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RESEARCH ARTICLE

Effect of irrigation regimes and nano-urea based nitrogen management on yield attributes, productivity, nutrient acquisition and use efficiency of wheat in Eastern Plateau region of India

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Abstract

Wheat (*Triticum aestivum* L.) production is vital for India's food security, with projections indicating a substantial 70-104 % increase in demand by 2050. However, Eastern Plateau regions face challenges of warmer climate leading to aberration in irrigation regimes (IRs) and nutrient, especially nitrogen (N) management resulting in lower productivity. Study revealed that IRs significantly influenced yield attributes viz., spikelets/spike and 1000-grain weight, with moisture stress during grain filling stages adversely impacting grain development, resulted in 29 % yield reduction. The 100 % recommended dose of nitrogen (RDN) resulted in significantly superior yield attributes; surpassing nano-urea based nitrogen application. The grain yield with 100 % RDN leading with the highest yield and grain N content of 7.0 and 14.5 % more compared to nano-urea based 50 % RDN+2 NUS (nano-urea spray) treatment respectively. Interaction effect of 3-irrigation regimes with 100 % RDN on grain yield was significantly superior over NUS nullifying the synergistic effect of NUS with IRs. However, 50 % RDN+2 NUS reported significantly ($p=0.05$) superior N content (0.42 %) and N uptake (31.30 kg/ha) in straw. Additionally, five irrigations exhibited significantly higher grain and total N uptake by 30.9 and 25.78 % compared to two irrigations, respectively. Apparent nitrogen recovery and agronomic nitrogen use efficiency were the highest in 50 % RDN+2 NUS due to better N acquisition and less amount of N application through NUS. Thus 3-irrigation regimes and 100 % RDN can be recommended as an agronomic management practice for maximising wheat productivity in Eastern Plateau region of India.

Keywords

irrigation regimes, moisture stress, nano-urea, nitrogen use efficiency, nutrient content, productivity

Introduction

Wheat, scientifically known as *Triticum aestivum* L. is a high-energy consuming winter cereal that provides 112.74 million tons of grain annually from an area of 30.5 million hectares, accounting for 35 % of India's food grain production (1). According to projections, the total demand for wheat is expected to climb by 32-38 % by 2030 (74 kg/capita) and by 70-104 % by 2050 (94 kg/capita), highlighting the necessity of giving priority to expand the production and acreage to guarantee food and nutritional security (2). Even though wheat is highly adaptable in India but its production in Jharkhand (a state in India's eastern plateau region) makes up less than 1 % of the country's total output. The crop is grown in an area of 2.21 lakh hectares, with an average productivity of 2.13 t/ha, which is lower than the national average of 3.5 t/ha. This is primarily because of the state's comparatively warmer climate (5-7 °C higher temperature), which affects the crop growth (3). This low productivity zone receives hot winds at grain filling stage which reduces growth duration and size of the grain. The Eastern States including Jharkhand have potential for higher wheat yields (4.5 t/ha) which was demonstrated by front-line demonstrations. Future improvements in production are expected from these low-productivity zones. The reduction of wheat cultivation in high-productivity areas could be driven by issues such as falling water tables, infestations of *Phalaris minor*, or the shift toward growing high-value crops. These changes could shift the focus of production to areas previously considered less productive. Irrigation during booting to heading phases improves spike and grain development and helps to increase productivity (4). Drought stress conditions negatively impact wheat yield and its components, highlighting the importance of proper irrigation management practices based on critical growth stages to minimize the yield gap (5). Nitrogen (N) deficiency in soils, is a significant factor contributing to the low productivity of wheat in Eastern India. Nitrogen serves as a fundamental structural component in various essential biological compounds such as proteins, enzymes, chlorophyll, Rubisco, nucleic acids and certain hormones. Consequently, nitrogen fertilization becomes a vital agronomic management practice to boost crop productivity, especially during the vegetative growth stages. Proper management of nitrogenous fertilizer is crucial for maximizing crop productivity. However, nitrogen losses such as nitrate leaching, denitrification and runoff to surface and groundwater reduce fertilizer efficiency to 50-60 %, causing economic losses and environmental pollution (6). To address these challenges, nano-fertilizers show promise in enhancing nutrient uptake and use efficiency, reducing losses through leaching and emissions and minimizing the risk of nutrient toxicity. However, information on the interaction between irrigation and different nitrogen management practices in the plateau region of India is limited. Keeping this in the context, a field experiment was set up to figure out the effect of various irrigation regimes and nitrogen management practices on the yield attributes, productivity, nutrient acquisition and use efficiency of wheat under eastern plateau region of India.

Materials and Methods

The field experiment was conducted at the farm of ICAR-Indian Agricultural Research Institute, Jharkhand during 2021-2022. The farm is situated at 24°16' N latitude, 85°21' E longitude and has an elevation of 628 meters above MSL. The long-term weather data of the site of experimentation denotes it as a semi-arid and sub-tropical climate with hot, dry summers in May and June and moderately cold winters from late November to January. The soil in the experimental field is sandy clay loam, offering good drainage and low water-holding capacity. It has an acidic pH of 5.85, low electrical conductivity (EC) of 0.712dS/m, low cation exchange capacity of 7.8 c mol (P^+)/kg, low organic carbon content of 0.25 % and low levels of available nitrogen and phosphorus (150.6 kg N/ha and 8.27 kg P_2O_5/ha) and medium availability of potassium (132.16 kg K_2O/ha). During the growing period, crop received a total rainfall of 100.5 mm, although it was unevenly distributed throughout the season. The experiment was set up in a split-plot design with the main plots assigned to three irrigation regimes (IRs) viz., I_1 (5-irrigations on a priority basis), I_2 (3-irrigations at CRI, flowering and milking stage) and I_3 (2-irrigations at CRI and flowering stage) and five nano urea-based nitrogen management practices (NMPs) in the subplots viz., N_0 (control without nitrogen application), N_1 (100 % RDN-120 kg N/ha, split as 1/3rd basal, 1/3rd at CRI and 1/3rd at the 2nd irrigation), N_2 (50 % RDN, half basal and half at CRI, with nano-urea spray at 60 DAS), N_3 (50 % RDN, half basal and half at CRI, with two nano-urea spray at 45 DAS & 70 DAS) and N_4 (75 % RDN, half basal and half at CRI, with nano-urea spray at 60 DAS) and replicated thrice. The main plot size was 22m x 5m, while the subplot size was 5m × 4m. N in the form of prilled urea was applied according to the treatments and full doses of phosphorus (P) and potassium (K) were applied as a basal application at a rate of N: P_2O_5: K_2O - 120:60:40 kg/ha. Nano-urea was applied @ 4 ml per litre of water in the evening time, as per the treatment specifications. The first irrigation was applied at the crown root initiation stage and subsequent irrigations were given based on recommended guidelines, taking local weather conditions into consideration. Irrigation was withheld 15 days before harvesting of the crop. The wheat variety DBW-187 (Karan Vandana) was sown with row spacing of 22.5 cm and a seed rate of 100 kg/ha. The pests and weed control measures were undertaken across the treatments throughout the crop growth period as and when required. At maturity, the number of effective tillers per square meter was determined by counting tillers with more than 50 % of the ear filled. The length of the main spikes of the plants, measured from the base to the tip of the floret (excluding awns), was recorded as ear length (in cm). The grain quantity within each ear head was assessed and their weight was recorded. The average value of the number of grains per spike was calculated. Before threshing, biological yield was measured and after threshing, the total grain weight and straw weight from the net plot area were recorded and converted to a metric ton per hectare basis at a constant moisture content of 12 %. The Harvest Index (HI) was calculated by using following expression (7).

$$HI = \frac{\text{Grain yield}}{\text{Biological yield}}$$

The modified alkaline potassium permanganate method was used to estimate the amount of available N (8), for available P Bray and Kurtz method was used (9). The available K (kg/ha) was extracted using neutral normal ammonium acetate solution and measured using a flame photometer. The N concentration in dried grain and straw samples was determined by Kjeldahl digestion method (8). The P content was quantified using the Vanado-molybdate phosphoric acid yellow colour method (11) with a Spectronic-20 colorimeter with blue filter and the K content of grain and straw was assessed using a Flame photometer (11). The grain protein content was determined by multiplying N content in percent with a factor 5.83 (12).

Partial Factor Productivity (PFP) is calculated by following formulas:

$$PFP = \frac{Y_f}{N_a}$$

Where,

Y_f = Yield obtained from fertilized plot

N_a = Nutrient applied (kg/ha)

Efficiency indices were computed using the following formulas -

Agronomic N use efficiency (ANUE) =

$$\frac{Y_t - Y_o}{A_t} \text{ Kg grain/kg N applied}$$

$$\text{Physiological N use efficiency } (PE_N) = \frac{Y_t - Y_o}{U_t - U_o}$$

$$\text{Apparent N recovery (ANR)} = \frac{U_t - U_o}{N_a} \times 100$$

N efficiency ratio (NER) =

$$\frac{\text{Dry matter yield (kg/ha)}}{\text{N accumulated at harvest (kg/ha)}}$$

Physiological efficiency index of N (PEN)=

$$\frac{\text{Grain yield (kg/ha)}}{\text{N absorbed by biomass (kg/}}$$

Where,

Y_t = Yield in the test treatment (kg/ha)

Y_0 = Yield in the control (kg/ha)

A_t = Units of N applied in the test treatment (kg/ha)

U_t = Uptake of N in the test treatment (kg/ha)

U_0 = Uptake of N in the control plot (kg/ha)

Na = N applied to the test treatment (kg/ha)

Data analysis for each character was conducted using Analysis of Variance (ANOVA) and the significance of a split plot design was assessed using the 'F' test (13). The analysis for the split plot design was carried out using an online data analysis module, specifically the strengthening statistical computing for NARS portal (https://sscnars.icar.gov.in/). The treatment comparisons were made at a significance level of 5 % and Critical Difference (CD) and standard error of means (SEm±) were calculated for each character. Graphical representations of the data were included as needed.

Results

Yield attributes

Irrigation regimes (IRs) did not have any significant difference in ear-bearing tillers/m^2, whereas among NMPs the highest no. of ear-bearing tillers (EBT)/m^2 was recorded with both N_1 and N_3, which were almost 102 % higher than control (Table 1 and Fig. 1). The highest percentage of EBT/m^2 was observed with N_3 (71.36 %) which was significantly superior to the N_1 (66.50 %) and N_4 (67.04 %). The NMPs settled a significant difference in ear length possessing the maximum ear length (10.64 cm) with N_1, similar with N_3. The N_2, N_4 and N_1 produced 26.1, 32.5 and 42.8 % more ear length over N_0. Among NMPs, N_3 resulted in the higher no. of spikelets per spike (21.44), statistically comparable to N_1, greater than other treatments (Fig. 2). Both I_1 and I_2 exhibited the highest no. of grains per ear head, surpassing I_3 treatments. The N_1 yielded the greatest grains per ear head, slightly outperforming N_3 and N_4. Remarkably N_1, N_2, N_3 and N_4 exhibited 95.15 %, 54.35 %, 86.41 % and 67.93 % higher grain per ear head, respectively, in comparison to the N_0. I_1 exhibited highest 1000-grain weight, significantly surpassing I_2 and I_3. On the other hand, N_1 achieved the maximum 1000-grain weight of 40.53 g, notably higher than other NMPs. Differences in 1000-grain weight, ranging from 8.4 % to 17.27 %, were observed due to various NMPs compared to the control.

Yield

Irrigation regimes has a significant effect (P value = 0.0038), whereas NMPs has a highly significant effect (P-value = 0), suggesting differences between at least two treatments and the interaction between them is also significant (P value = 0.003), suggesting that the effect of NMPs depends on the IRs treatments. Adequate irrigation (I_1) produced the higher yield

Table 1. Yield attributes and yield of wheat influenced by irrigation regime and nitrogen management practices

Treatment	EBT/m^2	Spike length (cm)	No. of spikelets/spike	No. of grains/ spike	1000-grain weight (g)	Grain yield (t/ha)	Straw yield (t/ha)	Biological yield (t/ha)	HI
Irrigation regime									
I_1	227.13	9.39	19.93^a	38.53^a	40.09^a	3.71^a	5.67	9.37^a	0.41
I_2	230.60	9.12	19.20^{ab}	38.13^a	39.27^b	3.64^a	5.63	9.26^a	0.40
I_3	217.27	9.30	18.13^b	33.73^b	35.41^c	2.82^b	5.05	7.87^b	0.37
SEm±	6.97	0.18	0.28	0.46	0.06	0.09	0.16	0.19	0.01
LSD (P≤0.05)	NS	NS	1.09	1.80	0.24	0.35	NS	0.76	NS
Nitrogen management									
N_0	129.78^d	6.36^d	15.44^d	22.89^e	34.56^d	1.23^e	1.52^d	2.75^d	0.45^a
N_1	263.11^a	10.64^a	21.11^a	44.67^a	40.53^a	4.62^a	7.41^a	12.03^a	0.38^{bc}
N_2	219.56^c	8.97^c	18.11^c	35.33^d	37.46^c	2.94^d	4.67^c	7.61^c	0.39^b
N_3	262.78^a	10.50^a	21.44^a	42.67^b	39.48^b	4.32^b	7.42^a	11.74^a	0.37^c
N_4	249.78^b	9.61^b	19.33^b	38.44^c	39.24^b	3.82^c	6.22^b	10.05^b	0.38^{bc}
SEm±	3.02	0.06	0.28	0.62	0.23	0.06	0.16	0.20	0.01
LSD (P≤0.05)	8.82	0.21	0.83	1.81	0.58	0.17	0.47	0.57	0.02
IRs×NMPs	NS	NS	NS	NS	NS	0.29	NS	NS	NS
NMPs×IRs	NS	NS	NS	NS	NS	0.43	NS	NS	NS

(I_1: 5 irrigations; I_2: 3 irrigations, I_3: 2 irrigations, N_0: control, N_1: 100 % RDN, N_2: 50 % RDN+1 NUS, N_3: 50 % RDN+2 NUS, N_4: 75 % RDN+1 NUS). Treatments with same letter are not significantly different (p=0.05)

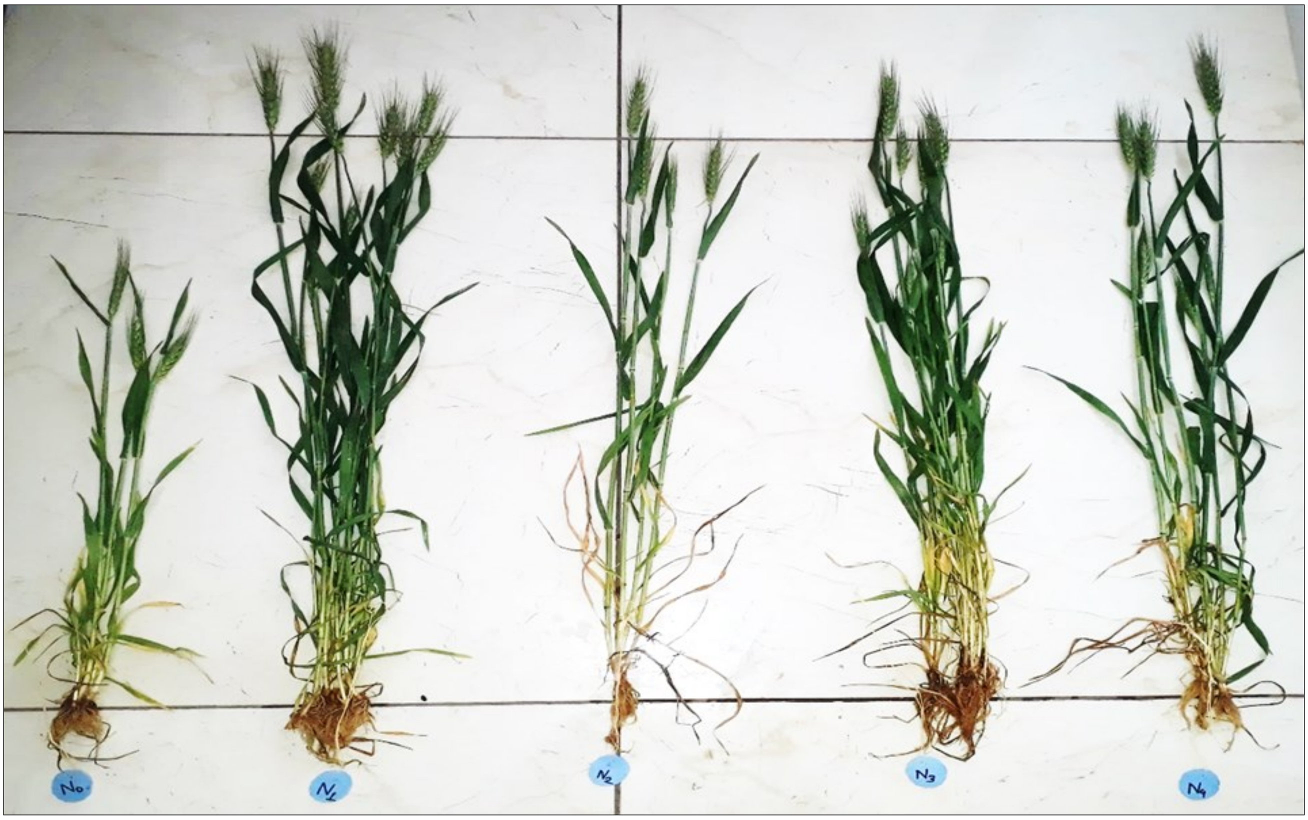

Fig. 1. Picture of the plant samples from experiment at flowering stage.
(From Left to Right:- N_0, N_1, N_2, N_3 and N_4)

Fig. 2. Effect of irrigation regimes and nitrogen management on spikes of wheat.

of 3.71 t/ha, comparable to I_2, which significantly surpass I_3 which resulted 29 % yield reduction compared to I_2. NMPs significantly impacted grain yield, N_3 followed as the second-best treatment with 4.32 t/ha, whereas N_1 leading with the highest yield, 7 % more yield compared to N_3, significantly outperforming other NMPs. Notably, yield under N_1 was 21 % more than N_4. N_3 recorded 45 % and 13 % more yield compared to N_2 and N_4 respectively. All NMPs - N_1, N_2, N_3 and N_4 yielded significantly higher results, increasing by 275.6 %, 139 %, 251 % and 210.5 % respectively, compared to the control (Table 1). Significant interactions emerged between IRs and NMPs where the higher yield was obtained with I_2N_1 and was statistically like I_1N_1, while the lowest yield was in I_3N_0. The study revealed no statistically significant differences between IRs in terms of straw yield. However, NMPs strongly influenced wheat straw output. N_1 (7.41 t/ha) and N_3 (7.42 t/ha) significantly increased straw yield compared to others. In the realm of IRs, elevated biological yield was evident with I_1 and I_2 showcased 19.05 and 17.66 % increase in productivity over I_3. The higher biological yield was observed in both N_1 and N_3 with yields of 337.4 % and 326.9 % higher than the control (N_0) respectively. In comparison, N_2 and N_4 yielded 176.7 % and 265.4 % higher than the control. Notably, NMPs had a substantial impact on the HI, with the control group (N_0) demonstrating a significantly higher index than other practices. Among managed nitrogen levels, N_3 had a lower harvest index, statistically like N_1 and N_4, but significantly different from N_2, which was also found to be similar to N_1 and N_4. The highest grain yield was obtained with I_2N_1 which was statistically like I_1N_1. whereas the lowest was observed in I_3N_0 (Fig. 3).

Protein content

Protein content demonstrated differences, reduced moisture correlated with increased protein with the lowest under I_1 and the highest (10.21 %) under I_3 irrigation regimes. N_1 had the highest protein (10.99 %), contrasting with the lowest in the control (Table 2). Application of higher doses of prilled urea in soil resulted more protein content compared to nano-urea application. Protein content of grains under N_4 was 8.1 % and 4 % more compared to N_3 and N_2 respectively. There is no significant interaction between IRs and NMPs.

N, P, K content and uptake by crop

Irrigation regimes did not significantly affect the nitrogen content in grain; however, higher irrigation levels resulted in a reduced nitrogen content, ranging from 1.67 % to 1.75 %, as shown in Table 2. Nitrogen content in straw decreased with fewer irrigations, with I_1 having the highest (0.37 %) and I_3 having the lowest (0.28 %) nitrogen content. N_1 recorded the highest grain nitrogen content (1.89 %) among practices, while control had the lowest. 1.48 %). N_2, N_3 and N_4 showed 1.72 %, 1.65 % and 1.79 % nitrogen content, respectively. N_1, N_2, N_3 and N_4 contained 27.70 %, 16.22 %, 11.48 % and 20.95 % respectively more nitrogen in grain compared to the control. N_3 had the highest straw nitrogen content (0.42 %), followed by N_1 (0.35 %), N_4 (0.34 %) and N_2 (0.32 %), with N_4 was statistically like both N_1 and N_2. Higher nitrogen content (0.45 %) in straw was observed in I_1N_3 treatment which was statistically like I_1N_1, I_2N_3 and I_1N_4 treatments. I_1 exhibited 30.9 % higher total N uptake compared to I_3 as grain N uptake of I_1 was 25.78 % greater than I_3. I_1 resulted the highest total N uptake (86.25 kg/ha) and resulted in 17.2 % and 47.6 % higher straw N uptake compared to I_2 and I_3. On the other hand, N_1 demonstrated the highest grain N uptake (86.88 kg/ha) and lowest under the control (18.09 kg/ha). N_3 (71.46 kg/ha) was like N_4 (67.92 kg/ha), both surpassing N_2 (50.80 kg/ha) in grain N uptake. Notably, in the interaction, the highest straw N uptake was observed in I_1N_3 (34.06 kg/ha), like I_1N_1 and I_2N_3 (Fig. 4). For the total N uptake, the highest total nitrogen uptake was observed in I_1N_1 (27.46 kg/ha) that was statistically similar with I_2N_1 (116.80 kg/ha) (Fig. 5).

Phosphorus (P) content in grains (0.3 %) and straw (0.07 %) showed no statistical differences across irrigation regimes (IRs). P content varied from 0.27 % to 0.32 % due to NMPs, with N_1 (0.32 %) and N_3 (0.31 %) exhibiting the higher values. For potassium (K), I_1 recorded the higher grain K content (0.36 %), followed by I_2 and I_3, with similar trends in straw. The highest K content (0.38 %) was observed in N_3, comparable to N_2 and N_4. Increased nano-urea doses enhanced grain K concentration but reduced straw K content. Grain P uptake was highest in I_1 (11.32 kg/ha), comparable to

Table 2. Nitrogen concentration, uptake and grain protein of wheat as influenced by irrigation regimes and nitrogen management practices

Treatment	N concentration in grain (%)	N concentration in straw (%)	N uptake in grain (kg/ha)	N uptake in straw (kg/ha)	Total N uptake (kg/ha)	Crude protein concentration of grain (%)
			Irrigation regimes			
I_1	1.67	0.37^{a}	63.43^{a}	22.82^{a}	86.25^{a}	9.72
I_2	1.70	0.31^{b}	63.23^{a}	19.47^{b}	82.70^{a}	9.90
I_3	1.75	0.28^{c}	50.43^{b}	15.46^{c}	65.89^{b}	10.21
SEm±	0.06	0.01	2.09	0.55	2.54	0.37
LSD (P≤0.05)	NS	0.02	8.23	2.15	9.98	NS
			Nitrogen management practices			
N_0	1.48^{d}	0.17^{d}	18.09^{d}	2.58^{e}	20.67^{e}	8.64^{d}
N_1	1.89^{a}	0.35^{b}	86.88^{a}	26.15^{b}	113.03^{a}	10.99^{a}
N_2	1.72^{bc}	0.32^{c}	50.80^{c}	14.97^{d}	65.77^{d}	10.03^{bc}
N_3	1.65^{c}	0.42^{a}	71.46^{b}	31.30^{a}	102.75^{b}	9.64^{c}
N_4	1.79^{b}	0.34^{bc}	67.92^{b}	21.27^{c}	89.19^{c}	10.42^{b}
SEm±	0.03	0.01	1.71	0.82	2.10	0.18
LSD (P≤0.05)	0.09	0.03	4.99	2.41	6.13	0.52
IRs×NMPs	NS	0.05	NS	4.18	10.61	NS
NMP×IRs	NS	0.05	NS	4.28	12.61	NS

(I_1: 5 irrigations; I_2: 3 irrigations, I_3: 2 irrigations, N_0: control, N_1: 100 % RDN, N_2: 50 % RDN+1 NUS, N_3: 50 % RDN+2 NUS, N_4: 75 % RDN+1 NUS). Treatments with same letter are not significantly different (p=0.05)

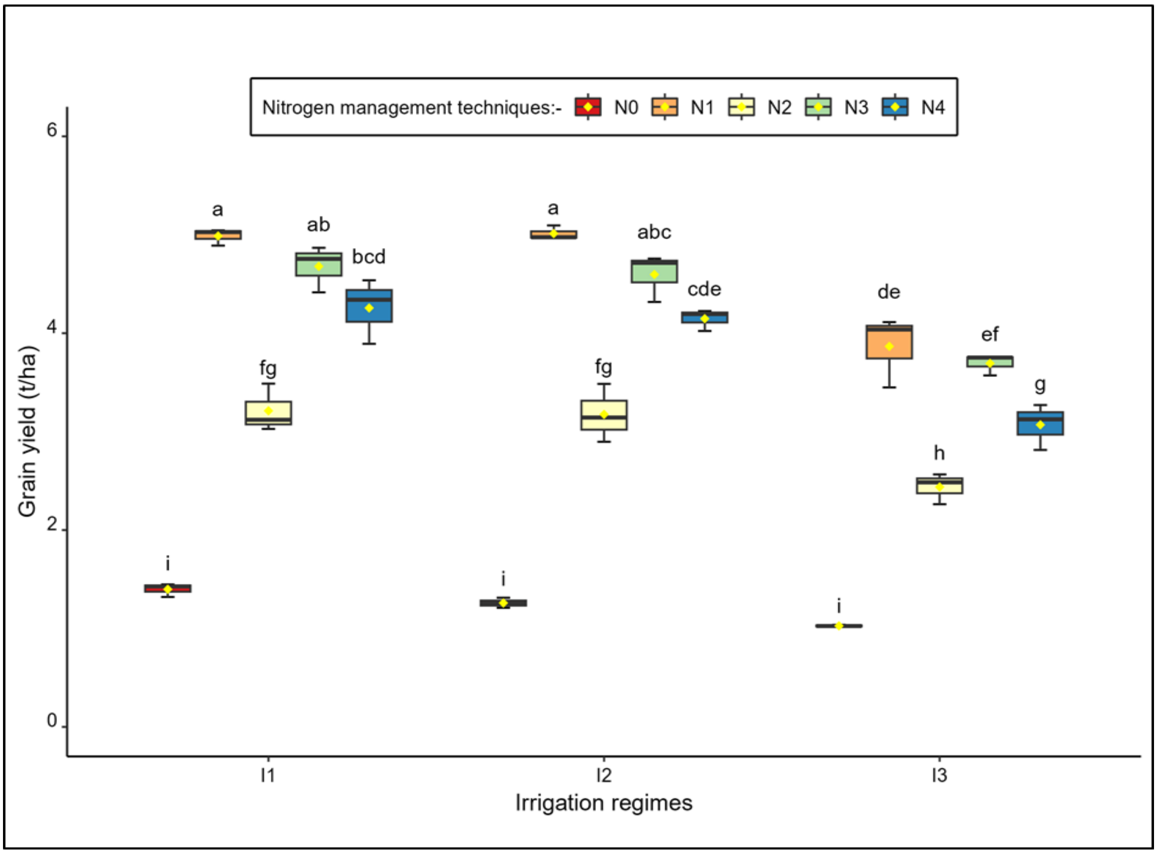

Fig. 3. Interaction effect of irrigation regimes and nitrogen management practices on the grain yield of wheat [Similar letters above boxplots signifies non-significance among treatments (p=0.05), (I_1: 5 irrigations; I_2: 3 irrigations, I_3: 2 irrigations, N_0: control, N_1: 100 % RDN, N_2: 50 % RDN+1 NUS, N_3: 50 % RDN+2 NUS, N_4: 75 % RDN+1 NUS)].

Upper bar is the maximum value, lower bar is minimum. Upper boundary of box is 3rd quartile, middle line is median and lower boundary of box is 1st quartile. The box size demonstrates the interquartile range. The dot in the middle of the box indicates mean value.

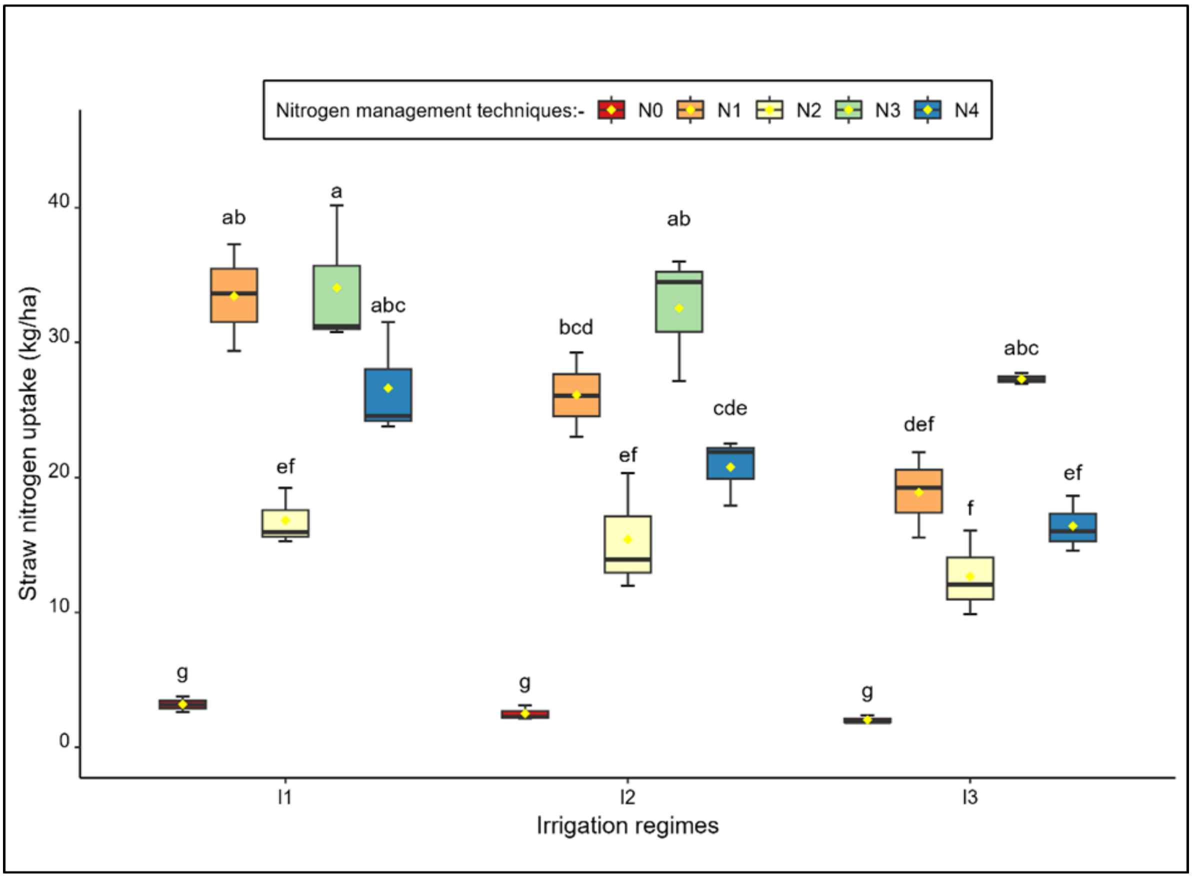

Fig. 4. Interaction effect of irrigation regimes and nitrogen management practices on the straw nitrogen uptake of wheat [Similar letters above boxplots signifies non-significance among treatments (p=0.05), (I_1: 5 irrigations; I_2: 3 irrigations, I_3: 2 irrigations, N_0: control, N_1: 100 % RDN, N_2: 50 % RDN+1 NUS, N_3: 50 % RDN+2 NUS, N_4: 75 % RDN+1 NUS).

Upper bar is the maximum value, lower bar is minimum. Upper boundary of box is 3rd quartile, middle line is median and lowerboundary of box is 1st quartile. The box size demonstrates the interquartile range. The dot in the middle of the box indicates mean value.

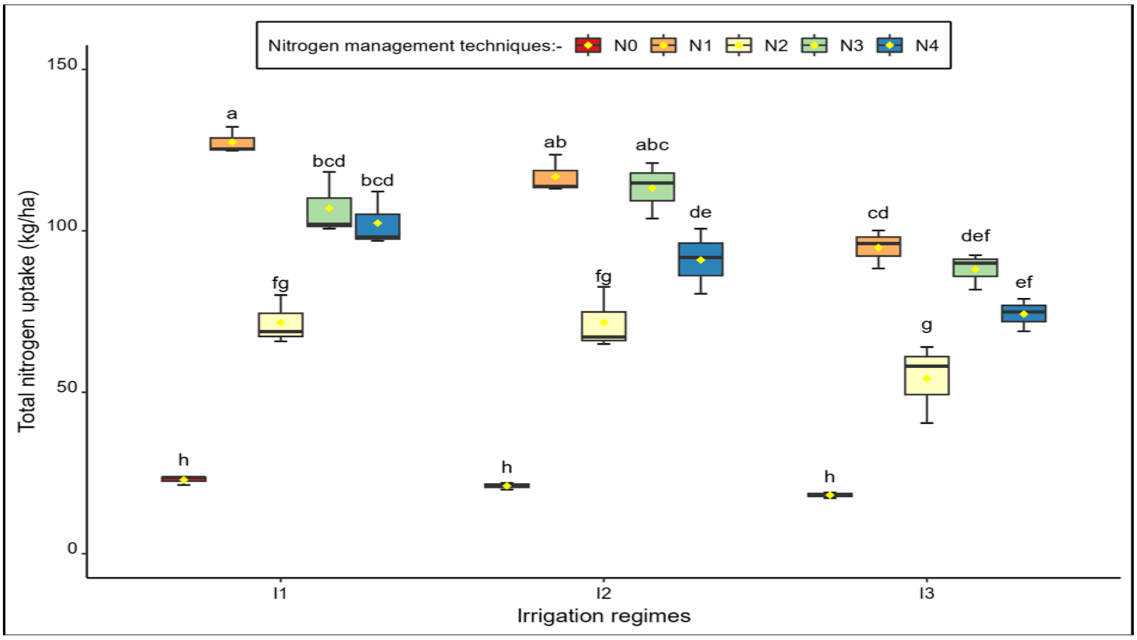

Fig. 5. Interaction effect of irrigation regimes and nitrogen management practices on the total nitrogen uptake of wheat [Similar letters above boxplots signifies non-significance among treatments (p=0.05), (I_1: 5 irrigations; I_2: 3 irrigations, I_3: 2 irrigations, N_0: control, N_1: 100 % RDN, N_2: 50 % RDN+1 NUS, N_3: 50 % RDN+2 NUS, N_4: 75 % RDN+1 NUS).

Upper bar is the maximum value, lower bar is minimum. Upper boundary of box is 3rd quartile, middle line is median and lower boundary of box is 1st quartile. The box size demonstrates the interquartile range. The dot in the middle of the box indicates mean value.

Table 3. Phosphorous and potassium concentration, uptake and grain protein of wheat as influenced by irrigation regimes and nitrogen management practices

Treatment	concentration in grain (%)		concentration in straw (%)		uptake in grain (kg/ha)		uptake in straw (kg/ha)		Total uptake (kg/ha)	
	P	K	P	K	P	K	P	K	P	K
					Irrigation regimes					
I_1	0.30	0.36	0.07	1.04	11.32^a	13.61^a	3.89	59.18^a	15.20^a	72.79^a
I_2	0.30	0.35	0.07	1.00	10.99^a	13.00^a	3.91	56.03^a	14.90^a	69.03^a
I_3	0.30	0.33	0.07	0.95	8.54^b	9.63^b	3.52	48.79^b	12.06^b	58.42^b
SEm±	0.01	0.01	0.01	0.04	0.19	0.16	0.16	1.83	0.26	1.93
LSD (P≤0.05)	NS	NS	NS	NS	0.74	0.64	NS	7.19	1.02	7.57
					Nitrogen management practices					
N_0	0.27^c	0.30^c	0.07	1.00^b	3.36^e	3.70^d	1.10^d	15.34^e	4.46^e	19.03^e
N_1	0.32^a	0.32^b	0.07	1.12^a	14.76^a	15.03^b	5.14^a	83.41^a	19.9^a	98.43^a
N_2	0.29^b	0.36^a	0.07	0.96^{bc}	8.62^d	10.71^c	3.33^c	45.14^d	11.94^d	55.85^d
N_3	0.31^a	0.38^a	0.07	0.93^c	13.55^b	16.45^a	5.14^a	68.19^b	18.69^b	85.36^b
N_4	0.29^b	0.38^a	0.07	0.97^{bc}	11.12^c	14.53^b	4.16^b	60.54^c	15.28^c	75.06^c
SEm±	0.01	0.01	0.00	0.01	0.37	0.33	0.21	1.73	0.28	1.93
LSD (P≤0.05)	0.02	0.02	NS	0.04	0.62	0.97	0.04	5.04	0.81	5.62
IRs×NMPs	NS	NS	NS	NS	1.07	1.68	NS	NS	NS	NS
NMPs×IRs	NS	NS	NS	NS	1.20	1.63	NS	NS	NS	NS

(I_1: 5 irrigations; I_2: 3 irrigations, I_3: 2 irrigations, N_0: control, N_1: 100 % RDN, N_2: 50 % RDN+1 NUS, N_3: 50 % RDN+2 NUS, N_4: 75 % RDN+1 NUS). Treatments with same letter are not significantly different (p=0.05)

I_2 and exceeded I_3 by 32.55 %. Among NMPs, N_3 (13.55 kg/ha) surpassed N_4 (11.12 kg/ha) and N_2 (8.62 kg/ha). N_1 recorded the highest straw P uptake (5.14 kg/ha), like N_3. Total P uptake was 346.2 % and 319.1 % higher in N_1 and N_4 compared to control, with N_3 exceeding N_2 and N_4 by 56.5 % and 22.1 %, respectively. The highest grain P uptake occurred in I_1N_1 (16.12 kg/ha), while the lowest was in I_3N_0. Potassium uptake followed similar trends. I_1 achieved the highest grain (13.61 kg/ha) and straw (59.18 kg/ha) K uptake, leading to the highest total K uptake (72.79 kg/ha), comparable to I_2 but significantly exceeding I_3. N_3 yielded the highest grain K uptake (16.45 kg/ha), surpassing N_1 (15.03 kg/ha) and N_4 (14.93 kg/ha). N_1 recorded the highest straw K uptake (83.41 kg/ha), resulting in 15.31 % more total K uptake compared to N_3, while N_3 exceeded N_2 and N_4 by 52.8 % and 13.74 %, respectively. The highest grain K uptake was observed in I1 N_4 (18.84 kg/ha), comparable to treatments I_1N_1, I_1N_2, I_2N_1 and I_2N_2 (Fig. 6) with the lowest in I_3N_0 (2.92 kg/ha).

Nitrogen use efficiency

The higher values of Agronomic Nitrogen Use Efficiency (ANUE) was achieved under irrigation regime I_2 (30.15 kg grain/kg N), like I_1 but significantly better than I_3 (Table 4). Among nitrogen levels, N_3 (60 kg N+2 nano-urea spray) showed the highest ANUE (51.48 kg grain/kg N), outperforming other practices. Interaction analysis indicated significant effects, with the highest ANUE in I_2N_3, like I_1N_3 (Fig. 7).

The higher rate of Apparent Nitrogen Recovery (ANR) was achieved under I_1 (79.28 kg N uptake/kg N applied), like I_2 (79.02 kg N uptake/kg N applied), while I_3 had the lowest ANR (60.49 kg N uptake/kg N applied). N_3 exhibited the highest ANR (136.52 kg N uptake/kg N applied), notably surpassing other treatments.

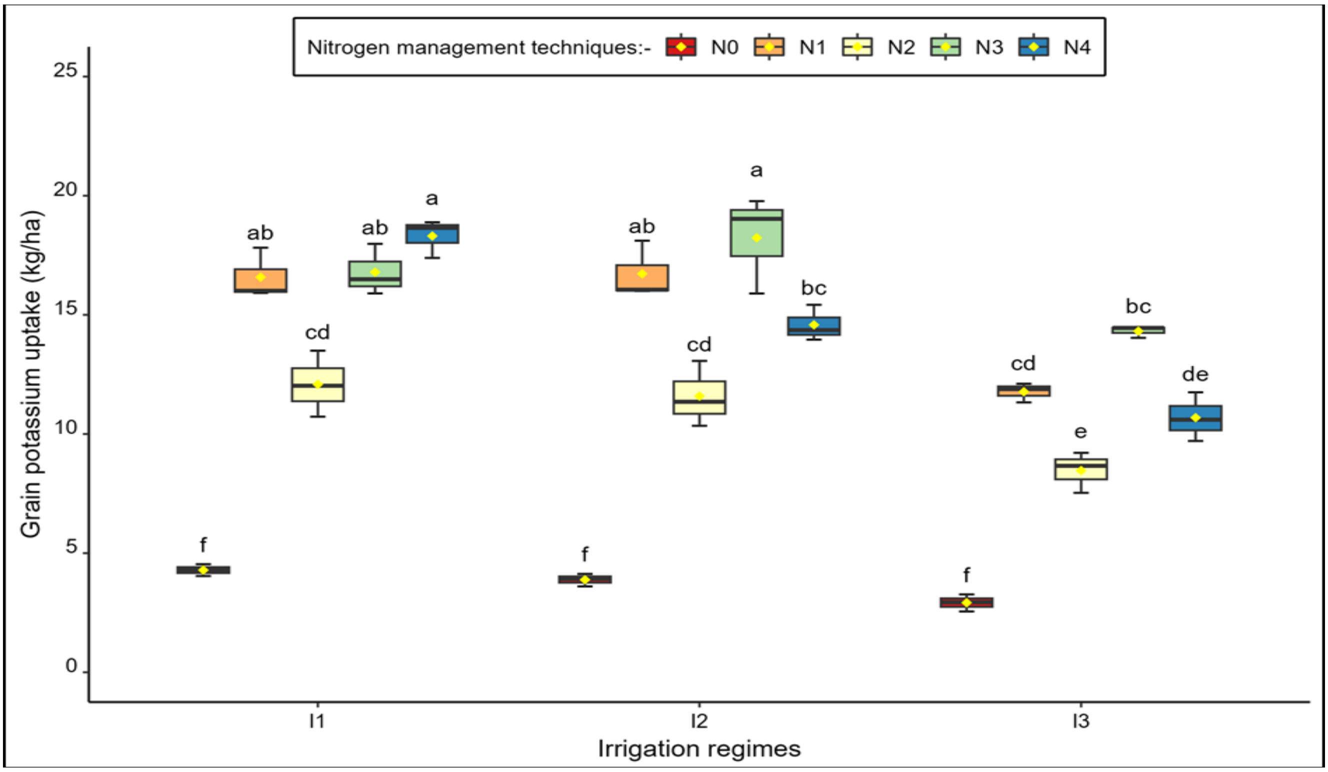

Fig. 6. Interaction effect of irrigation regimes and nitrogen management practices on the grain potassium uptake of wheat [Similar letters above boxplots signifies non-significance among treatments (p=0.05), (I_1: 5 irrigations; I_2: 3 irrigations, I_3: 2 irrigations, N_0: control, N_1: 100 % RDN, N_2: 50 % RDN+1 NUS, N_3: 50 % RDN+2 NUS, N_4: 75 % RDN+1 NUS).

Upper bar is the maximum value, lower bar is minimum. Upper boundary of box is 3rd quartile, middle line is median and lower boundary of box is 1st quartile. The box size demonstrates the interquartile range. The dot in the middle of the box indicates mean value.

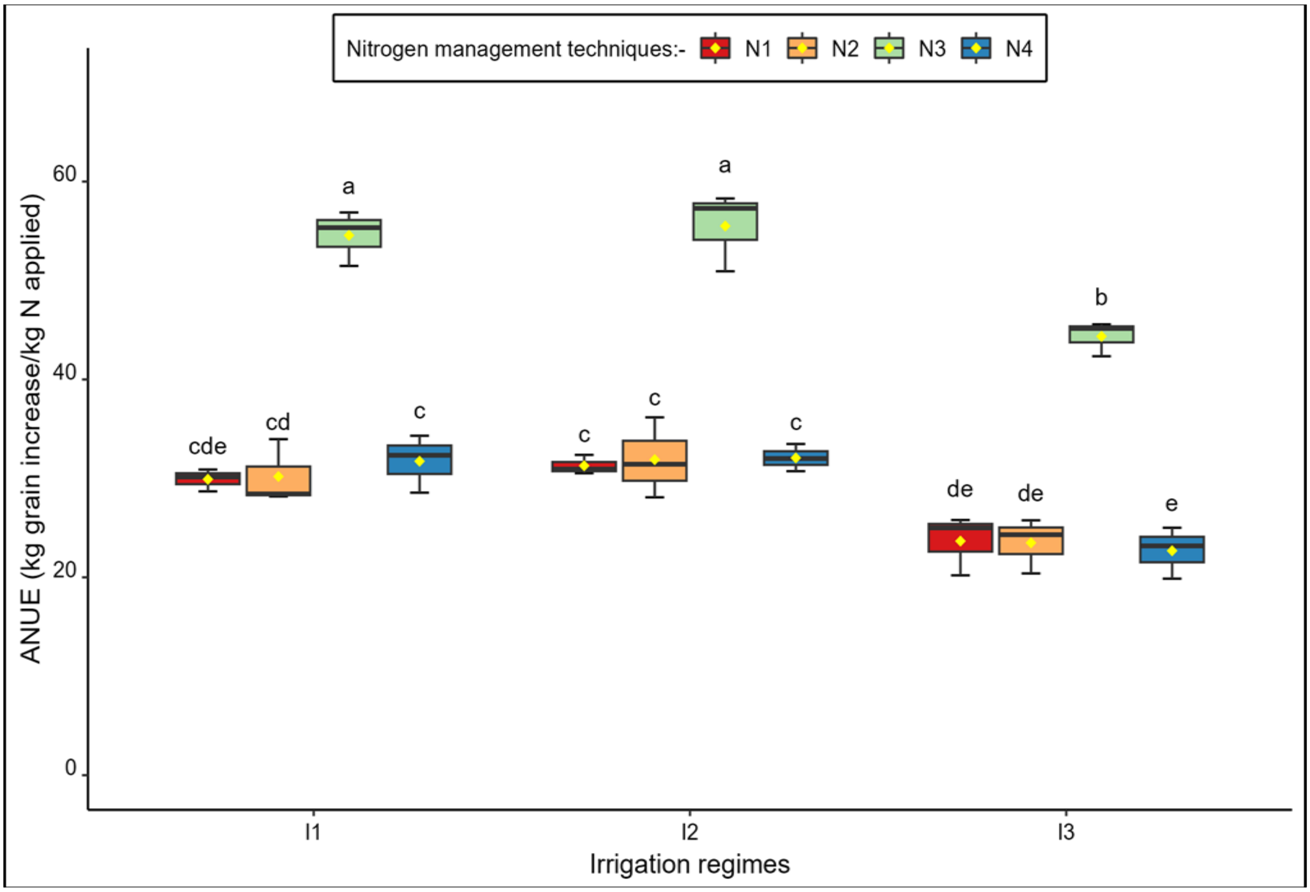

Fig. 7. Interaction effect of irrigation regimes and nitrogen management practices on the agronomic nitrogen use efficiency of wheat [Similar letters above boxplots signifies non-significance among treatments (p=0.05), (I_1: 5 irrigations; I_2: 3 irrigations, I_3: 2 irrigations, N_0: control, N_1: 100 % RDN, N_2: 50 % RDN+1 NUS, N_3: 50 % RDN+2 NUS, N_4: 75 % RDN+1 NUS).

Upper bar is the maximum value, lower bar is minimum. Upper boundary of box is 3rd quartile, middle line is median and lowerboundary of box is 1st quartile. The box size demonstrates the interquartile range. The dot in the middle of the box indicates mean value.

Table 4. Effect of irrigation regimes and nitrogen management practices on various nitrogen use efficiencies

Treatment	ANUE (kg grain/ kg N)	ANR (kg N uptake/kg N applied)	PE_N (kg grain/kg N uptake)	NER	PEN	PFP_N
			Irrigation regimes			
I_1	29.28ᵃ	79.28ᵃ	29.41	112.81	46.17	44.02ᵃ
I_2	30.15ᵃ	79.02ᵃ	31.11	116.41	46.84	43.43ᵃ
I_3	22.84ᵇ	60.49ᵇ	30.62	122.08	45.45	33.66ᵇ
SEm±	0.96	3.31	1.57	1.88	1.63	1.11
LSD (P≤0.05)	3.78	12.99	NS	NS	NS	4.34
			Nitrogen management practices			
N_0	-	-	-	133.04ᵃ	59.3ᵃ	-
N_1	28.28ᵇ	76.97ᵇ	36.85	107.17ᶜ	40.95ᶜ	38.52ᵈ
N_2	28.53ᵇ	75.09ᵇ	38.98	116.48ᵇ	45.28ᵇ	48.97ᵇ
N_3	51.48ᵃ	136.52ᵃ	37.94	114.82ᵇ	42.21ᶜ	71.90ᵃ
N_4	28.83ᵇ	76.08ᵇ	38.13	113.99ᵇ	43.02ᵇᶜ	42.46ᶜ
SEm±	0.75	3.04	1.06	1.83	1.78	0.80
LSD (P≤0.05)	2.18	8.87	NS	5.34	2.52	2.32
IRs×NMPs	3.78	NS	NS	NS	NS	NS
NMPs×IRs	5.01	NS	NS	NS	NS	NS

(NER: Nitrogen efficiency ratio, ANUE: Agronomic nitrogen use efficiency, PE_N: Physiological nitrogen use efficiency, ANR: Apparent nitrogen recovery, PEN: Physiological efficiency index of nitrogen, PFP_N: Partial factor productivity of N). Treatments with same letter are not significantly different (p=0.05)

(I_1: 5 irrigations; I_2: 3 irrigations, I_3: 2 irrigations, N_0: control, N_1: 100 % RDN, N_2: 50 % RDN+1 NUS, N_3: 50 % RDN+2 NUS, N_4: 75 % RDN+1 NUS)

N_2 (60 kg N + 50g N from nano-urea) displayed the highest physiological N use efficiency (38.98 kg grain/kg N uptake) followed by N_4, N_3 and N_1 (38.13, 37.94 and 36.85 kg grain/kg N uptake respectively).

The control (N_0) demonstrated the highest nitrogen efficiency ratio (133.04), while N_1 had the lowest ratio (107.17) attributed to higher N accumulation by the crop at harvest compared to other treatments.

The control (N_0) exhibited the highest physiological efficiency index of nitrogen (59.3), while N_1 had the lowest value (40.95). Notably, N_2 demonstrated significantly higher physiological efficiency index (45.02).

The maximum value of partial factor productivity of nitrogen (PFP_N) was achieved under I_1 (44.02 kg grain/kg N applied), like I_2 (43.43 kg grain/kg N applied), while I_3 had the lowest (33.36 kg grain/kg N applied). N_3 demonstrated the highest value of PFP_N (71.9 kg grain/kg N applied), outperforming other levels like N_1, N_2 and N_4 had values of 38.52, 48.97 and 42.46 kg grain/kg N applied respectively.

Stepwise regression analysis

Correlation panel graph between different parameters of wheat i.e., number (no.) of spikelet per spike, no. of grains per spike, grain yield, N use efficiency and others were analysed (Fig. 8). Grain yield was highly correlated with number (no.) of spikelet per spike (R^2=0.916), no. of grains/spike (R^2=0.968). Grain yield was also highly correlated with grain N uptake (R^2=0.976); total N uptake (R^2=0.985). Also, total N uptake was highly correlated with the grain N uptake (R^2=0.990). Partial factor productivity of N was highly correlated with straw N

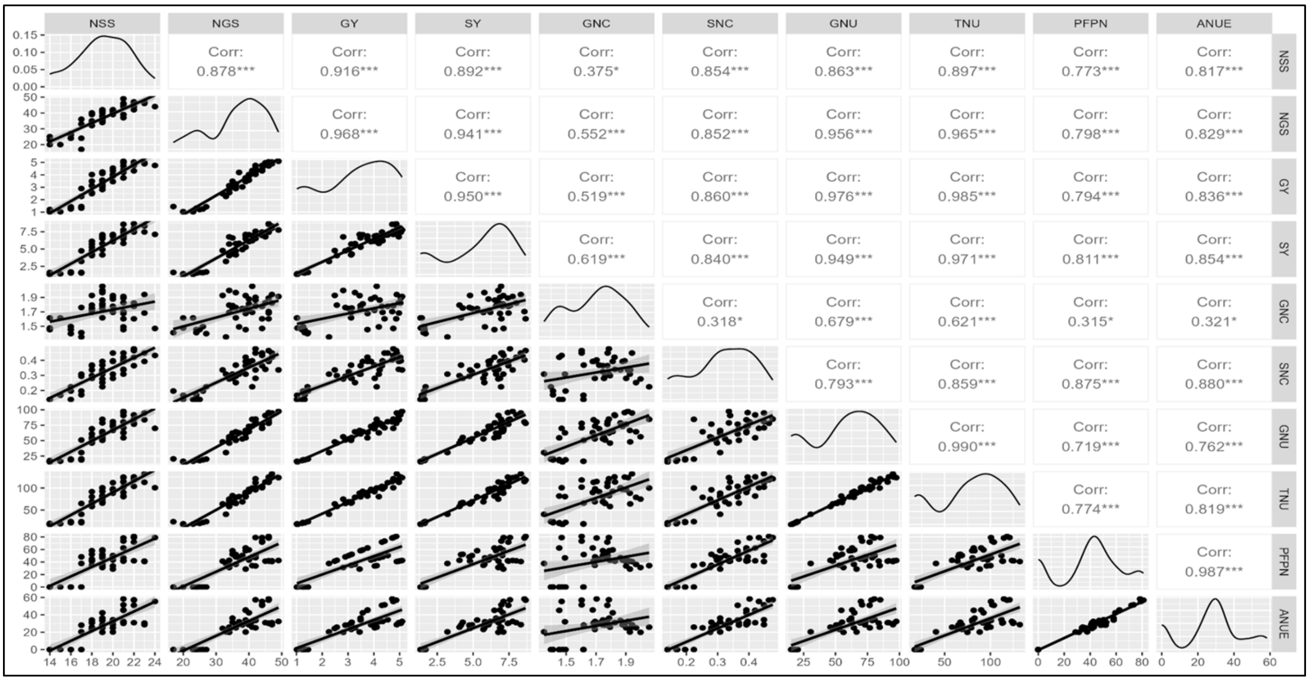

Fig. 8. Correlation panel graph between different parameters of wheat (N=45) [NSS: number (no.) of spikelet/ spike, NGS: no. of grains/spike, GY: Grain Yield, SY: Straw Yield, GNC: Grain Nitrogen Concentration, SNC: Straw N Concentration, GNU: Grain N Uptake, TNU: Total N Uptake, PPFN: Partial Factor Productivity of N, ANUE: Agronomic N Use Efficiency, Significance level: p=0.05*, p=0.01**, p=0.001** .

concentration (R^2=0.875); straw yield (R^2=0.811) grain yield (R^2=0.794). Agronomic nitrogen use efficiency was also correlated with grain yield (R^2=0.836); straw yield (R^2=0.854); and total N uptake (R^2=0.819).

Discussion

Yield attributes and yield

Irrigation regimes had substantial significant influence on the yield attributing characters i.e., spikelets per spike, grains per spike, 1000 grain weight. Minute variation in spikelets per spike was observed (Table 1) due to availability of soil moisture up to flowering stage under different irrigation regimes (14, 15). Optimum moisture availability throughout all growth stages increased the number of fertile grains, which likely resulted in a higher number of grains per ear head under the I_1 irrigation regimes. Whereas moisture stress as well as heat stress during the grain filling stage significantly reduced the number of grains in the spike (Table 1) in I_3 (14, 16). Heat stress generally increases the no. of sterile spikelets in the ear (17). Reduction in 1000-grain weight mainly because of moisture stress at grain filling stage adversely affected the translocation of photosynthates to reproductive parts (18). Heat stress at this stage also had a negative effect on kernel weight (19, 20). Differences in ear length and effective tillers / m^2 brought on by different irrigation regimes were not statistically significant since these two yield attributes were determined before flowering and frequent rainfall up to the flowering stage was unable to produce any variation in these parameters. So, water stress as well as terminal heat stress at later stages significantly affected translocation of carbohydrates from source to sink. Due to higher temperature increased respiration rates (21) and declined photosynthetic rate (22) resulted in decreased grain filling duration (23) and thereby reduction in grain yield (24).

The nitrogen-based treatments had substantial impact on all yield-attributing variables, including spike length, spikelets / spike, grains / spike, 1000 grain weight and effective bearing tillers / m^2, which resulted in significant effect on grain, straw and biological yield. Stimulatory effects of N on tillering through cytokinin synthesis resulted in an increase in the number of wheat plants with productive tillers (25). Greater competition for nutrients exists in the lower levels of N application resulted in lower effective tiller percentage (26). Nitrogen application at the stem elongation stage significantly increases productive tillers/m^2 (27). In contrast, percentage effective tillers per square metre (table. 1) were the highest with N_3 (50 % RDN+2 NUS at 45 and 70 DAS) compared to N_1. 100 % RDN, the better survival of tillers with N_3 resulted in more ears per plant. This might be due to the application of nano-urea at the active tillering stage, which ensured better nitrogen availability when needed. An increase in N level from 80 to 150 kg/ha significantly improved the effective tillers per unit area (28). Ear length increased with increasing nitrogen levels from 0 to 120 kg N/ha (29). A high level of N nutrition during ear differentiation helped plants to produce more no. of spikelets in the spikes and spike length (14,30). A high amount of N nutrition during ear differentiation may prolong the activity of the apical dome, so the application of N fertilizer at the stem-elongation stage increases no. of grains per ear head (30). The greater availability of nitrogen at this stage is the key factor for better yield (31, 32). Application of nano-urea at 45 and 70 DAS greatly helped florets to develop grain compared to other nano-urea treated plots. A 25.6 % reduction in grains/spike was observed in the control plot compared to sufficient nitrogen applied plots (33). Increase in photosynthetic activity and photosynthate translocation due to nitrogen fertilisation, improved photosynthate partitioning in yield attributes and generated more grains with larger sizes, which in turn increased yield. Nano-urea application at 45 DAS helped plants to develop more vegetative growth compared to other nano-urea treated plots where the application was done at 60 DAS. The higher grain yield is attributed to better yield components viz., grain number / ear, 1000 grain weight, HI and weight of grain/ear. Grain yield of wheat was closely related to the LAI, aboveground biomass accumulation (34) and its remobilization into reproductive parts (33). Nitrogen application helped to increase these yield attributes significantly (Table 1). Increasing post-anthesis biomass production is an effective approach to increase crop yield (29, 34). The interaction between the grain yield with nitrogen management and irrigation regimes was significant (Fig. 3) as availability of nitrogen is strongly correlated with irrigation regimes practices (15, 35). When nitrogen is limited, the plant's ability to produce leaves and store energy in the form of dry matter is restricted. This reduction in vegetative growth significantly impacted straw yield (34, 36). Nano-urea application at 45 DAS resulted in more vegetative growth compared to other treatments. The variation in straw yield may be attributed to different doses of nitrogen application during the vegetative growth stages. (37, 38). Adequate irrigation ensures that water stress is minimized, allowing plants to maintain their metabolic processes, enhances nutrient transport, reduces the no. of chaffy grains, all these contributed to higher HI (39).

Protein content

Although non-significant variation was observed in the protein content of wheat due to different irrigation regimes. Protein levels generally increased when moisture availability decreased. This might be because of moisture stress circumstances lead to reduced carbohydrate production (40). As a result, more nitrogen was building up every grain of starch. The nitrogen content in the grain was diluted by the accumulated starch due to increased irrigation, resulting in a lower protein content (41). The amount of N applied had significant effect on the protein content of wheat grains. In the present study increased nitrogen application significantly increased the protein content of wheat grains by stimulating the accumulation of gliadins and glutenins (42). Nitrogen significantly increased the amounts of leucine, phenylalanine and TAA (Total Amino Acid) in wheat grains (43). In addition, higher nitrogen considerably increased the protein and amino acid content of wheat grain compared to low nitrogen application, as well as the amounts of TAA, EAA (Essential Amino Acids) and NAA (Non-essential Amino Acids) (44). Due to the high concentrations of glutamate (Glu) and alanine (Ala) in NAA, wheat grains accumulated more NAA than EAA when nitrogen was applied (44, 4).

N, P, K content and uptake by crop

Nutrient uptake in crops is influenced by nutrient content and productivity. The uptake of nitrogen, phosphorus and potassium by grain and straw were significantly affected by irrigation regimes due to variations in grain yield. 100 % RDN resulting in higher N, P and K content and uptake in grain and straw (Table 2 and 3). Probably the reason behind this is the numerous healthier roots and higher the density of roots, which may have contributed to better uptake of nitrogen, potassium and phosphorus from soil (45). The increase in total nitrogen uptake at the higher nitrogen rates may be explained by the greater nitrogen content in the grains and higher yield, which allowed them to accumulate more nitrogen (46). Higher N availability in the soil at high nitrogen levels enhanced N uptake by the crop which positively influenced N uptake through grain and straw. Probable reason behind higher K content in grain under N_3 compared to N_1 is application of nano-urea helps better translocation of K from straw to grain. That's N uptake of straw and grain K uptake was the highest in N_3. Higher P and K uptake due to higher N might be attributed to higher biological yield on higher doses of N application (46).

Nitrogen use efficiency

Irrigation regimes didn't produce any effect on physiological nitrogen use efficiency (PE_N) and physiological efficiency index of nitrogen (PEN) as both irrigation regimes possess the same effect on grain yield and uptake of nitrogen by wheat. Whereas apparent nitrogen recovery (ANR) and ANUE were higher with higher irrigation regimes because of higher yield with the same amount of nitrogen application (Table 4). Higher nitrogen use efficiency at higher irrigation levels, was attributed to better N mineralization and minimal nitrogen loss through leaching and volatilization at the optimal soil moisture condition, which ultimately led to better plant uptake of nitrogen and, consequently, growth and yield (47). Apparent recovery efficiency was significantly increased with increasing the irrigation levels (15). Among the NMPs, both the PEN and nitrogen efficiency ratio (NER) were higher in control as the yield as well as nitrogen uptake was less by the crop. Both ANR and ANUE were higher in N_3 as the yield obtained from N_3 was higher, but the application of N was comparatively less from N_1. Uptake of N was almost similar for both nano-urea and granular urea, but the amount of nitrogen was the main difference. In N_3 amount of N was 60kg+100g/ha (60 kg from urea and 100g from nano urea) whereas in N_1 it was 120 kg/ha but the uptake of N for these two treatments were 102.75 and 113.03 kg N/ha, respectively. As more uptake of N with less amount of nitrogen application so ANR was better for N_3. Long term nano-urea application (N_3) is not sustainable as the plant uptake large amount of nitrogen from soil and make the soil more deficient in nitrogen. Higher doses of N reduce ANR and Physiological nitrogen use efficiency (34). Higher partial factor productivity (Table 4) was found with irrigation regime where higher number of irrigations were applied. Higher yield from higher irrigation regimes with the same amount of N, P and K fertilizer was the main reason for higher partial factor productivity of nutrients. Among the nitrogen management techniques, higher PFP_N was obtained with N_3 due to low level of N (60 kg N through prilled urea+100g N from nano-urea) resulted in comparative higher grain yield. Higher doses of N reduced PFP_N of the crop compared to lower doses (15).

Stepwise regression analysis

Grain yield (Fig. 8) was highly correlated with no. of spikelet/ spike, no. of grains/spike (48). The increment in grain yield per spike was in turn associated to a concomitant increase in grain numbers per spike 19 % increment, grain number (21 %) and grain yield per spikelet (25 %). As N uptake is the product of N concentration and dry matter yield, strong relationship always exists between them (49). Grain yield is also corelated with grain N and protein concentration (50).

Conclusion

Based on the experiment, it was observed that applying irrigation at the milky stage of wheat in I_1 and I_2 irrigation regimes helped to prevent significant reduction in the yield of wheat variety DBW-187. Furthermore, nano-urea application at sub-optimum nitrogen doses did not adequately supply nitrogen compared to the standard 100 % RDN, resulting in significantly higher growth and grain yield with 100 % RDN. Increased nitrogen application enhanced both protein content and amino acid accumulation, underscoring the significance of nitrogen management for enhancing grain quality. Integrated approaches of combining increased irrigation and optimized nitrogen management led to higher partial factor productivity of nutrients, emphasizing the importance of sustainable practices for maximizing wheat productivity and nutrient efficiency. In conclusion, the most favourable combination for achieving higher wheat productivity in the eastern plateau region of India was 100 % RDN with three times irrigation.

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Authors' contributions

All authors have contributed to the paper on conceptualization, review & editing, supervision, investigation, data collection, formal analysis, writing - original draft: All authors reviewed the results and approved the final version of the 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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