Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Optimizing Sowing Date, Irrigation Scheduling and Nitrogen Management for Wheat (Triticum aestivum L.): Two-Year Pooled Analysis and DSSAT-CERES-Wheat Model Evaluation for the Vindhyan Zone

Wasim Khan

khanwasim1122@gmail.com

Sam Higginbottom Institute of Agriculture https://orcid.org/0000-0003-3288-5360

Research Article

Keywords: DSSAT-CERES-Wheat, Grain yield, Irrigation scheduling, Nitrogen management, Pooled analysis, Sowing date

Posted Date: August 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10790800/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Optimizing Sowing Date, Irrigation Scheduling and Nitrogen Management for Wheat (*Triticum aestivum* L.): Two-Year Pooled Analysis and DSSAT-CERES-Wheat Model Evaluation for the Vindhyan Zone

Wasim Khan[1]*, Rajesh Singh[2], Shraddha Rawat[3]

[1]PhD, Department of Agronomy, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, Uttar Pradesh 211007, India

[2]Professor, Department of Agronomy, Naini Agricultural Institute, SHUATS, Prayagraj, Uttar Pradesh 211007, India

[3]Assistant Professor, Department of Agronomy, Naini Agricultural Institute, SHUATS, Prayagraj, Uttar Pradesh 211007, India

**Corresponding author. E-mail: khanwasim1122@gmail.com; ORCID: Wasim Khan https://orcid.org/0000-0003-3288-5360; Shraddha Rawat https://orcid.org/0000-0002-4351-3178*

Abstract

Sowing time, irrigation scheduling and nitrogen management jointly determine wheat productivity, and crop simulation models such as DSSAT-CERES-Wheat offer a route to extend two-year field results to a wider range of conditions. This study evaluated the pooled (2019-20 and 2020-21) effect of these three factors on growth, yield and profitability of wheat, and calibrated/validated the DSSAT-CERES-Wheat model (v4.7) for the Vindhyan agro-climatic zone. A split-plot field trial with three replications was conducted over two rabi seasons at the Crop Research Farm, SHUATS, Prayagraj, with two sowing dates (20 November, 20 December), three irrigation schedules and three nitrogen levels (80, 120, 160 kg N ha^{-1}) as eighteen treatment combinations. First-year data were used to calibrate genetic coefficients of cultivar HD 2967, and second-year data were used for independent validation of phenology, leaf area index (LAI) and yield. On a pooled basis, 20 November sowing, four irrigations (CRI, tillering, booting, milking) and 160 kg N ha^{-1} produced the tallest plants, highest dry matter, LAI and yield attributes, with grain yield of 3.44 and biological yield of 7.94 t ha^{-1} and the highest net return and benefit-cost ratio, the $D_1I_3N_3$ combination giving the best economics. The calibrated model predicted days to anthesis and maturity within 1-2 days of observation (nRMSE < 1.5%, d > 0.98) and reproduced LAI closely (nRMSE 7.8% calibration, 6.2% validation; d > 0.95). Grain and biological yields were simulated with r^2 of 0.92-0.96 in calibration and 0.93-0.95 in validation, confirming good-to-excellent model accuracy. Timely sowing, adequate irrigation and higher nitrogen consistently improved wheat productivity and profitability, and the DSSAT-CERES-Wheat model, once calibrated for cultivar HD 2967, reliably reproduced phenology, LAI and grain yield for the Vindhyan Zone, supporting its use as a decision-support tool for regional wheat management.

Keywords: DSSAT-CERES-Wheat · Grain yield · Irrigation scheduling · Nitrogen management · Pooled analysis · Sowing date

Introduction

Wheat (*Triticum aestivum* L.) is the world's second most widely produced food crop and the second-ranked cereal in India after rice, underpinning national food and nutritional security [1]. India harvested 110.55 million tonnes of wheat from 31.40 million hectares in 2022-23, and Uttar Pradesh alone contributed 35.51 million tonnes from 9.85 million hectares [2]. Within the rice-wheat system of the Indo-Gangetic Plains, however, stagnating resource-use efficiency and imbalanced input management increasingly limit further yield gains, so optimising sowing time, irrigation scheduling and nitrogen nutrition together remains central to sustaining productivity.

Sowing date governs the temperature and photoperiod regime a wheat crop experiences through its vegetative and reproductive phases; timely sowing allows the crop to complete grain filling before the onset of terminal heat, whereas delayed sowing shortens this period and depresses yield [3]. Water availability at crown root initiation, tillering, booting and grain filling similarly governs nutrient uptake and assimilate translocation, so that irrigation scheduling has a direct bearing on productivity [4]. Nitrogen, in turn, drives tillering, canopy expansion and biomass accumulation, and an optimum, split-applied dose is essential for

profitable cultivation; excessive or poorly timed nitrogen reduces nutrient-use efficiency without a proportional yield gain [5]. Because these three factors interact, agronomic recommendations developed for one location and cultivar do not transfer directly to another, and field trials repeated over only one or two seasons cannot by themselves capture the full range of seasonal weather that a recommendation must withstand.

Process-based crop simulation models offer a complementary route to this problem. DSSAT and its CERES-Wheat module simulate phenology, growth and yield daily from soil, weather, cultivar and management data, and once calibrated and validated locally, can extrapolate trials across seasons and screen options impractical to test exhaustively in the field [6,7]. The model's performance is, however, cultivar- and site-specific, and its genetic coefficients must be calibrated afresh for each cultivar and re-validated for each new agro-climatic zone before the model can be used with confidence [8].

Information on the combined and interactive effects of sowing date, irrigation scheduling and nitrogen management on wheat, pooled over more than one season, together with a locally calibrated and validated DSSAT-CERES-Wheat model, remains inadequate for the Vindhyan agro-climatic zone of Uttar Pradesh. The present study was therefore undertaken (i) to evaluate the pooled, two-year effect of sowing dates, irrigation scheduling and nitrogen levels on the growth, yield attributes, yield and economics of wheat cultivar HD 2967, and (ii) to calibrate and independently validate the DSSAT-CERES-Wheat model (v4.7) for this cultivar and zone using the corresponding two years of field observations.

Materials and Methods

Experimental Site

The field trial was conducted over two consecutive rabi seasons (2019-20 and 2020-21) at the Crop Research Farm, Department of Agronomy, SHUATS, Prayagraj, Uttar Pradesh, India (25°57′ N, 81°19′ E, 98 m amsl). The site has a subtropical, semi-arid climate with hot dry summers and cool dry winters, and receives about 934 mm annual rainfall, mainly in the monsoon (June-September).

Weather During the Crop-Growing Period

Weekly meteorological data were recorded at the Agro-Meteorological Observatory, College of Forestry, SHUATS; seasonal means are in Table 1 and weekly trends in Figs. 1-2. The crop received 84.70 mm of rain in 2019-20 and 18.60 mm in 2020-21 against a district long-period average of 934 mm year^{-1} — in both seasons well below the long-period norm, though 2019-20 received appreciably more rain than 2020-21, spread across several weeks in December, January and February rather than concentrated in a single event. Mean maximum temperature was about 3.4 °C higher in 2020-21 than in 2019-20, while minimum temperature and relative humidity were broadly comparable between years.

Table 1 Seasonal weather summary during the wheat-growing period (standard meteorological weeks 47-16, late November to late April), Rabi 2019-20 and 2020-21, SHUATS, Prayagraj

Parameter	2019-20	2020-21
Mean maximum temperature (°C)	27.55	30.92
Mean minimum temperature (°C)	11.88	13.40
Mean maximum relative humidity (%)	88.09	87.42
Mean minimum relative humidity (%)	55.39	51.58
Total rainfall during crop season (mm)	84.70	18.60

Values are means of standard meteorological weeks 47 (mid/late November) through 16 (late April) of each season; source: Meteorological Observatory, College of Forestry, SHUATS, Prayagraj.

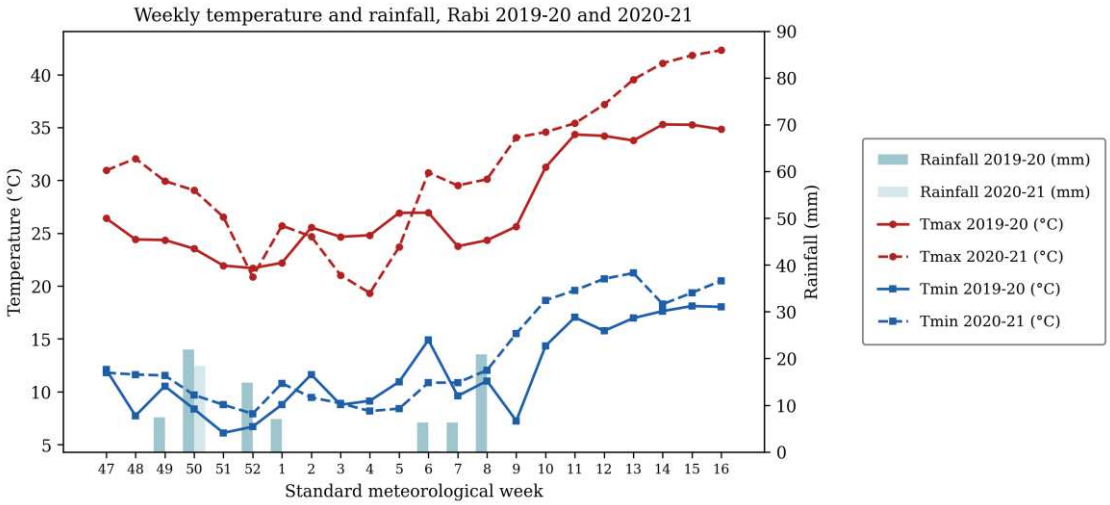


Fig. 1 Weekly maximum and minimum temperature and rainfall during the wheat-growing period, Rabi 2019-20 and 2020-21

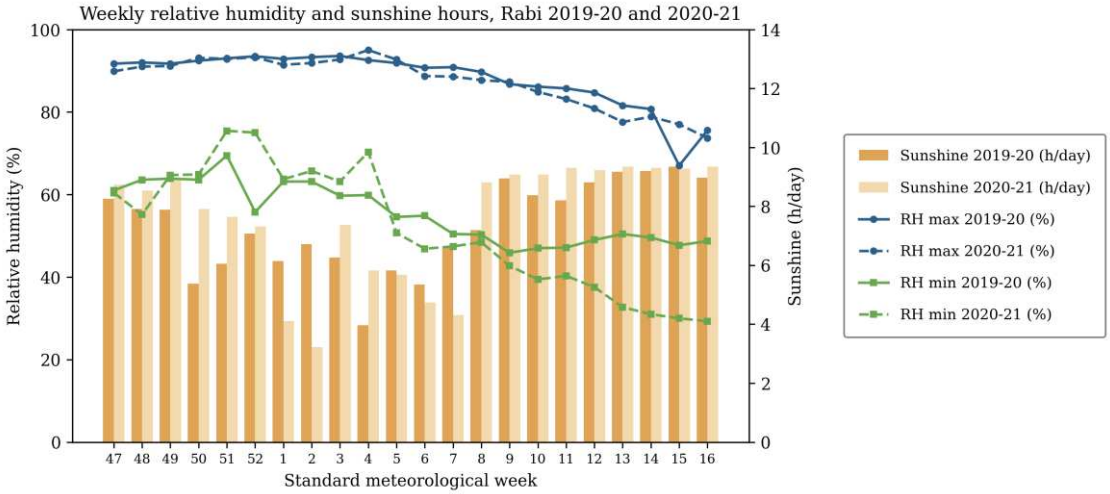


Fig. 2 Weekly relative humidity and sunshine hours during the wheat-growing period, Rabi 2019-20 and 2020-21

Soil Characteristics

Pre-sowing composite soil samples (0-15 cm) were sandy loam in texture (58.75% sand, 25.15% silt, 16.45% clay) in both years. The soil was slightly alkaline (pH 7.7) with low soluble salts, low in organic carbon and available nitrogen, and medium in available phosphorus and potassium (Table 2).

Table 2 Pre-sowing physico-chemical properties of the experimental soil (0-15 cm depth)

Property	2019-20	2020-21
Soil reaction (pH, 1:2.5)	7.7	7.7
Electrical conductivity (dS m^{-1})	0.41	0.45
Organic carbon (%)	0.38	0.39
Available nitrogen (kg ha^{-1})	174.62	178.53
Available phosphorus (kg ha^{-1})	19.50	20.36
Available potassium (kg ha^{-1})	223.28	229.42

Experimental Design and Treatments

The trial 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, each replicated three times in both years.

Crop Establishment and Nutrient Management

Wheat cultivar HD 2967 was sown manually on the designated dates in both years (100 kg ha^{-1} seed rate, 22.5 cm row spacing; seed treated with carbendazim 2 g kg^{-1}). Gross plot size was 12.15 m^2 and net plot size 10.08 m^2. A uniform basal dose of 60 kg P_2O_5 ha^{-1} and 40 kg K_2O ha^{-1} was applied through diammonium phosphate and muriate of potash, while nitrogen was supplied through urea at the three treatment levels in three splits — half as basal and the remainder at 25 and 45 days after sowing (DAS). Under the zone-wise Package of Practices for the North Eastern Plains Zone published by ICAR-Directorate of Wheat Research, Karnal, the recommended dose of fertilizer differs with sowing time — 150:60:40 kg N:P_2O_5:K_2O ha^{-1} for timely-sown and 120:60:40 kg N:P_2O_5:K_2O ha^{-1} for late-sown wheat [9] — so that, for D_1, N_3 (160 kg N ha^{-1}) closely approximates the recommended dose while N_1 and N_2 represent about 53% and 80% of it; for D_2, N_2 (120 kg N ha^{-1}) matches the recommended dose exactly, while N_1 and N_3 represent about 67% and 133% of it. Irrigation was applied at crown root initiation (21 DAS), tillering (40 DAS), booting (75 DAS) and milking (100 DAS) as per the treatment schedule, and weeds were controlled with post-emergence sulfosulfuron 75% + metsulfuron-methyl 5% WG at 40 g ha^{-1} around 30 DAS, with all other agronomic operations kept uniform across treatments.

Observations Recorded

Plant height, tiller number per running metre, dry weight per plant and leaf area index (LAI) were recorded at 20, 40, 60, 80 and 100 DAS, and crop growth rate (CGR) and relative growth rate (RGR) were computed for successive growth intervals. At maturity, effective tillers m^{-2}, spike length, grains per spike and test weight were recorded, and grain, straw and biological yield and harvest index were computed by standard procedures. Cost of cultivation, gross monetary return (GMR), net monetary return (NMR) and benefit-cost (B:C) ratio were estimated from prevailing input costs and minimum support prices for each year.

Statistical Analysis

Data for each year were analysed using the appropriate split-plot ANOVA, and a pooled analysis of variance across the two years was subsequently carried out following standard procedures for combined analysis of split-plot experiments, after testing for homogeneity of error variances between years. Treatment means were compared using the critical difference (CD) at P = 0.05; the pooled means, standard errors of difference [SE(d±)] and CD values are reported in the tables that follow.

Calibration and Validation of the DSSAT-CERES-Wheat Model

The DSSAT-CERES-Wheat model (v4.7) [7] was used to simulate phenology (days to anthesis and maturity), LAI, and grain and biological yield for all eighteen treatment combinations. Field observations from 2019-20 were used to derive the genetic coefficients of cultivar HD 2967 by iteratively adjusting the coefficients until simulated phenology and yield closely matched the corresponding observed values (calibration); the independent 2020-21 observations were then used, without further coefficient adjustment, to test the model under a second, climatically distinct season (validation). The calibrated genetic coefficients are given in Table 3.

Table 3 Calibrated genetic coefficients of the DSSAT-CERES-Wheat model for cultivar HD 2967

Parameter	Code	HD 2967
Days at optimum vernalising temperature required to complete vernalization	P1V	15
Percentage reduction in development rate in a photoperiod 10 h shorter than the threshold, relative to the threshold	P1D	90
Grain-filling (excluding lag) phase duration (°C day)	P5	936
Kernel number per unit canopy weight at anthesis (# g^{-1})	G1	28
Standard kernel size under optimum conditions (mg)	G2	37
Standard, non-stressed dry weight of a single tiller (including grain) at maturity (g)	G3	2
Interval between successive leaf-tip appearances (°C day)	PHINT	90

Model performance was assessed using the coefficient of determination (R^2), mean bias error (MBE), root mean square error (RMSE), normalised root mean square error (nRMSE) and index of agreement (d), calculated as follows:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i-\bar{O})(S_i-\bar{S})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(S_i-\bar{S})^2}}\right]^2 \quad (1)$$

where O_i and S_i are observed and simulated values, respectively, and $\bar{O}$ and $\bar{S}$ are their corresponding means.

$$MBE = \frac{\sum_{i=1}^{n}(S_i-O_i)}{n} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i-O_i)^2}{n}} \quad (3)$$

$$nRMSE = \frac{RMSE}{\bar{O}} \times 100 \quad (4)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i-O_i)^2}{\sum_{i=1}^{n}(|S_i-\bar{O}|+|O_i-\bar{O}|)^2} \quad (5)$$

where:

- O_i = observed value

- S_i = simulated value

- $\bar{O}$ = mean observed value

- $\bar{S}$ = mean simulated value

- n = number of observations

nRMSE < 10% and d close to 1.0 indicate excellent agreement.

Results and Discussion

Weather Conditions

The two seasons differed mainly in maximum temperature and rainfall (Table 1; Figs. 1, 2); 2020-21 was warmer and drier, with slightly earlier phenology and lower yield of most treatments (cf. Table 8). In 2020-21, rainfall was negligible, so irrigation was effectively the sole source of soil-moisture variation. In 2019-20, rainfall was higher (84.70 mm) and fell across several weeks, some coinciding with crown root initiation and booting; still below the long-period norm, irrigation-treatment differences in 2019-20 thus reflect the dominant, not sole, source of soil-moisture variation.

Growth Attributes

Timely sowing (D_1), the highest irrigation frequency (I_3) and the highest nitrogen level (N_3) consistently produced taller plants, more tillers, greater dry matter accumulation and higher LAI than their respective alternatives, on a pooled basis, at both 80 and 100 DAS (Table 4). At 100 DAS, D_1 exceeded D_2 by 10.4 cm in plant height, 4.7 tillers m^{-1} and 0.90 g $plant^{-1}$ dry weight; I_3 exceeded I_1 by 12.1 cm, 13.1 tillers m^{-1} and 1.11 g $plant^{-1}$ dry weight; and N_3 exceeded N_1 by 4.6 cm, 6.5 tillers m^{-1} and 1.68 g $plant^{-1}$ dry weight. Interactions were, apart from a significant sowing-date × irrigation effect on plant height (60-100 DAS) and an irrigation × nitrogen effect on tiller number (40-60 DAS), non-significant (Supplementary Table S2), indicating the three factors acted largely additively on vegetative growth.

Table 4 Pooled (2019-20 and 2020-21) effect of sowing dates, irrigation scheduling and nitrogen levels on growth attributes of wheat cv. HD 2967 at 80 and 100 DAS

Treatment	Plant height (cm)		Tillers (no. m^{-1} row)		Dry weight (g $plant^{-1}$)		LAI	
	80 DAS	100 DAS	80 DAS	100 DAS	80 DAS	100 DAS	80 DAS	100 DAS
Sowing dates								
D_1 (20 Nov)	78.27	81.64	86.88	76.33	6.429	8.359	3.696	3.203
D_2 (20 Dec)	70.14	71.21	78.68	71.59	5.705	7.455	3.476	2.969
SE(d±)	1.43	2.19	2.11	2.08	0.126	0.165	0.086	0.065
CD (P=0.05)	2.98	4.57	4.39	4.34	0.264	0.344	0.180	0.135
Irrigation levels								
I_1 (CRI+Boot)	68.30	70.18	75.57	67.68	5.630	7.355	2.625	2.341
I_2 (CRI+Till+Boot)	74.67	76.78	82.59	73.42	6.079	7.903	4.042	3.426
I_3 (CRI+Till+Boot+Milk)	79.64	82.32	90.91	80.78	6.493	8.463	4.090	3.492
SE(d±)	1.75	2.68	2.58	2.55	0.155	0.202	0.105	0.079
CD (P=0.05)	3.65	5.60	5.38	5.31	0.323	0.421	0.220	0.165
Nitrogen levels								
N_1 (80 kg ha^{-1})	71.89	73.90	79.08	70.59	5.375	7.033	3.052	2.633
N_2 (120 kg ha^{-1})	74.60	76.84	82.66	74.19	6.146	7.978	3.708	3.158
N_3 (160 kg ha^{-1})	76.13	78.53	86.60	77.11	6.680	8.710	3.997	3.467
SE(d±)	2.03	2.20	2.36	2.34	0.154	0.155	0.103	0.080
CD (P=0.05)	4.07	4.42	4.74	4.71	0.309	0.312	0.208	0.161

DAS, days after sowing; LAI, leaf area index; SE(d±), standard error of difference between means; CD, critical difference.

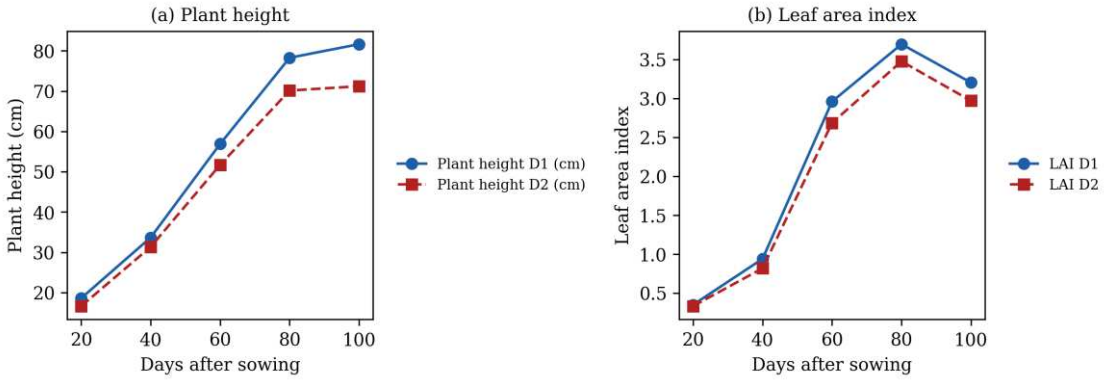


Fig. 3 Progression of (a) plant height and (b) leaf area index from 20 to 100 DAS under the two sowing dates (pooled across irrigation and nitrogen levels)

The superiority of D_1 over D_2 reflects the more favourable temperature regime available to early-sown wheat through the vegetative phase, allowing greater meristematic activity and canopy expansion before terminal heat associated with late sowing sets in [3]. The progressive increase in dry matter and LAI with irrigation frequency reflects the role of adequate soil moisture at crown root initiation, tillering and booting in sustaining cell division and expansion, both of which are essential for tiller survival and leaf-area

development [4]. Likewise, higher nitrogen availability promoted a larger, longer-lived canopy intercepting more radiation, consistent with nitrogen's role in chlorophyll synthesis.

Yield Attributes

Yield-contributing characters followed the same ranking as growth attributes on a pooled basis: $D_1 > D_2$, $I_3 > I_2 > I_1$ and $N_3 > N_2 > N_1$ for effective tillers, spike length, grains per spike and test weight (Table 5). Timely sowing increased effective tillers by 10.6%, grains per spike by 12.9% and test weight by 6.2%; four irrigations increased them by 18.5%, 15.5% and 5.2%; and 160 kg N ha^{-1} increased them by 8.4%, 6.5% and 3.8% over their respective lowest levels. Interactions were non-significant (Supplementary Table S3), though $D_1I_3N_3$ gave the numerically highest values.

Table 5 Pooled effect of sowing dates, irrigation scheduling and nitrogen levels on yield attributes of wheat

Treatment	Effective tillers (no. m^{-2})	Spike length (cm)	Grains per spike	Test weight (g)
Sowing dates				
D_1 (20 Nov)	332.13	10.65	40.41	35.48
D_2 (20 Dec)	300.14	9.75	35.78	33.40
SE(d±)	8.43	0.22	0.82	0.37
CD (P=0.05)	17.59	0.45	1.72	0.78
Irrigation levels				
I_1 (CRI+Boot)	292.06	9.48	35.30	33.59
I_2 (CRI+Till+Boot)	310.34	10.18	38.20	34.42
I_3 (CRI+Till+Boot+Milk)	346.00	10.95	40.79	35.32
SE(d±)	10.33	0.27	1.01	0.46
CD (P=0.05)	21.54	0.56	2.10	0.96
Nitrogen levels				
N_1 (80 kg ha^{-1})	302.24	9.81	36.76	33.68
N_2 (120 kg ha^{-1})	318.49	10.29	38.38	34.68
N_3 (160 kg ha^{-1})	327.68	10.50	39.15	34.95
SE(d±)	8.84	0.25	0.94	0.58
CD (P=0.05)	17.78	0.49	1.88	1.17

Yield and Harvest Index

Grain, straw and biological yield showed a highly consistent pooled response to all three factors, while harvest index remained statistically unaffected (Table 6). Timely sowing (D_1) produced 11.1% more grain and 10.0% more biological yield than late sowing (D_2); four irrigations (I_3) produced 32.9% more grain and 29.0% more biological yield than two irrigations (I_1); and 160 kg N ha^{-1} (N_3) produced 33.3% more grain and 31.9% more biological yield than 80 kg N ha^{-1} (N_1). The pooled sowing date × irrigation × nitrogen interaction (Supplementary Table S4), although statistically non-significant, was numerically highest for $D_1I_3N_3$ (grain yield 4.02 t ha^{-1}) and lowest for $D_2I_1N_1$ (grain yield 2.05 t ha^{-1}), a nearly two-fold range that underlines the practical importance of combining the three inputs correctly rather than optimising any one factor in isolation.

Table 6 Pooled effect of sowing dates, irrigation scheduling and nitrogen levels on yield and harvest index of wheat

Treatment	Grain yield (t ha⁻¹)	Straw yield (t ha⁻¹)	Biological yield (t ha⁻¹)	Harvest index (%)
Sowing dates				
D₁ (20 Nov)	3.19	4.19	7.38	43.13
D₂ (20 Dec)	2.87	3.81	6.68	42.79
SE(d±)	0.10	0.13	0.21	1.38
CD (P=0.05)	0.21	0.27	0.44	NS
Irrigation levels				
I₁ (CRI+Boot)	2.52	3.44	5.96	42.17
I₂ (CRI+Till+Boot)	3.22	4.24	7.45	43.12
I₃ (CRI+Till+Boot+Milk)	3.35	4.34	7.69	43.59
SE(d±)	0.12	0.16	0.26	1.70
CD (P=0.05)	0.25	0.33	0.54	NS
Nitrogen levels				
N₁ (80 kg ha⁻¹)	2.58	3.44	6.02	42.80
N₂ (120 kg ha⁻¹)	3.07	4.07	7.14	42.91
N₃ (160 kg ha⁻¹)	3.44	4.50	7.94	43.18
SE(d±)	0.11	0.12	0.22	1.43
CD (P=0.05)	0.23	0.24	0.44	NS

NS, not significant at P=0.05.

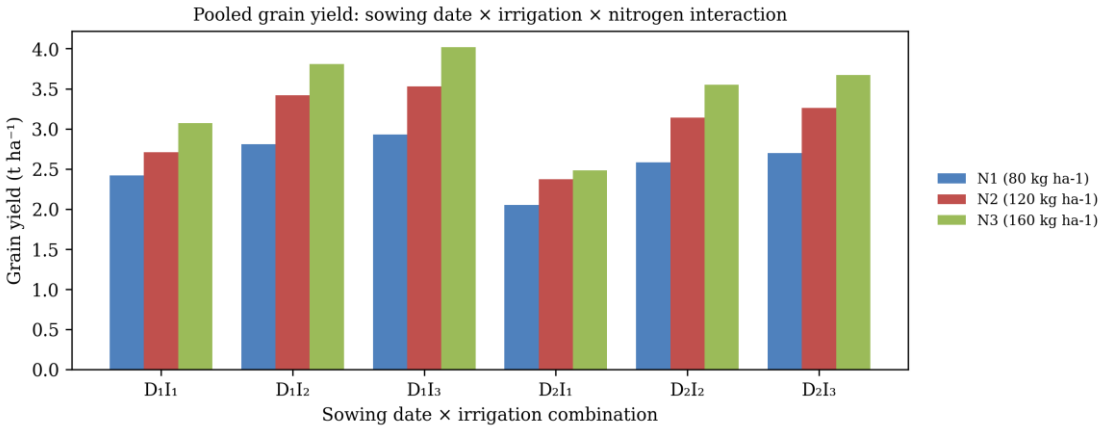


Fig. 4 Pooled grain yield of wheat under the sowing date × irrigation × nitrogen interaction, showing the maximum yield at $D_1I_3N_3$ and minimum at $D_2I_1N_1$

The strong yield response to irrigation frequency reflects the cumulative benefit of maintaining adequate soil moisture through crown root initiation, tillering, booting and grain filling, consistent with yield gains from irrigation and nitrogen management reported for wheat in the eastern Indo-Gangetic Plains [4]. The proportionate rise in yield with nitrogen up to 160 kg N ha⁻¹ mirrors the improvement in effective tillers, grains per spike and test weight already described, and is consistent with the higher recommended dose of 150 kg N ha⁻¹ prescribed by ICAR for timely-sown wheat in this zone [9].

Economics

Cost of cultivation varied only modestly with treatment (Rs 37,404-40,174 ha⁻¹ across treatments), whereas gross and net monetary returns varied several-fold, so profitability was governed chiefly by yield rather than input cost (Table 7). On a pooled basis, D_1 returned Rs 68,416 ha⁻¹ GMR and Rs 29,884 ha⁻¹ NMR against Rs 61,563 and Rs 23,031 ha⁻¹ for D_2 (11.1% and 29.8% higher, respectively); I_3 returned Rs 71,762 GMR and Rs 32,103 NMR ha⁻¹, 32.5% and 91.2% higher than I_1; and N_3 returned Rs 73,669 GMR and Rs 34,623

NMR ha^{-1}, 33.0% and 99.2% higher than N_1. The B:C ratio followed the same pattern, rising from 1.45 (I_1) to 1.81 (I_3) and from 1.46 (N_1) to 1.88 (N_3). Consistent with the pooled grain-yield interaction, $D_1I_3N_3$ gave the single highest pooled economics of any treatment (Supplementary Table S6) — GMR Rs 86,098, NMR Rs 45,924 ha^{-1} and B:C ratio 2.15 — confirming that timely sowing with adequate irrigation and higher nitrogen is the most profitable strategy tested, consistent with irrigation-nutrient benefits reported for wheat elsewhere [5].

Table 7 Pooled effect of sowing dates, irrigation scheduling and nitrogen levels on the economics of wheat cultivation

Treatment	Cost of cultivation (Rs ha^{-1})	GMR (Rs ha^{-1})	NMR (Rs ha^{-1})	B:C ratio
Sowing dates				
D_1 (20 Nov)	38,532	68,416	29,884	1.77
D_2 (20 Dec)	38,532	61,563	23,031	1.59
Irrigation levels				
I_1 (CRI+Boot)	37,404	54,195	16,791	1.45
I_2 (CRI+Till+Boot)	38,532	69,012	30,480	1.79
I_3 (CRI+Till+Boot+Milk)	39,659	71,762	32,103	1.81
Nitrogen levels				
N_1 (80 kg ha^{-1})	38,017	55,405	17,388	1.46
N_2 (120 kg ha^{-1})	38,532	65,894	27,362	1.71
N_3 (160 kg ha^{-1})	39,046	73,669	34,623	1.88

GMR, gross monetary return; NMR, net monetary return; B:C, benefit-cost.

Calibration and Validation of the DSSAT-CERES-Wheat Model

Statistical comparison of observed and simulated values across all eighteen treatments (Table 8) shows that the calibrated model reproduced days to anthesis and maturity almost exactly, with RMSE below 2 days and nRMSE below 1.5% in both calibration (2019-20) and validation (2020-21), and Willmott's d exceeding 0.98 in every case — performance consistent with earlier CERES-Wheat calibrations for north Indian conditions that report RMSE of 1-3 days for phenological events [10,11]. Leaf area index was also well simulated, with nRMSE of 7.8% in calibration and 6.2% in validation and d above 0.95 in both datasets, indicating that the calibrated genetic coefficients (Table 3) adequately captured canopy development under the full range of sowing, irrigation and nitrogen treatments tested.

Grain yield was simulated with r^2 of 0.96 and nRMSE of 6.5% in calibration, and r^2 of 0.95 and nRMSE of 12.3% in validation, indicating a consistent tendency of the model to slightly over-predict grain yield (mean bias of +112 kg ha^{-1} in calibration and +267 kg ha^{-1} in validation) but still within the range generally considered good-to-excellent agreement for CERES-Wheat applications [12,13]. Biological yield followed a similar pattern, with r^2 of 0.92 and nRMSE of 6.6% in calibration and r^2 of 0.93 and nRMSE of 14.0% in validation, confirming that the calibrated coefficients captured overall dry-matter production consistently across both seasons.

Table 8 Statistical evaluation of the calibrated (2019-20) and validated (2020-21) DSSAT-CERES-Wheat model across all sowing date × irrigation × nitrogen treatments (n = 18 per dataset)

Parameter	Dataset	Mean observed	Mean simulated	r^2	MBE	RMSE	nRMSE (%)	d
Days to emergence	Calibration (2019-20)	5.00	4.50	1.00	-0.50	0.71	14.14	0.80
	Validation (2020-21)	5.00	3.50	1.00	-1.50	1.58	31.62	0.62
Days to anthesis	Calibration (2019-20)	84.06	84.00	0.74	-0.06	1.22	1.46	0.92
	Validation (2020-21)	81.50	81.50	0.96	0.00	1.15	1.42	0.99
Days to maturity	Calibration (2019-20)	127.67	128.00	0.94	0.33	1.73	1.36	0.99
	Validation (2020-21)	123.67	124.00	0.94	0.33	1.73	1.40	0.99
LAI	Calibration (2019-20)	4.04	3.93	0.88	-0.12	0.32	7.80	0.96
	Validation (2020-21)	3.13	3.08	0.97	-0.05	0.19	6.17	0.99
Grain yield (kg ha^{-1})	Calibration (2019-20)	3106.6	3218.2	0.96	111.7	202.0	6.50	0.96
	Validation (2020-21)	2949.8	3216.7	0.95	266.8	362.4	12.28	0.94
Biological yield (kg ha^{-1})	Calibration (2019-20)	7161.8	6926.3	0.92	-235.5	471.5	6.58	0.96
	Validation (2020-21)	6901.3	6015.6	0.93	-885.8	967.6	14.02	0.88

MBE, mean bias error; RMSE, root mean square error; nRMSE, normalised RMSE; d, Willmott's index of agreement. Statistics computed directly from paired observed-simulated values recorded for each of the eighteen sowing date × irrigation × nitrogen treatment combinations. The full treatment-wise observed and simulated data underlying this table are provided in Supplementary Table S5.

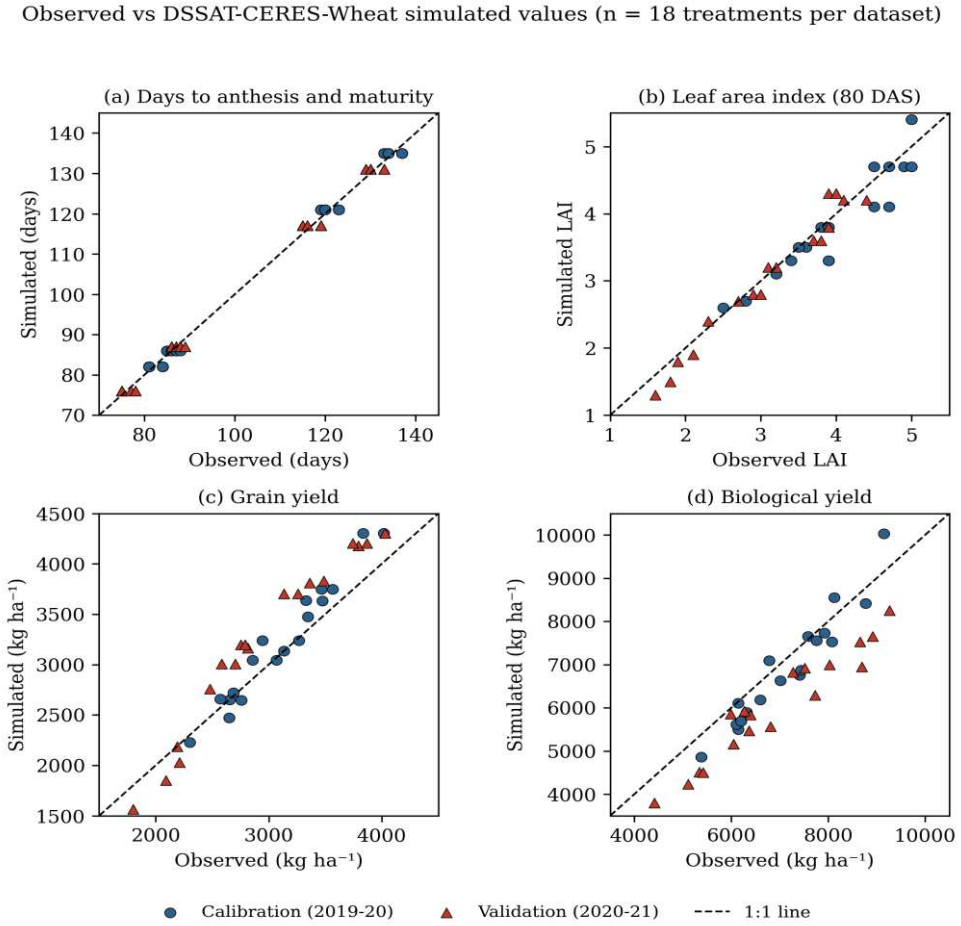


Fig. 5 Observed versus DSSAT-CERES-Wheat simulated (a) days to anthesis and maturity, (b) leaf area index at 80 DAS, (c) grain yield and (d) biological yield, for the calibration (2019-20) and validation (2020-21) datasets, relative to the 1:1 line

Overall, the model performed excellently for phenology and LAI and well-to-excellently for grain and biological yield in both the calibration and validation datasets. This is consistent with earlier findings that CERES-Wheat, once calibrated with one season of local data, reliably reproduces the timing of phenological events and grain and biomass yield under a new season's weather [16,17]. Practically, this means the calibrated model reported here can be used with confidence to schedule irrigation and nitrogen management, and to extrapolate the pooled agronomic recommendations of the present study to other seasons in the Vindhyan Zone.

Conclusions

Over two rabi seasons, timely sowing on 20 November, four irrigations at crown root initiation, tillering, booting and milking, and nitrogen application at 160 kg ha^{-1} consistently produced the tallest, most vigorous crop and the highest pooled grain, straw and biological yield, with the $D_1I_3N_3$ combination also delivering the highest net return and benefit-cost ratio. The DSSAT-CERES-Wheat model, calibrated for cultivar HD 2967 using 2019-20 data and independently validated with 2020-21 data, reproduced phenology, LAI, grain yield and biological yield with good-to-excellent accuracy in both seasons. Together, the pooled field results and the calibrated model provide a locally verified basis for recommending timely sowing, adequate irrigation and a higher nitrogen dose for wheat cultivar HD 2967 in the Vindhyan Zone, and a validated simulation tool that can extend these recommendations to seasons and conditions beyond those directly tested.

Supplementary Information

The online version contains supplementary material comprising Tables S1-S6: weekly weather (S1); pooled interaction means for growth (S2), yield attributes (S3), yield/harvest index (S4); DSSAT observed/simulated data (S5); economics (S6).

Acknowledgements

The authors thank the Department of Agronomy, SHUATS, for the field facilities used.

Author Contributions

Conceptualization: Wasim Khan, Rajesh Singh; Data Collection, Analysis, Writing: Wasim Khan; Review: All authors; Supervision: Rajesh Singh, Shraddha Rawat.

Funding

The authors did not receive support from any organization for the submitted work.

Data Availability

The datasets generated and analysed during the present study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest: The authors have no relevant financial or non-financial interests to disclose.

Ethical Approval: Not applicable; the study involved field cultivation of a crop and did not involve human participants, animals or their biological material.

References

1. FAOSTAT (2023) Food and agriculture data: crops and livestock products. https://www.fao.org/faostat/en/#home

2. Anonymous (2023) Agricultural research data book. Indian Council of Agricultural Research, New Delhi

3. Farooq M, Hussain M, Siddique KHM (2014) Drought stress in wheat during flowering and grain-filling periods. Crit Rev Plant Sci 33(4):331-349. https://doi.org/10.1080/07352689.2014.875291

4. Sahoo S, Mukhopadhyay P, Sinha AK, Bhattacharya PM, Rakesh S, et al (2022) Yield, nitrogen-use efficiency, and distribution of nitrate-nitrogen in the soil profile as influenced by irrigation and fertilizer nitrogen levels under zero-till wheat in the eastern Indo-Gangetic plains of India. Front Environ Sci 10:970017. https://doi.org/10.3389/fenvs.2022.970017

5. Mandal KG, Hati KM, Misra AK, Bandyopadhyay KK, Mohanty M (2005) Irrigation and nutrient effects on growth and water-yield relationship of wheat (Triticum aestivum L.) in central India. J Agron Crop Sci 191:416-425. https://doi.org/10.1111/j.1439-037X.2005.00160.x

6. Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT (2003) The DSSAT cropping system model. Eur J Agron 18:235-265. https://doi.org/10.1016/S1161-0301(02)00107-7

7. Hoogenboom G, Porter CH, Boote KJ, Shelia V, Wilkens PW, Singh U, White JW, Asseng S, Lizaso JI, Moreno LP, Pavan W, Ogoshi R, Hunt LA, Tsuji GY, Jones JW (2019) The DSSAT crop modeling ecosystem. In: Boote KJ (ed) Advances in crop modeling for a sustainable agriculture. Burleigh Dodds Science Publishing, pp 173-216. https://doi.org/10.19103/AS.2019.0061.10

8. Krishnan P, Pramanik Maity P, Kundu M (2021) Sensitivity analysis of cultivar parameters to simulate wheat crop growth and yield under moisture and temperature stress conditions. Heliyon 7(7) e07602. https://doi.org/10.1016/j.heliyon.2021.e07602

9. Kumar A et al (2014) Wheat cultivation in India: pocket guide. Extension Bulletin No. 52, ICAR-Directorate of Wheat Research, Karnal

10. Patel C, Nema AK, Singh RS, Yadav MK, Singh SK, Singh SM (2017) Evaluation of DSSAT-CERES model for irrigation scheduling of wheat crop in Varanasi region of Uttar Pradesh. J Agrometeorol 19(2):120-124. https://doi.org/10.54386/jam.v19i2.683

11. Patel HR, Patel GG, Shroff JC, Pandey V, Shekh AM, Vadodaria RP, Bhatt BK (2010) Calibration and validation of CERES-wheat model for wheat in middle Gujarat region. J Agrometeorol 12(1):114-117. https://doi.org/10.54386/jam.v12i1.1286

12. Andarzian B, Hoogenboom G, Bannayan M, Shirali M, Andarzian B (2015) Determining optimum sowing date of wheat using CSM-CERES-Wheat model. J Saudi Soc Agric Sci 14(2):189-199. https://doi.org/10.1016/j.jssas.2014.06.001

13. Attia A, Rajan N, Xue Q, Nair S, Ibrahim A, Hays D (2016) Application of DSSAT-CERES-Wheat model to simulate winter wheat response to irrigation management in the Texas High Plains. Agric Water Manag 165:50-60. https://doi.org/10.1016/j.agwat.2015.11.002

14. Abera EA (2019) Calibration and validation of CERES-wheat in DSSAT model for yield simulation under future climate in Adet, North Western Ethiopia. Afr J Agric Res 14(8):509-518

15. Wei Y, Ru H, Leng X, He Z, Ayantobo OO, Javed T, Yao N (2022) Better performance of the modified CERES-Wheat model in simulating evapotranspiration and wheat growth under water stress conditions. Agriculture 12(11):1902. https://doi.org/10.3390/agriculture12111902

16. Bannayan M, Hoogenboom G (2008) Weather analogue: a tool for real-time prediction of daily weather data realizations based on a modified k-nearest neighbor approach. Environ Model Softw 23(5):703-713. https://doi.org/10.1016/j.envsoft.2007.09.011

17. Vinay GN, Gautam S, Rawat S (2021) Simulation of wheat crop at different irrigation levels using DSSAT model for Prayagraj. Pharma Innov J 10(8S):1232-1237