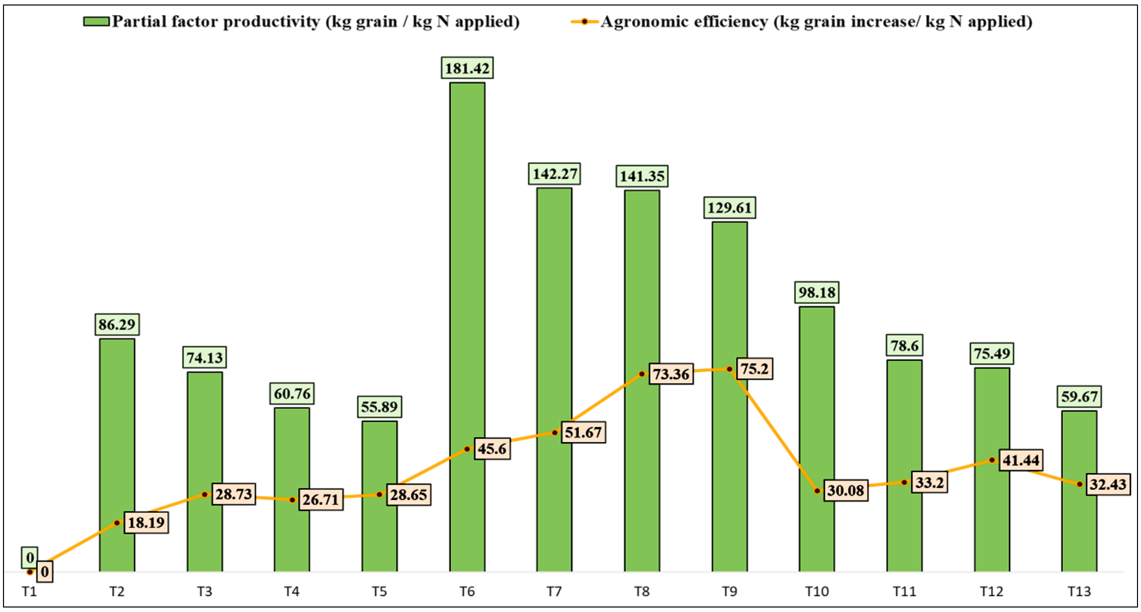

Fig 1: Effect of nano-urea and fertilizer deep placement on partial factor productivity and agronomic efficiency under wet direct seeded kharif rice.

Conclusion

The present study demonstrated that nitrogen management practices influenced nutrient uptake and nitrogen use efficiency in wet direct-seeded rice. Integration of nano-urea application or fertilizer deep placement with recommended nitrogen levels improved the uptake of nitrogen, phosphorus and potassium compared to conventional surface application. Higher partial factor productivity was observed under reduced nitrogen doses combined with nano- urea, while higher agronomic efficiency was recorded under moderate to higher nitrogen levels integrated with nano-urea or fertilizer deep placement. The results indicate that improving the method and timing of nitrogen application is more effective than increasing nitrogen dose. Overall, nano-urea application and fertilizer deep placement emerge as promising strategies for enhancing nitrogen use efficiency and promoting sustainable nutrient management in wet direct seeded rice.

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