



Productivity and Profitability of Wheat (*Triticum aestivum* L.) as Influenced by Sowing Dates, Irrigation Schedules and Nitrogen Levels

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ABSTRACT

Background: Agronomic management practices, particularly sowing time, irrigation scheduling and nitrogen application, have a significant impact on wheat productivity and profitability. The present study was conducted to investigate the combined effects of these factors on the growth, yield and economic performance of wheat.

Methods: Field investigations were undertaken during the *rabi* season of 2020-21 at the Crop Research Farm, SHUATS, Prayagraj, Uttar Pradesh. The trial was arranged in a split-plot design with three replications involving two sowing dates (20 November and 20 December), three irrigation regimes and three nitrogen doses (80, 120 and 160 kg N ha⁻¹).

Result: Earlier sowing on 20 November resulted in better crop growth and higher productivity than sowing on 20 December. Irrigation supplied at CRI, tillering, booting and milking stages (I₃) achieved the highest grain production (3.36 t ha⁻¹). Similarly, application of 160 kg N ha⁻¹ (N₃) produced the greatest grain yield (3.41 t ha⁻¹) and biological yield (7.96 t ha⁻¹). The treatment combination D₁I₃N₃ generated the maximum net income (₹ 47,777 ha⁻¹) and benefit-cost ratio (2.19). Overall, appropriate sowing time, sufficient irrigation and higher nitrogen availability contributed to enhanced crop performance and economic returns.

Key words: Grain yield, Irrigation scheduling, Nitrogen management, Profitability, Sowing date, Wheat.

INTRODUCTION

Wheat (*Triticum aestivum* L.) ranks next to rice among India's food grains and is central to national food and nutritional security (Government of India, 2024). Within the rice-wheat system of the Indo-Gangetic Plains, however, declining resource-use efficiency and imbalanced input management have raised concerns about long-term sustainability, making optimal sowing time, irrigation scheduling and balanced nutrition essential to maintaining productivity (Gupta *et al.*, 2003).

Sowing time strongly influences wheat growth: timely planting exploits favourable temperatures through the vegetative and reproductive phases, whereas late sowing brings terminal heat stress that shortens grain filling and depresses yield (Farooq *et al.*, 2014; Zhao *et al.*, 2017), a pattern also reported elsewhere in the Indo-Gangetic Plains (Yusuf *et al.*, 2019). Water availability at critical stages-crown root initiation, tillering, booting, grain filling-similarly governs nutrient uptake and assimilate movement, so deficit restricts productivity (Rekaby *et al.*, 2019; Zhang *et al.*, 2010). Nitrogen drives tillering, canopy expansion and biomass accumulation; deficiency limits yield while excess reduces nutrient-use efficiency, so an optimum dose is essential for profitable cultivation (Prasad and Hobbs, 2018). Combined irrigation-nitrogen management improves productivity and nutrient-use efficiency in late-sown wheat (Kumar *et al.*, 2018), integrating nitrogen with other fertility inputs enhances growth under diverse conditions (Devi *et al.*, 2026) and coordinated water-

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nitrogen management broadly improves resource-use efficiency and economic viability (Wan *et al.*, 2022; Fischer, 2011).

While the individual contributions of sowing date, irrigation and nitrogen nutrition to wheat productivity are well documented, information on their combined and interactive effects under the agro-climatic conditions of Prayagraj, Uttar Pradesh remains inadequate. The present investigation was therefore undertaken to evaluate the influence of sowing dates, irrigation scheduling and nitrogen application, individually and in interaction, on the growth, yield and economics of wheat.

MATERIALS AND METHODS

Experimental site

An experiment was conducted during the rabi season of 2020-21 at the Crop Research Farm, Department of Agronomy, SHUATS, Prayagraj, Uttar Pradesh, India (25°57'N, 81°19'E, 98 m amsl). Prayagraj has a subtropical, semi-arid climate with hot dry summers and cool dry winters and an average annual rainfall of about 934 mm, mostly during the monsoon (June-September).

Weather conditions during the crop growing period

Weekly meteorological data recorded during the crop growing period (*rabi* 2020-21) at the Agro-Meteorological Observatory, College of Forestry, SHUATS, Prayagraj, are presented in Table 1. The crop received a total rainfall of only 18.60 mm (against the district's long-period average of 934 mm annum⁻¹), confined mainly to the 50th standard meteorological week (18.40 mm, 10-16 December), with the remaining weeks practically rain-free-confirming that differences among the irrigation treatments (I_1 , I_2 and I_3) reflect the imposed schedules rather than rainfall.

Soil characteristics

Pre-sowing soil samples were sandy loam in texture (58.75% sand, 25.15% silt, 16.45% clay), slightly alkaline

(pH 7.7) with low soluble salts (EC 0.41 dS m⁻¹), low in organic carbon (0.39%) and available nitrogen (178.53 kg ha⁻¹) and moderate in available phosphorus (20.36 kg ha⁻¹) and potassium (229.42 kg ha⁻¹).

Experimental design and treatments

The experiment was laid out in a split-plot design with three replications: two sowing dates (D_1 = 20 November, D_2 = 20 December) as main plots, three irrigation schedules as sub-plots- I_1 (CRI + booting), I_2 (CRI + tillering + booting) and I_3 (CRI + tillering + booting + milking)-and three nitrogen levels as sub-sub-plots- N_1 (80), N_2 (120) and N_3 (160 kg N ha⁻¹)-giving eighteen treatment combinations.

Crop establishment and nutrient management

Wheat variety HD 2967 was sown manually on 20 November and 20 December 2020 (100 kg ha⁻¹ seed rate, 22.5 cm row spacing, 5 cm plant spacing; seed treated with Bavistin at 2 g kg⁻¹). Gross plot size was 12.15 m² (4.05 × 3.00 m) and net plot size 10.08 m² (3.60 × 2.80 m).

A uniform dose of 60 kg P₂O₅ ha⁻¹ and 40 kg K₂O ha⁻¹ was applied *via* DAP and MOP, while nitrogen was supplied *via* urea at the three treatment levels. As per the zone-wise Package of Practices published by ICAR-Directorate of Wheat Research, Karnal (now ICAR-Indian Institute of

Table 1: Weekly meteorological data (Maximum/minimum temperature, relative humidity and rainfall) recorded during the crop growing period (*rabi* 2020-21) at the Agro-meteorological Observatory, College of Forestry, SHUATS, Prayagraj.

Standard meteorological week	Period	Max. temp. (°C)	Min. temp. (°C)	Max. RH (%)	Min. RH (%)	Rainfall (mm)
47 th	19-25 Nov	30.94	11.80	89.86	60.43	0.00
48 th	26 Nov-02 Dec	32.07	11.63	91.00	55.14	0.00
49 th	03-09 Dec	29.94	11.54	91.14	64.71	0.00
50 th	10-16 Dec	29.06	9.69	93.14	64.86	18.40
51 st	17-23 Dec	26.54	8.77	92.86	75.43	0.00
52 nd	24-31 Dec	20.88	7.93	93.25	75.00	0.00
1 st	01-07 Jan	25.71	10.80	91.43	63.71	0.00
2 nd	08-14 Jan	24.69	9.46	91.86	65.71	0.00
3 rd	15-21 Jan	21.03	8.91	92.71	63.14	0.00
4 th	22-28 Jan	19.34	8.17	95.00	70.29	0.00
5 th	29 Jan-04 Feb	23.69	8.40	92.71	50.71	0.00
6 th	05-11 Feb	30.74	10.86	88.71	46.86	0.20
7 th	12-18 Feb	29.51	10.86	88.57	47.43	0.00
8 th	19-25 Feb	30.11	12.04	87.71	48.43	0.00
9 th	26 Feb-04 Mar	34.06	15.51	87.29	42.71	0.00
10 th	05-11 Mar	34.57	18.66	84.86	39.43	0.00
11 th	12-18 Mar	35.40	19.59	83.14	40.29	0.00
12 th	19-25 Mar	37.17	20.69	80.86	37.57	0.00
13 th	26 Mar-01 Apr	39.54	21.23	77.57	32.71	0.00
14 th	02-08 Apr	41.09	18.29	78.86	31.00	0.00
15 th	09-15 Apr	41.83	19.37	77.00	30.00	0.00
16 th	16-22 Apr	42.31	20.51	73.71	29.29	0.00
Total	-	-	-	-	-	18.60

Source: Meteorological observatory, College of Forestry, SHUATS, Prayagraj.

Wheat and Barley Research) for the North Eastern Plains Zone, which includes Prayagraj, the recommended dose of fertilizer (RDF) differs with sowing time: 150:60:40 kg N:P₂O₅:K₂O ha⁻¹ for timely sown and 120:60:40 kg N:P₂O₅:K₂O ha⁻¹ for late sown wheat (Kumar *et al.*, 2014). Accordingly, for D₁, N₃ (160 kg N ha⁻¹) closely approximates the RDF (150 kg N ha⁻¹), while N₂ and N₁ represent about 80% and 53% of it; for D₂, N₂ (120 kg N ha⁻¹) exactly matches the RDF, while N₁ and N₃ represent about 67% and 133% of it. Nitrogen was applied in three splits-half as basal and the rest at 25 and 45 DAS.

Irrigation and crop management

Irrigation was applied at crown root initiation (21 DAS), tillering (40 DAS), booting (75 DAS) and milking (100 DAS) as per treatment schedule. Weeds were controlled with post-emergence Sulfosulfuron 75% + Metsulfuron methyl 5% WG @ 40 g ha⁻¹ at about 30 DAS, with recommended practices otherwise uniform across treatments.

Observations recorded

Data on plant height, number of tillers per running meter, dry weight per plant and leaf area index (LAI) were collected at 20, 40, 60, 80 and 100 DAS of crop growth. At maturity, effective tillers m⁻², spike length, grains per spike and test weight were recorded and grain yield, straw yield, biological yield and harvest index computed by standard procedures.

Economic analysis and statistical analysis

Cost of cultivation, gross/net monetary return and benefit-cost ratio were estimated using prevailing market prices. Data were analysed by ANOVA for a split-plot design (Gomez and Gomez, 1984); means were compared by CD at P = 0.05 and the D × I, D × N, I × N and D × I × N interactions tested and discussed below.

RESULTS AND DISCUSSION

Growth attributes

Growth attributes were significantly influenced by sowing dates, irrigation scheduling and nitrogen levels at both 80 and 100 DAS (Table 2). Timely sowing (D₁) recorded significantly higher plant height (73.48 cm at 80 DAS; 75.73 cm at 100 DAS), tillers per running metre (84.16; 72.19), dry weight per plant (6.209 g; 7.891 g) and LAI (3.298; 3.052) than delayed sowing (D₂, 5.398 g and 6.950 g dry weight at 80 and 100 DAS, respectively), attributable to favourable temperatures and a longer crop duration (Meena *et al.*, 2015; Hussain *et al.*, 2021; Dar *et al.*, 2021).

Among irrigation schedules, I₃ significantly increased plant height (75.94 cm at 80 DAS; 77.24 cm at 100 DAS), tillers per running metre (84.48; 77.02) and dry weight per plant (6.289 g; 8.020 g) over I₁ (66.34 cm; 67.17 cm plant height; 67.86; 63.68 tillers; 5.374 g; 6.912 g dry weight), remaining comparable to I₂ for LAI (3.647/3.406 vs 3.653/3.390). Its continued superiority at 100 DAS, after the fourth milking-stage irrigation, shows that this late irrigation

Table 2: Effect of sowing dates, irrigation scheduling and nitrogen levels on growth attributes of wheat.

Treatments	Plant height (cm)		Tillers per running meter		Dry weight per plant (g)		Leaf area index (LAI)	
	80 DAS	100 DAS	80 DAS	100 DAS	80 DAS	100 DAS	80 DAS	100 DAS
A. Dates of sowing								
D ₁ - 20 November	73.48	75.73	81.29	72.19	6.209	7.891	3.298	3.052
D ₂ - 20 December	68.70	68.47	71.08	68.06	5.398	6.950	2.953	2.777
SE (d±)	1.87	2.36	2.42	2.53	0.177	0.239	0.107	0.093
CD (P=0.05)	4.16	5.87	5.38	NS	0.395	0.532	0.237	0.207
B. Irrigation levels								
I ₁ - CRI + Booting	66.34	67.17	67.86	63.68	5.374	6.912	2.077	1.949
I ₂ - CRI + Tillering + Booting	70.99	71.88	76.21	69.67	5.747	7.331	3.653	3.390
I ₃ - CRI + Till. + Boot + Milk	75.94	77.24	84.48	77.02	6.289	8.020	3.647	3.406
SE (d±)	2.28	3.22	2.96	3.1	0.217	0.292	0.131	0.114
CD (P=0.05)	5.09	7.18	6.59	6.9	0.483	0.651	0.291	0.253
C. Nitrogen levels								
N ₁ (80 kg ha ⁻¹)	69.33	70.23	72.38	66.74	5.107	6.611	2.643	2.456
N ₂ (120 kg ha ⁻¹)	71.28	72.30	75.95	70.34	5.896	7.477	3.230	3.041
N ₃ (160 kg ha ⁻¹)	72.66	73.77	80.23	73.29	6.407	8.174	3.503	3.248
SE (d±)	2.01	2.81	2.84	2.79	0.210	0.285	0.117	0.108
CD (P=0.05)	4.15	5.81	5.87	5.76	0.434	0.587	0.242	0.222

sustained growth into the post-anthesis period (Zhang *et al.*, 2010; Dhaliwal *et al.*, 2020).

Nitrogen significantly influenced growth at both stages, with N_3 (160 kg N ha⁻¹) recording the highest plant height (72.66 cm; 73.77 cm), tillering (80.23; 73.29), dry weight per plant (6.407 g; 8.174 g) and LAI (3.503; 3.248), followed by N_2 (71.28 cm; 72.30 cm; 5.896 g; 7.477 g) and N_1 (69.33 cm; 70.23 cm; 5.107 g; 6.611 g), consistent with greater chlorophyll synthesis and canopy development (Dagash *et al.*, 2014; Waraich *et al.*, 2007).

Yield attributes

Yield attributes were significantly affected by sowing date and irrigation, whereas nitrogen significantly influenced only test weight (Table 3). D_1 produced significantly higher effective tillers m⁻² (311.71), spike length (10.71 cm), grains spike⁻¹ (40.22) and test weight (35.94 g) than D_2 , reflecting the shortened duration and terminal heat stress under delayed sowing (Farooq *et al.*, 2014; Zhao *et al.*, 2017).

I_3 recorded the highest effective tillers m⁻² (325.67), spike length (10.97 cm), grains spike⁻¹ (39.91) and test weight (35.95 g); the milking-stage (100 DAS) irrigation unique to I_3 evidently improved assimilate translocation to developing grains (Kanwal *et al.*, 2020; Dhaliwal *et al.*, 2020). N_3 gave the highest test weight (35.27 g); effective tillers, spike length and grains per spike did not differ significantly with nitrogen (Waraich *et al.*, 2007).

Grain yield, straw yield and biological yield

Grain, straw and biological yield varied significantly across all three factors (Table 4). D_1 recorded significantly higher grain yield (3.08 t ha⁻¹), straw yield (4.11 t ha⁻¹) and biological yield (7.19 t ha⁻¹) than D_2 , consistent with reduced grain development under the heat stress of delayed sowing (Hussain *et al.*, 2021; Zhao *et al.*, 2017).

I_3 gave the highest grain yield (3.36 t ha⁻¹), straw yield (4.38 t ha⁻¹) and biological yield (7.73 t ha⁻¹). Adequate moisture throughout critical stages enhanced nutrient uptake, photosynthetic efficiency and assimilate translocation, raising grain production; since only 18.60 mm of rainfall fell over the whole crop period (Table 1), this advantage over I_1 and I_2 can be attributed almost entirely to scheduled irrigation, underlining the value of the 100-DAS milking-stage irrigation for grain filling under these near rain-free conditions (Zhang *et al.*, 2010; Rekaby *et al.*, 2019).

N_3 gave the highest grain yield (3.41 t ha⁻¹), straw yield (4.55 t ha⁻¹) and biological yield (7.96 t ha⁻¹)-about 15% and 38% higher grain yield than N_2 (2.97 t ha⁻¹) and N_1 (2.47 t ha⁻¹), respectively. Enhanced nitrogen availability promoted vigorous vegetative growth, greater leaf area development and improved photosynthetic activity, raising biomass accumulation and grain production; this tracks the zone's sowing-date-specific RDF (150 kg N ha⁻¹ for D_1 , 120 kg N ha⁻¹ for D_2), as N_3 approximates or exceeds the RDF under both dates and gave the best yield, while N_1 remained well below it and gave the lowest, consistent with Prasad and Hobbs (2018); Mehrabi and Sepaskhah (2018) and Kumar *et al.* (2018).

Harvest index

Harvest index was not significantly affected by sowing date, irrigation or nitrogen, indicating a stable partitioning of assimilates between grain and biomass across treatments.

Interaction effect of sowing dates, irrigation scheduling and nitrogen levels

The $D \times I$, $D \times N$, $I \times N$ and $D \times I \times N$ interactions were each tested separately for grain yield, reflecting the different error terms of the split-plot design. None attained significance

Table 3: Effect of sowing dates, irrigation scheduling and nitrogen levels on yield attributes of wheat.

Treatments	Effective tillers per square meter	Spike length (cm)	Number of grains per spike	Test weight (g)
A. Sowing dates				
D_1 - 20 November	311.71	10.71	40.22	35.94
D_2 - 20 December	281.49	9.69	34.38	33.43
SE (d±)	11.00	0.31	1.10	0.35
CD (P=0.05)	24.51	0.69	2.45	0.78
B. Irrigation levels				
I_1 - CRI+ Booting	272.69	9.42	34.85	33.44
I_2 - CRI+ Tillering+ Booting	291.45	10.21	37.15	34.67
I_3 - CRI+ Till+ Boot+ Milk	325.67	10.97	39.91	35.95
SE (d±)	13.48	0.38	1.34	0.43
CD (P=0.05)	30.02	0.84	3.00	0.96
C. Nitrogen levels				
N_1 - 80 kg ha ⁻¹	284.17	9.79	36.19	33.85
N_2 - 120 kg ha ⁻¹	298.62	10.31	37.59	34.94
N_3 - 160 kg ha ⁻¹	307.01	10.49	38.13	35.27
SE (d±)	12.37	0.36	1.27	0.49
CD (P=0.05)	NS	NS	NS	1.01

Table 4: Effect of sowing dates, irrigation scheduling and nitrogen levels on the yield of wheat.

Treatments	Grain yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Biological yield (t ha ⁻¹)	Harvest index (%)
A. Sowing dates				
D ₁ - 20 November	3.08	4.11	7.19	42.71
D ₂ - 20 December	2.82	3.80	6.62	42.44
SE (d±)	0.11	0.15	0.23	1.48
CD (P=0.05)	0.24	0.34	0.51	NS
B. Irrigation levels				
I ₁ - CRI + Booting	2.27	3.26	5.52	41.00
I ₂ - CRI + Tillering + Booting	3.23	4.22	7.45	43.32
I ₃ - CRI + Till + Boot + Milk	3.36	4.38	7.73	43.41
SE (d±)	0.13	0.19	0.28	1.81
CD (P=0.05)	0.30	0.42	0.63	NS
C. Nitrogen levels				
N ₁ - 80 kg ha ⁻¹	2.47	3.32	5.80	42.51
N ₂ - 120 kg ha ⁻¹	2.97	3.98	6.95	42.55
N ₃ - 160 kg ha ⁻¹	3.41	4.55	7.96	42.67
SE (d±)	0.12	0.17	0.26	1.63
CD (P=0.05)	0.25	0.36	0.53	NS

Table 5 (a-d): Grain yield (t ha⁻¹) as affected by the D×I, D×N, I×N and D×I×N interactions.

a- Grain yield (t ha ⁻¹) as affected by the D × I interaction, 2020-21			
Irrigation	D ₁ (20 Nov)	D ₂ (20 Dec)	
I ₁	2.50	2.04	
I ₂	3.30	3.15	
I ₃	3.44	3.28	
SE (d±)	0.19	0.19	
CD (P=0.05)	NS	NS	
b- Grain yield (t ha ⁻¹) as affected by the D × N interaction, 2020-21			
Nitrogen	D ₁ (20 Nov)	D ₂ (20 Dec)	
N ₁	2.58	2.36	
N ₂	3.11	2.83	
N ₃	3.55	3.28	
SE (d±)	0.17	0.17	
CD (P=0.05)	NS	NS	
c- Grain yield (t ha ⁻¹) as affected by the I × N interaction, 2020-21			
Nitrogen	I ₁	I ₂	I ₃
N ₁	2.00	2.67	2.75
N ₂	2.29	3.25	3.37
N ₃	2.52	3.77	3.95
SE(d±)	0.21	0.21	0.21
CD (P=0.05)	NS	NS	NS
d- Grain yield (t ha ⁻¹) as affected by the D × I × N interaction, 2020-21			
Treatment (D×I×N)	N ₁ (80 kg ha ⁻¹)	N ₂ (120 kg ha ⁻¹)	N ₃ (160 kg ha ⁻¹)
D ₁ I ₁	2.19	2.48	2.82
D ₁ I ₂	2.75	3.36	3.80
D ₁ I ₃	2.79	3.49	4.03
D ₂ I ₁	1.80	2.09	2.21
D ₂ I ₂	2.58	3.13	3.75
D ₂ I ₃	2.70	3.26	3.87
SE (d±) D×I×N	0.44	0.44	0.44
CD (P=0.05)	NS	NS	NS

Table 6: Effect of sowing dates, irrigation scheduling and nitrogen levels on the economics of wheat.

Treatments	Treatment combinations	Cost of cultivation (₹ ha ⁻¹)	Gross monetary return (₹ ha ⁻¹)	Net monetary return (₹ ha ⁻¹)	B: C ratio
D ₁ I ₁ N ₁	20 th November + Two irrigation at CRI (21 DAS) and booting stage (75 DAS) + 80 kg N ha ⁻¹	36920.00	48472.00	11552.00	1.31
D ₁ I ₁ N ₂	20 th November + Two irrigation at CRI (21 DAS) and booting stage (75 DAS) + 120 kg N ha ⁻¹	37448.00	54900.00	17452.00	1.47
D ₁ I ₁ N ₃	20 th November + Two irrigation at CRI (21 DAS) and booting stage (75 DAS) + 160 kg N ha ⁻¹	37975.00	62219.00	24244.00	1.64
D ₁ I ₂ N ₁	20 th November + Three irrigation at CRI (21 DAS), tillering stage (40 DAS) and booting stage (75 DAS) + 80 kg N ha ⁻¹	38048.00	60224.00	22176.00	1.58
D ₁ I ₂ N ₂	20 th November + Three irrigation at CRI (21 DAS), tillering stage (40 DAS) and booting stage (75 DAS) + 120 kg N ha ⁻¹	38576.00	73463.00	34887.00	1.90
D ₁ I ₂ N ₃	20 th November + Three irrigation at CRI (21 DAS), tillering stage (40 DAS) and booting stage (75 DAS) + 160 kg N ha ⁻¹	39103.00	82862.00	43759.00	2.12
D ₁ I ₃ N ₁	20 th November + Four irrigation at CRI (21 DAS), tillering stage (40 DAS), booting stage (75 DAS) and milking stage (100 DAS) + 80 kg N ha ⁻¹	39175.00	60962.00	21787.00	1.56
D ₁ I ₃ N ₂	20 th November + Four irrigation at CRI (21 DAS), tillering stage (40 DAS), booting stage (75 DAS) and milking stage (100 DAS) + 120 kg N ha ⁻¹	39703.00	76183.00	36480.00	1.92
D ₁ I ₃ N ₃	20 th November + Four irrigation at CRI (21 DAS), tillering stage (40 DAS), booting stage (75 DAS) and milking stage (100 DAS) + 160 kg N ha ⁻¹	40230.00	88007.00	47777.00	2.19
D ₂ I ₁ N ₁	20 th December + Two irrigation at CRI (21 DAS) and booting stage (75 DAS) + 80 kg N ha ⁻¹	36920.00	39891.00	2971.00	1.08
D ₂ I ₁ N ₂	20 th December + Two irrigation at CRI (21 DAS) and booting stage (75 DAS) + 120 kg N ha ⁻¹	37448.00	46300.00	8852.00	1.24
D ₂ I ₁ N ₃	20 th December + Two irrigation at CRI (21 DAS) and booting stage (75 DAS) + 160 kg N ha ⁻¹	37975.00	49004.00	11029.00	1.29
D ₂ I ₂ N ₁	20 th December + Three irrigation at CRI (21 DAS), tillering stage (40 DAS) and booting stage (75 DAS) + 80 kg N ha ⁻¹	38048.00	56544.00	18496.00	1.49
D ₂ I ₂ N ₂	20 th December + Three irrigation at CRI (21 DAS), tillering stage (40 DAS) and booting stage (75 DAS) + 120 kg N ha ⁻¹	38576.00	68623.00	30047.00	1.78
D ₂ I ₂ N ₃	20 th December + Three irrigation at CRI (21 DAS), tillering stage (40 DAS) and booting stage (75 DAS) + 160 kg N ha ⁻¹	39103.00	81915.00	42812.00	2.09
D ₂ I ₃ N ₁	20 th December + Four irrigation at CRI (21 DAS), tillering stage (40 DAS), booting stage (75 DAS) and milking stage (100 DAS) + 80 kg N ha ⁻¹	39175.00	59190.00	20015.00	1.51
D ₂ I ₃ N ₂	20 th December + Four irrigation at CRI (21 DAS), tillering stage (40 DAS), booting stage (75 DAS) and milking stage (100 DAS) + 120 kg N ha ⁻¹	39703.00	71245.00	31542.00	1.79
D ₂ I ₃ N ₃	20 th December + Four irrigation at CRI (21 DAS), tillering stage (40 DAS), booting stage (75 DAS) and milking stage (100 DAS) + 160 kg N ha ⁻¹	40230.00	84551.00	44321.00	2.10

[SE(d±), CD (P = 0.05): $D \times I = 0.19$, NS; $D \times N = 0.17$, NS; $I \times N = 0.21$, NS; $D \times I \times N = 0.44$, NS]. Nevertheless, the treatment-wise means (Table 5a-5d) showed a consistent pattern: $D \times I$ and $D \times N$ both peaked at I3/N3 under both sowing dates, with a marginally larger gain under D1; $I \times N$ showed the clearest trend, with the N1→N3 gain growing larger at higher irrigation (I_1 : +0.52; I_2 : +1.10; I_3 : +1.20 t ha⁻¹) and D₁I₃N₃ gave the highest yield overall (4.03 t ha⁻¹) against the lowest at D₂I₁N₁ (1.80 t ha⁻¹), a mild positive tendency for irrigation and nitrogen to reinforce one another despite the lack of significance.

A broadly similar, economically more visible pattern held for economic parameters (Table 6): D₁I₃N₃ gave the highest gross and net monetary returns, exceeding the sum of the independent gains of D₁, I₃ and N₃-a positive economic interaction despite the non-significant yield interaction-mirroring interactive irrigation-nitrogen responses reported for wheat (Kumar *et al.*, 2018; Mehrabi and Sepaskhah, 2018) and a related cereal, barley (Al-Menaie *et al.*, 2024), examined further below.

Economics

Economics was markedly influenced by treatment combination (Table 6). D₁I₃N₃ (timely sowing + four irrigations + 160 kg N ha⁻¹) recorded the highest gross monetary return (₹ 88,007 ha⁻¹), net monetary return (₹ 47,777 ha⁻¹) and benefit-cost ratio (2.19), followed by D₁I₂N₃ (three irrigations at CRI, tillering and booting + 160 kg N ha⁻¹) with the second-highest B:C ratio (2.12) and net return of ₹ 43,759 ha⁻¹-91.6% and 96.8% of the top treatment's net return and B:C ratio, despite one fewer irrigation. The fourth, milking-stage irrigation added only ₹ 1,127 ha⁻¹ to cost but ₹ 4,018 ha⁻¹ to net return, remaining justified; yet the closeness of the ratios reflects diminishing marginal returns once nitrogen is non-limiting (N₃), with most of the four-irrigation schedule's profitability already captured with three. D₁I₃N₃ thus offers the highest overall profitability, while D₁I₂N₃ is a practical, nearly-as-profitable alternative wherever water, labour or energy for a fourth irrigation is constrained-a common situation under declining groundwater availability in this zone-consistent with the resource-use efficiency gains from timely sowing and adequate irrigation-nitrogen management (Kanwal *et al.*, 2020; Bashir *et al.*, 2017; Wan *et al.*, 2022).

CONCLUSION

Sowing dates, irrigation schedules and nitrogen levels significantly affected wheat growth, yield and profitability, with effects largely additive under the near rain-free conditions (18.60 mm total) of 2020-21. Timely sowing with irrigation at CRI, tillering, booting and milking stages and 160 kg N ha⁻¹ (close to the zone's 150 kg N ha⁻¹ RDF) gave the best returns; D₁I₃N₃ is recommended for the Vindhyan zone, with D₁I₂N₃ as a nearly equivalent, less water-intensive alternative under water constraints.

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Disclaimers

The views and conclusions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj. The authors are solely responsible for the accuracy and integrity of the data and information presented in this manuscript.

Informed consent

Not applicable. This study did not involve human participants, animals, or any procedures requiring ethical approval or informed consent.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The research was conducted independently and no external funding agency had any role in the design of the study, data collection, analysis, interpretation of results, manuscript preparation, or decision to publish.

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