



RESEARCH ARTICLE

Influence of sowing windows and irrigation scheduling on agro-meteorological indices and wheat yield

Bheem Pareek^{1,2*}, Ranbir Singh Rana², Sandeep Manuja², Nitesh Kumar³, Navjot Rana^{4*} & Narendra Pareek⁵

¹Department of Agronomy, Rajasthan Agricultural Research Institute (RARI), Sri Karan Narendra Agriculture University (SKNAU), Jobner, Jaipur 302 018, Rajasthan, India

²Department of Agronomy, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishwavidyalaya, Palampur 176 062, Himachal Pradesh, India

³ICAR-Indian Institute of Wheat and Barley Research, Karnal 132 001, Haryana, India

⁴Department of Agronomy, School of Agriculture, Lovely Professional University, Jalandhar 144 411, Punjab, India

⁵Department of Agronomy, Sri Karan Narendra Agriculture University (SKNAU), Jobner, Jaipur 303 329, Rajasthan, India

*Correspondence email - bheem.pareek0002@gmail.com; navjotrana7@gmail.com

Received: 05 February 2026; Accepted: 31 March 2026; Available online: Version 1.0: 27 April 2026

Cite this article: Bheem P, Ranbir SR, Sandeep M, Nitesh K, Navjot R, Narendra P. Influence of sowing windows and irrigation scheduling on agro-meteorological indices and wheat yield. Plant Science Today. 2026; 13(sp2): 1-12. <https://doi.org/10.14719/pst.14003>

Abstract

At the experimental research farm of the Department of Agronomy, Experimental Research Farm in Palampur, Himachal Pradesh, during the rabi seasons of 2021–2022 and 2022–2023, a field experiment titled “Agro meteorological indices influenced by different sowing windows and irrigation scheduling using weather model and spatial data of wheat in Western Himalayas” was carried out. The experiment comprised a split plot design with 3 replications and included 5 irrigation treatments: rainfed conditions (I1), 2 irrigations (I2), 3 irrigations (I3), irrigation scheduling based on Penman Monteith modified (I4) and irrigation scheduling based on spatial reference ET of grid (I5). The crop sown on 25th October had the highest values of growing degree days (GDD), helio-thermal units (HTU), heat use efficiency (HUE), photo-thermal units (PTU) and photo-thermal index (PTI) compared to the crop sown on 10th December in 2021–2022 and 2022–2023. This helped to increase the grain yield by 47.4 and 35.8 %, respectively, over the crop sown on 10th December. Due to the highest values of GDD, HTU, HUE, PTU and PTI observed under the highest irrigation treatments, the largest increase in grain yield was recorded with 3 irrigations (33.1 and 19.4 %) and Penman Monteith modified (33.7 and 13.5 %) over rainfed conditions. The findings recommend timely sowing around late October and the use of weather-based irrigation scheduling-especially the Penman-Monteith method as sustainable strategies to improve wheat productivity and climate resilience in the Western Himalayan region. These practices optimise thermal indices and water use efficiency, supporting adaptive agriculture under variable climatic conditions.

Keywords: growing degree days; heat units; helio-thermal units; irrigation scheduling; Penman Monteith modified; photo-thermal units

Introduction

Wheat (*Triticum aestivum* L.) is a commonly adapted rabi crop in Himalayan regions of India, which range from warm, humid to dry, cold climates. Warm temperatures are ideal for wheat maturity, whereas cool temperatures are favourable for the vegetative stage (1, 2). Seasonal variations in temperature have an impact on the crop's phenological development. The sowing time is one of the most important factors affecting the crop's phenological development and the conversion of biomass into economic yield (3). One of the main objectives of agrometeorological research is to estimate crop production as a function of weather, soil and crop management factors. Such study has applications across broad temporal and geographic dimensions, ranging from within-season crop management method change to national and worldwide agricultural output forecasts. Wheat is a temperature-sensitive crop that, in the Western Himalayan region-particularly in mid-hill zones like Palampur-is frequently subjected to fluctuating temperatures. Cold spells during establishment and unseasonal warming during reproductive phases can accelerate maturity and reduce yield

potential. Such climatic variability in this agro-ecological zone necessitates precise sowing and irrigation strategies to stabilise wheat productivity. To maximise production and guarantee that biological output is efficiently transformed into commercial produce, it is essential to sow at the optimal period (4, 5). Because normal sowing has a longer growing period than late sowing, it generally supports a bigger biomass accumulation thus, superior grain and biological yields (6). The accumulated heat units approach makes it feasible to conduct field research on the effects of temperature on the phenology and yield of agricultural plants (7). The number of degree-days accrued at each stage of growth varies significantly across varieties, even though it is mostly constant and unaffected by the date of planting. In North Indian settings, wheat maturity rose because of a persistent rise in the surrounding temperature throughout the delayed planting period (8, 9). Understanding the exact length of phenological phases and their impact on agricultural productivity in each crop-growing area is thus essential. Wheat requires 400 to 650 mm of water for optimal yields, depending on the temperature, growing season duration and soil quality. The CRI (crown root initiation), booting, flowering and

milking stages are the 4 irrigations that will provide the most wheat yields. Moderate deficit irrigation may sometimes demonstrate a balance between lost yield and enhanced water usage efficiency, making it a feasible alternative in water-scarce places. The extent of yield decline varies according on the severity of the water deficit and the timing of the stress. Deficit irrigation produces lower wheat yields, which means that less water is used than is necessary to produce the grain (9, 10). Conversely, CRI is the most important irrigation step. Higher yields and maximal tillering, booting and grain filling were the outcomes of water application at CRI (11). When watered, wheat crops need 5 to 6 irrigations spaced 20 to 21 days apart. Wheat production depends on the quantity and timing of irrigation under dry, semi-arid and rainfed conditions. Weather influences the amount of water crops need and when to water them. The first strategy involves irrigating the crop at certain phases of growth, while the second involves irrigating the field when soil moisture levels are low, regardless of the crop's stage of development (12). Improve water use efficiency of water resources and the long-term sustainability of agro-ecosystems, it is essential to precisely calculate evapotranspiration (ET). Water may be saved by modelling irrigation schedule and reducing irrigation water use depending on current weather conditions using the ET estimation procedure. Evapotranspiration may be predicted using a variety of methods for determining exact crop water needs (13). The present research was designed to ascertain the phenology and heat unit needs of wheat under different sowing windows. Despite advances in crop-weather modelling, the research gap remains in region-specific strategies that integrate the sowing window optimisation with a dynamic irrigation scheduling using weather and spatial data, particularly in the agro-ecological conditions of the Western Himalayas. While previous studies have focused either on thermal indices or irrigation scheduling individually, limited research has examined their combined impact on wheat phenology, yield and resource use efficiency in this region (14). To address this, the present study was guided by the following the research questions: How do different sowing windows influence the accumulation of agrometeorological indices and phenological development of wheat? What are the effects of various irrigation scheduling strategies-particularly those based on weather models such as the Penman-Monteith method and spatial reference evapotranspiration -on wheat grain yield and water-use efficiency? Furthermore, can an integrated approach combining optimal sowing time and ET-based irrigation scheduling enhance the sustainability and productivity of wheat farming in the Western Himalayas? To answer these questions, the study aimed to evaluate the effect of different sowing windows on thermal indices and phenological development of wheat; assess the impact of irrigation scheduling strategies-including rainfed, fixed-schedule and ET-based treatments on yield and water productivity; and ultimately recommend sustainable, climate-resilient practices for wheat cultivation in the Western Himalayan region through integration of agrometeorological and spatial data.

Materials and Methods

During the rabi seasons of 2021–2022 and 2022–2023, a field experiment was conducted at the Department of Agronomy's research farm at CSK HP Krishi Vishwavidyalaya in Palampur (Himachal Pradesh, India). The experimental farm is situated 1224 m above sea level at 32°4' N, 76°3' E (Fig. 1). Agro-climatically, Palampur is in Himachal Pradesh's sub-temperate humid zone,

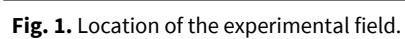
which is distinguished by warm summers and chilly winters. The average weekly weather data for the cropping seasons (October 2021–May 2022) and (October 2022–May 2023) were collected at the Department of Agronomy's meteorological observatory at the College of Agriculture, CSK Himachal Pradesh Krishi Vishwavidyalaya, Palampur. With 15 treatments (3 planting dates in main plot and 5 irrigation schedules based on weather predictions in sub plot), the field experiment was set up in a split plot design and was replicated 3 times. To prevent water from flowing between the plots, 1 m buffer zone was maintained between them. Individual experiment plots were 4.50 m by 3 m and to stop water loss, bunds of 15 cm were constructed. A tractor-drawn disc harrow was used to prepare the experimental field. A thick pre-sowing irrigation (10 cm) was used to guarantee that the soil profile had enough moisture for germination. During the rabi season of 2021–2022 and 2022–2023, the first, second and third sowings were completed on 25th October, 20th November and 10th December, respectively. The HPW 368 wheat variety's seed was seeded by line sowing in furrows, using a seed rate of 100 kg ha⁻¹. The crop was fertilised with 120 kg N, 60 kg P₂O₅ and 40 kg K₂O ha⁻¹. Using urea (46 % N), SSP (16 % P₂O₅) and MOP (60 % K₂O), the main nutrients nitrogen (N), phosphorus (P) and potassium (K) were administered, respectively. The remaining half of the nitrogen was supplied in 2 equal splits, one at maximal tillering and the other just before the halt of spike emergence (Fig. 1). A baseline dosage of half of the N and a full dose of P and K were applied. Weeding, bug control and pest management were examples of intercultural activities carried out as needed.

Weather conditions

To quantify the indices, meteorological data were collected at the Department of Agronomy's meteorological observatory at the College of Agriculture, CSK Himachal Pradesh Krishi Vishwavidyalaya, Palampur. Agrometeorological indicators were calculated using measurements of crop phenology and weather parameters. The weekly maximum and minimum temperatures over the growth season varied from 10.5 to 30.5 °C and 2.3 to 17.9 °C, respectively, as according to a quick look at Fig. 2a. A total of 610 mm of rainfall fell during the agricultural season in rabi 2021–2022. During the crop season, the relative humidity varied from 34.2 to 72.3 %. Throughout the growth season, the average weekly sunlight varied from 3.0 to 10.1 hr. Throughout the crop's growth period, the average weekly wind speed and evaporation varied from 5.9 to 7.9 km hr⁻¹ and 1.7 to 7.3 mm, respectively. In contrast, 774.3 mm of rain fell during the agricultural season in rabi 2022–2023. During the crop season relative humidity fluctuated between 48.4 and 80.6 % every week. During the growth season, the average weekly sunlight varied between 2.2 and 8.9 hr. Throughout the crop's growth phase, the average weekly wind speed and evaporation varied from 5.2 to 8.0 km hr⁻¹ and 1.6 to 5.3 mm, respectively (Fig. 2b).

Agro meteorological indices measurement

The daily mean temperature above base temperature, expressed in °C day, was added together to determine cumulative growth degree days (GDD). The formula provided by Nuttonson (15) was used to compute this. The heat usage efficiency (HUE) was computed by dividing the accumulated dry matter (kg ha⁻¹) by the accumulated heat units (degree-day), which were represented in kg ha⁻¹ degree day⁻¹. Using Chakarvarty and Sastry's technique (16), cumulative helio-thermal units (HTU) were calculated by multiplying the HU by the real bright sunlight hours, which are given in °C day hours.



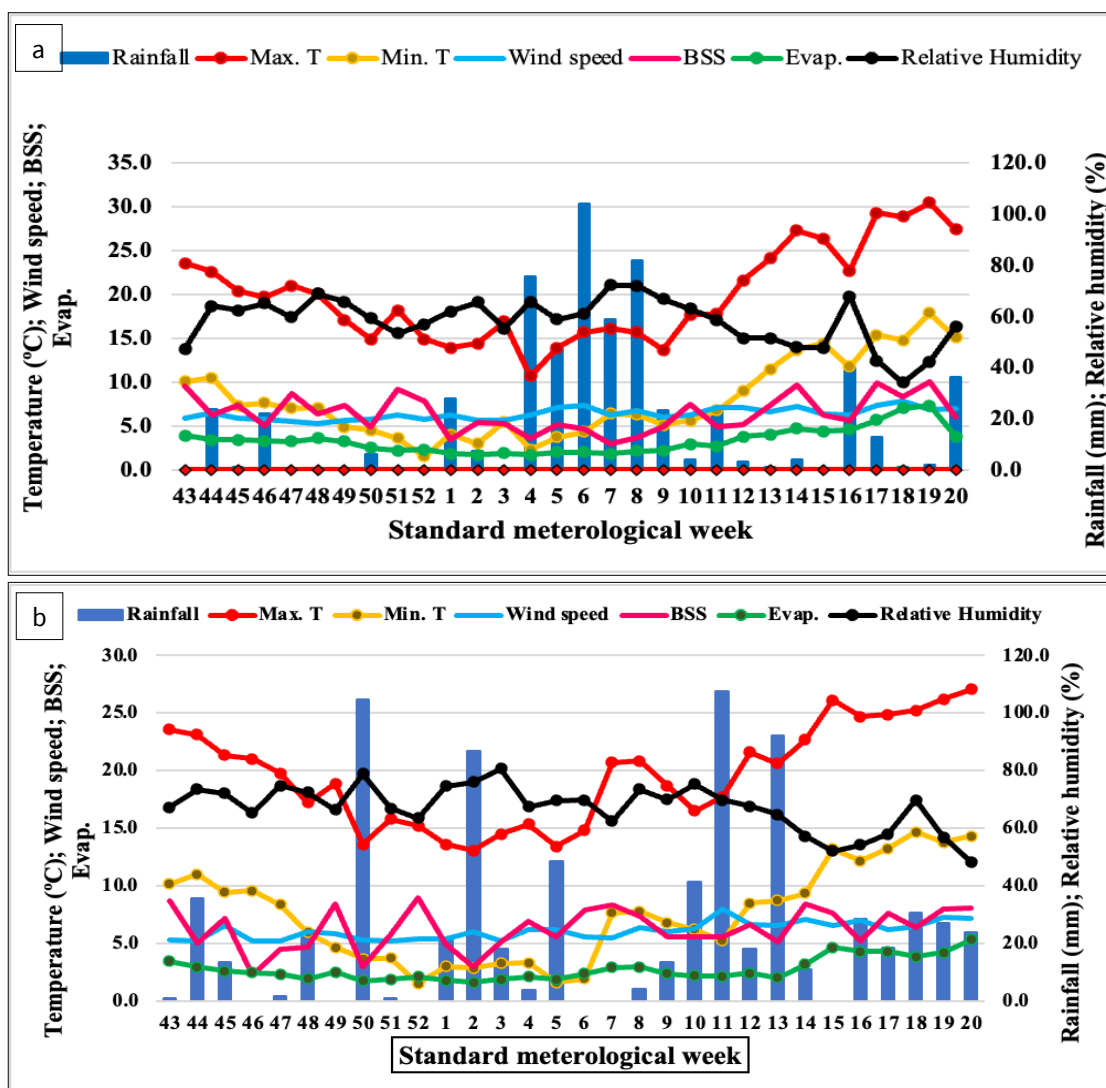


Fig. 2. Mean weekly meteorological parameters during the rabi seasons: (a) 2021-2022; (b) 2022-2023.

$$HTU = GDD \times BSS$$

Where BSS = Bright sunshine hours (1)

The increasing degree days and the duration of the day in hours over a certain time were multiplied to determine photo thermal units (17).

$$PTU = GDD \times D$$

The seed yield was divided by the total number of helio-thermal units to get the helio-thermal usage efficiency, which was then represented as $\text{kg } ^\circ\text{C day}^{-1} \text{ hr}^{-1}(2)$. The Pheno-thermal index (PTI), which is represented in degree-days per growth day using Chakravarty and Sastry's method (16), was computed by dividing the number of days between 2 phenological stages by the degree days consumed between 2 phenological stages.

Penman-Monteith method

By integrating the energy balance with the mass transfer approach. The Penman-Monteith method for the combination equation is (18),

$$ET_0$$

$$= [0.408 \Delta (R_n - G) + \gamma (900 / (T + 273)) u_2 (e_s - e_a)] / [\Delta + \gamma (1 + 0.34 u_2)]$$

Where are the following: e_s saturation vapour pressure (kPa), e_a actual vapour pressure, $e_s - e_a$ saturation vapour pressure deficit (kPa), Δ slope vapour pressure curve ($\text{kPa } ^\circ\text{C}^{-1}$), γ psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), T mean daily air temperature at 2 m height ($^\circ\text{C}$),

R_n net radiation at the crop surface ($\text{MJ m}^{-2} \text{ day}^{-1}$), G soil heat flux density ($\text{MJ m}^{-2} \text{ day}^{-1}$) and T mean daily air temperature at 2 m height ($^\circ\text{C}$) (3). Using the FAO Penman Monteith definition for ET_0 , crop coefficients at study sites may be calculated by comparing the calculated ET_0 with the observed ET_c .

Yield studies

Grain yield

Following the cleaning of the threshed grains, their weight was measured on an electronic scale and translated to kilograms per hectare. A moisture meter was used to measure the grains moisture content and the grain yield was adjusted to 14 % moisture content.

The following formula was used to adjust yield at 14 % moisture content (4). Grain yield was recorded from the net plot area and converted into kilograms per hectare. Where M represents the measured grain moisture percentage. The grain yield was adjusted to 14 % standard moisture content using the following formula:

$$\text{Grain yield} = (\text{Observed grain yield} \times (100 - M)) / (100 - 14)$$

Straw yield

To determine the straw yield, the total biomass of each net plot was subtracted from the grain yield as reported from each net plot. After that, the straw yield per net plot was converted to kilograms per hectare.

Soil properties

Before the experiment began, composite soil samples were collected at a depth of 0–15 cm from each of the 3 replications. The samples underwent several physico-chemical analyses. A study of the data revealed that the soil in the experimental field had an acidic reaction and was silty clay loam in texture. The soil was rated as intermediate in terms of accessible nitrogen, phosphate and potassium as well as organic carbon. The soil's physical and mechanical characteristics are investigated. The mechanical study shows that sand makes up 22.20 % of the soil while silt and clay make up 43.80 and 30.90 % of the soil, respectively. The soil texture is tested using the international pipette technique and is classified as silty clay loam (Piper, 1966) (19).

The pH of the soil was measured using a 1:2.5 soil-water solution and it is 5.6 for the chemical analysis (20). An organic carbon content of 0.68 % was obtained by the wet digesting technique (21). 374.3 kg ha⁻¹ of nitrogen is available when using the alkaline permanganate technique (22). Olsen's approach produced 22 kg ha⁻¹ of available phosphorus (23). While the ammonium acetate extraction technique produced 221 kg ha⁻¹ of available potassium (24).

Statistical Analysis and reference management

The OPSTAT software (<https://opstat.somee.com/opstat/>) was used to conduct the analysis of variance and examine the relevance of dates of sowing and irrigation schedules. The variables studied were phenological parameters (Complete emergence, Maximum tillering, 50 % flowering, Physiological maturity), growing degree days, helio thermal units, photo thermal units, grain yield and straw yield. A critical difference test ($\alpha = 0.05$) was employed to separate the means. Graphs were created using Microsoft Excel (<https://office.microsoft.com/excel>).

Results

Phenological parameters

The effect of different dates of sowing and irrigation schedules based on weather models significantly influenced the phenological development of wheat during the 2021–2022 and 2022–2023 cropping seasons (Fig. 1). Among the sowing dates, the sowing on 25th October (S1) required the longest duration to reach phenological stages such as complete emergence, maximum tillering, 50 % flowering and physiological maturity across both years. Physiological maturity under S1 occurred at 167 days in 2021–2022 and 170 days in 2022–2023, whereas late sowing on 10th December

(S3) significantly shortened the crop duration, with maturity occurring at 142 days in 2021–2022 and 145 days in 2022–2023. Complete emergence was fastest in S3, occurring at 8 days in 2021–2022 and 9 days in 2022–2023, compared to S1 where emergence occurred at 13 days in 2021–2022 and 14 days in 2022–2023.

Crop longevity was significantly influenced by irrigation schedules. The longest crop duration was recorded under meteorological model-based irrigation schedules, namely Penman-Monteith (I4) and spatial ET (I5), where physiological maturity occurred in 165 days during 2021–2022 and 168 days during 2022–2023. In contrast, rainfed conditions (I1) resulted in the shortest crop duration, with physiological maturity occurring in 144 days in 2021–2022 and 146 days in 2022–2023. A similar trend was seen in the time of maximal tillering and blooming, with advanced phases occurring earlier under rainfed and late-sown circumstances. These results demonstrate that weather-model-based early planting and irrigation extended the wheat crop's life, potentially increasing production potential.

Growing degree days

During both cropping seasons (2021–2022 and 2022–2023), the growth degree day (GDD) needs and heat use efficiency (HUE) of wheat were greatly impacted by the date of sowing and irrigation schedule (Table 1). Sowing on 25th October (S1) resulted in a considerably larger GDD accumulation throughout all phenological phases, including maximum tillering, 50 % flowering and physiological maturity. In 2021–2022 and 2022–2023, physiological maturity required 1247.5 and 1193.6 days °C, respectively. This was much better than the sowing on 10th December (S3), which had the lowest GDD requirement (1127.8 and 1028.2 day °C). In a similar vein, heat usage efficiency peaked under S1 (8.8 and 8.9 kg ha⁻¹ day⁻¹ °C⁻¹) and decreased with delayed planting, reaching a notable minimum under S3 (7.6 and 8.2 kg ha⁻¹ day⁻¹ °C⁻¹).

The GDD and HUE were also significantly impacted by irrigation timing based on weather predictions. The 3 irrigation schedule (I3) and Penman-Monteith-based irrigation (I4) produced much higher GDD values for physiological maturity in both years (1213.5 and 1132.7; 1213.5 and 1130.3 day °C, respectively). However, 3 irrigations (I3) produced the greatest HUE (8.8 and 9.0 kg ha⁻¹ day⁻¹ °C⁻¹), while rainfed conditions (I1) produced the lowest HUE (7.3 and 8.6). In 2021–2022, there was a substantial difference in HUE across irrigation schedules; however, in 2022–2023, there was no significant difference. These results highlight the significance of early planting and the best irrigation techniques for optimising wheat crop yield and thermal resource use efficiency.

Table 1. Effect of date of sowing and irrigation scheduling on growing degree day requirements (day °C) and heat use efficiency of wheat

Treatment	Maximum tillering		50 % flowering		Physiological maturity		HUE (kg ha ⁻¹ degree day ⁻¹)	
	2021–2022	2022–2023	2021–2022	2022–2023	2021–2022	2022–2023	2021–2022	2022–2023
Date of sowing								
25 th October (S1)	500.2	499.7	691.5	678.5	1247.5	1193.6	8.8	8.9
20 th November (S2)	318.5	283.2	533.2	507.3	1183.5	1105.9	8.6	9.3
10 th December (S3)	230.2	195.6	432.8	453.4	1127.8	1028.2	7.6	8.2
S.Em±	0.5	1.8	0.4	2.9	11.3	7.7	0.2	0.2
CD ($p = 0.05$)	2.1	7.3	1.5	11.6	44.3	30.4	0.7	0.7
Irrigation schedules based on weather models								
Rainfed (I1)	344.5	321.1	539.2	529.0	1147.3	1077.4	7.3	8.6
2 irrigations (I2)	349.0	325.2	551.8	546.6	1183.2	1107.6	8.7	8.9
3 irrigations (I3)	352.6	329.4	560.6	556.2	1213.5	1132.7	8.8	9.0
Penman monteith (I4)	353.3	329.9	564.2	561.0	1213.5	1130.3	8.6	8.6
Spatial ET (I5)	348.5	324.9	546.5	539.0	1173.7	1098.1	8.4	8.9
S.Em±	1.1	1.1	2.3	3.3	6.8	5.2	0.3	0.2
CD ($p = 0.05$)	3.1	3.2	6.7	9.8	19.8	15.3	0.8	NS

Helio thermal units

During the 2021–2022 and 2022–2023 seasons, the dates of sowing and the timing of irrigation had a substantial impact on the helio thermal unit (HTU) accumulation in the wheat (Table 2). At every phenological stage, the maximum HTU accumulation was obtained from early sowing on 25th October (S1). In 2021–2022 and 2022–2023, S1 reported physiological maturity at 8357.4 and 7351.9 °C day hr, respectively. This was far higher than the HTU observed under 10th December sowing (S3), which was 7732.5 and 6946.2 °C day hr.

In contrast to rainfed conditions (I1), which accumulated the lowest HTU (7639.9 and 6902.1 °C day hr), 3 irrigations (I3) and Penman-Monteith-based scheduling (I4) recorded significantly higher HTU at physiological maturity (8251.8 and 8239.3 in 2021–22; 7355.7 and 7341.6 °C day hr in 2022–2023, respectively). The I3 and I4 performed better than other irrigation treatments at early development stages, following a similar pattern. These findings demonstrate how properly planned irrigation and timely planting both contribute to maximising solar energy usage, which raises thermal efficiency and may increase wheat output (Fig. 3).

Photo thermal units

During the 2021–2022 and 2022–2023 seasons, varying planting dates and irrigation schedules had a substantial impact on the accumulation of photo thermal units (PTU) in wheat (Table 3). Out of all the phenological phases, the 25th of October (S1) produced the greatest PTU accumulation among the sowing dates. PTU values under S1 at physiological maturity were 13622.8 and 12939.6 °C day hr in 2021–2022 and 2022–2023, respectively. These values were much higher than those of the late-planted crop on 10th December (S3), which had the lowest PTUs values (13171.8 and

11909.2 °C day hr). Similar patterns showed that S1 continuously collected much more PTUs at 50 % flowering and maximum tillering, demonstrating the benefit of early planting in terms of effective use of both thermal and photoperiodic resources.

In terms of irrigation scheduling, the Penman-Monteith approach (I4) and the application of 3 irrigations (I3) demonstrated noticeably greater PTU levels at physiological maturity. In the 2 corresponding years, I3 recorded 13752.4 and 12739.5 °C day hr, whereas I4 recorded 13752.0 and 12707.2 °C day hr. On the other hand, rainfed circumstances (I1) showed the lowest PTU accumulation, with daytime temperatures of 12896.6 and 12026.9 °C. These results show that early planting and proper irrigation scheduling-especially when based on scientific models-improve the photothermal environment for wheat, promoting better crop growth and development.

Grain yield (kg ha⁻¹)

In 2021–2022 and 2022–2023, the dates of planting and the timing of irrigation had a substantial impact on wheat grain output (Table 4). In comparison to late planting on 10th December (S3), which recorded the lowest yields of 3006 kg ha⁻¹ and 3148 kg ha⁻¹, respectively, 25th October (S1) reported the greatest grain yield, with 4432 kg ha⁻¹ in 2021–2022 and 4275 kg ha⁻¹ in 2022–2023. Crop growth and production were enhanced by timely seeding, which made better use of thermal and radiation resources. In terms of irrigation schedules, the Penman-Monteith technique (I4) and 3 irrigations (I3) yielded the maximum grain yields. In the same years, I4 produced 4158 and 3905 kg ha⁻¹, whereas I3 reported 4140 and 4109 kg ha⁻¹. The rainfed condition (I1), on the other hand, produced the lowest grain output (3111 and 3441 kg ha⁻¹), suggesting that appropriate irrigation timing is necessary to optimise grain production (Fig. 4).

Table 2. Effect of date of sowing and irrigation scheduling on helio thermal units (°C day hr) of wheat

Treatment	Maximum tillering		50 % flowering		Physiological maturity	
	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23
Date of sowing						
25 th October (S1)	3538.9	2710.5	4647.1	3772.5	8357.4	7351.9
20 th November (S2)	2291.8	1619.2	3228.5	3136.5	7902.2	7189.5
10 th December (S3)	1402.6	1058.5	2343.5	2924.1	7732.5	6946.2
S.Em±	4.6	16.0	4.1	20.6	108.8	65.0
CD ($p = 0.05$)	18.1	62.9	16.1	80.9	427.3	255.4
Irrigation schedules based on weather models						
Rainfed (I1)	2372.4	1767.7	3345.4	3159.4	7639.9	6902.1
2 irrigations (I2)	2408.3	1792.3	3392.7	3282.2	7967.8	7148.6
3 irrigations (I3)	2429.9	1817.4	3446.4	3343.7	8251.8	7355.7
Penman monteith (I4)	2437.6	1814.1	3471.3	3374.6	8239.3	7341.6
Spatial ET (I5)	2407.4	1788.8	3376.0	3228.4	7888.0	7064.7
S.Em±	7.8	6.9	12.1	24.1	64.3	46.7
CD ($p = 0.05$)	22.7	20.1	35.5	70.2	187.6	136.3

Table 3. Effect of date of sowing and irrigation scheduling on photo thermal units (°C day hr) of wheat

Treatment	Maximum tillering		50 % flowering		Physiological maturity	
	2021–2022	2022–2023	2021–2022	2022–2023	2021–2022	2022–2023
Date of sowing						
25 th October (S1)	5175.3	5177.7	7115.4	6992.5	13622.8	12939.6
20 th November (S2)	3216.6	2860.8	5471.6	5227.3	13403.7	12460.8
10 th December (S3)	2323.4	1974.6	4525.1	4792.0	13171.8	11909.2
S.Em±	5.4	19.0	4.3	33.9	83.5	100.2
CD ($p = 0.05$)	21.4	74.6	16.9	133.2	327.8	393.5
Irrigation schedules based on weather models						
Rainfed (I1)	3520.6	3287.2	5558.4	5478.5	12896.6	12026.9
2 irrigations (I2)	3565.4	3328.6	5696.7	5673.5	13358.6	12415.7
3 irrigations (I3)	3602.0	3371.7	5793.1	5778.8	13752.4	12739.5
Penman monteith (I4)	3609.7	3376.2	5833.4	5833.2	13752.0	12707.2
Spatial ET (I5)	3561.2	3324.9	5638.7	5589.0	13237.6	12293.4
S.Em±	10.7	11.2	25.7	37.5	74.0	68.2
CD ($p = 0.05$)	31.4	32.8	75.2	109.6	216.1	199.2

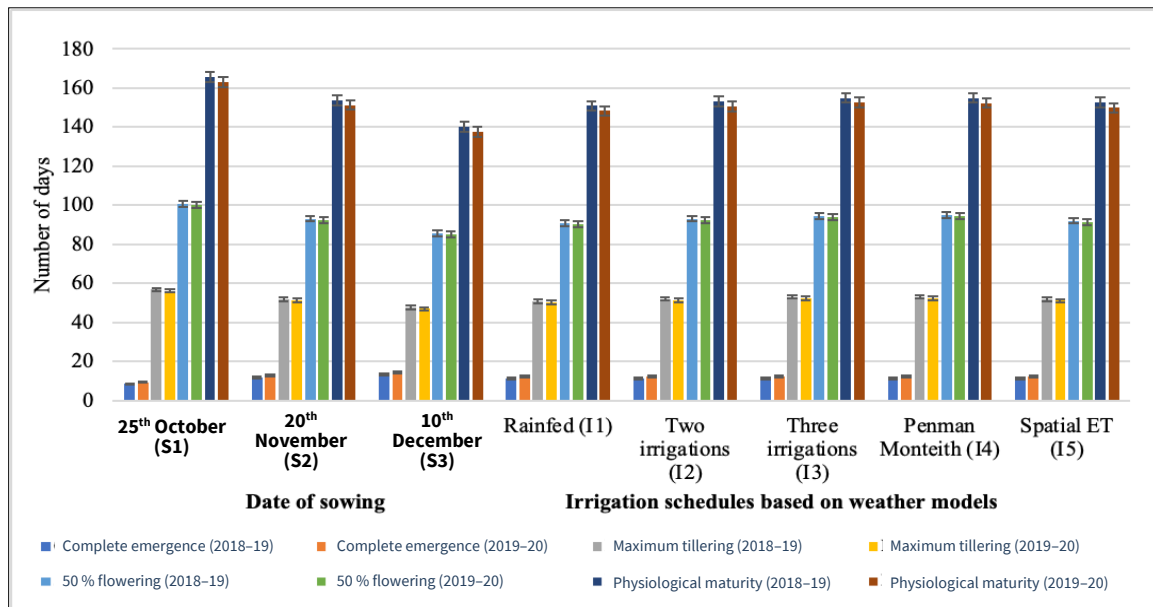


Fig. 3. Effect of date of sowing and irrigation scheduling on phenology (days) of wheat.

Table 4. Effect of date of sowing and irrigation scheduling on grain and straw yield of wheat

Treatment	Grain yield		Straw yield	
	2021-22	2022-23	2021-22	2022-23
Date of sowing				
25 th October (S1)	4432	4275	6565	6342
20 th November (S2)	4048	4079	6224	6250
10 th December (S3)	3006	3148	5648	5312
S.Em±	53	59	85	108
CD ($p = 0.05$)	208	231	336	425
Irrigation schedules based on weather models				
Rainfed (I1)	3111	3441	5365	5864
2 irrigations (I2)	3922	3916	6412	5956
3 irrigations (I3)	4140	4109	6573	6146
Penman monteith (I4)	4158	3905	6293	5888
Spatial ET (I5)	3812	3798	6086	5987
S.Em±	102	65	189	82
CD ($p = 0.05$)	298	188	551	239

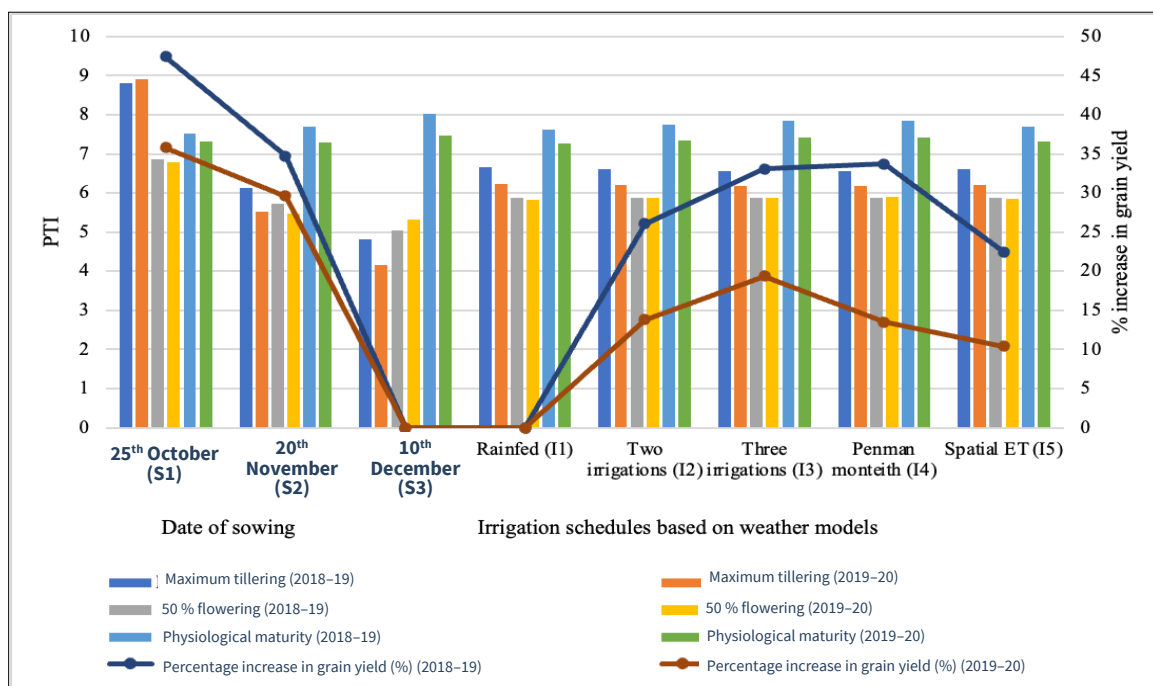


Fig. 4. Effect of date of sowing and irrigation scheduling on pheno-thermal index and percent increase in grain yield of wheat.

Straw yield (kg ha⁻¹)

Both sowing dates and irrigation schedules had a considerable impact on straw yield, which trended similarly to grain yield. Early sowing on 25th October (S1) generated the most straw (6565 kg ha⁻¹ in 2021–2022 and 6342 kg ha⁻¹ in 2022–2023), while sowing on 10th December (S3) yielded the least (5648 and 5312 kg ha⁻¹ in 2022–2023). Better vegetative development was probably encouraged by early seeding, which increased the build-up of biomass (Table 4). The Penman-Monteith technique (I4) produced 6293 and 5888 kg ha⁻¹ of straw, whereas 3 irrigations (I3) produced the highest straw yield among irrigation treatments (6573 and 6146 kg ha⁻¹). The lowest straw yield of 5365 and 5864 kg ha⁻¹ was obtained under rainfed circumstances (I1).

Discussion

Phenological parameters

Lower mean temperatures throughout the sowing window negatively impacted seed germination and early seedling vigour, which is why wheat seeded on 10th December showed delayed emergence. Wheat planted on 25th October, on the other hand, benefited from somewhat warmer early-season temperatures, which accelerated emergence and prolonged the vegetative stage, especially the tillering and jointing phases, before the start of reproductive development. These findings are consistent with past research that found that later planting dates resulted in increasing emergence delays and shorter crop durations. When compared to crops seeded earlier in the month, namely on 1st December, crops sown around 20th December, for example, showed the greatest emergence lag (25, 26). Suboptimal temperature conditions, which restrict enzyme activity and inhibit physiological growth during the germination stage, are the main cause of this delay.

Furthermore, temperature stress and compounding soil moisture deficiencies, which both hasten physiological development, may be the cause of the shorter phenological periods under rainfed circumstances. Early maturity and a shorter grain filling time were probably caused by stress-induced blooming and accelerated senescence brought on by limited water supply throughout the reproductive phases (27). High temperatures during the grain filling period, particularly in March, probably caused forced maturity in late-planted wheat, shortening the crop's life cycle and lowering its potential yield. Previous studies that indicate late-planted wheat is susceptible to early blooming and maturity because of exposure to supra-optimal temperatures during critical developmental transitions (28, 29) support this phenomenon. The synchronisation of development phases with favourable climatic conditions is ensured by early planting and adequate watering, which eventually supports increased production and resource-use efficiency.

Growing degree days and heat use efficiency

The crop planted on 25th October had the largest concentration of GDD, indicating a longer exposure to favourable heat conditions throughout crucial development phases. Enhanced biomass buildup resulted from the optimal vegetative and reproductive growth facilitated by this longer temperature window. Late-sown crops were exposed to relatively higher temperatures during reproductive stages, which shortened phenological phases and reduced the duration for biomass accumulation. The experimental

weather data confirmed considerable temperature variability during the crop growth period, with maximum temperatures ranging from 10.5 to 30.5 °C and minimum temperatures from 2.3 to 17.9 °C, thereby influencing crop development and thermal time accumulation (30, 31). These circumstances frequently coexist with terminal heat stress, which reduces the amount of time that resources may be acquired and grown. Higher GDD values under Penman-Monteith irrigation scheduling suggest that adequate soil moisture availability promoted longer growth times and improved thermal unit consumption (32). Longer leaf activity and improved sink-source balance were made possible by the interaction of temperature and water availability. Limited water supply in rainfed settings caused growth phases to accelerate under stress, which decreased GDD at every stage (33). These findings highlight how the sowing window and water availability combine to affect heat buildup and wheat phenology development (34, 35).

Wheat that is seeded early and ideally has a greater HUE, which indicates that collected thermal energy is effectively converted into biomass and grain production. This is explained by the synchronisation of important phenophases with favourable temperature regimes, especially tillering, booting and grain filling, which encouraged active photosynthesis and efficient use of resources (36). Effective assimilate transfer throughout grain development was also made possible by the early stages' strong vegetative growth. Despite comparable or only marginally lower GDD buildup, lower HUE in delayed sowing is probably caused by the advent of heat stress during reproductive stages, which hinders grain filling and lowers dry matter partitioning (36). By reducing water stress, maximum irrigation regimes (such as 3 irrigations and Penman-Monteith scheduling) improved assimilate translocation, stomatal conductance and canopy temperature control, all of which led to greater HUE among irrigation treatments (37, 38). On the other hand, because of extended water stress and less than ideal thermal use efficiency throughout crucial development stages, poor HUE under rainfed circumstances is associated with reduced biomass buildup and grain output (39, 40).

Helio thermal units and photo thermal units

Increased cumulative solar radiation and thermal energy availability during crucial phenological phases are reflected in higher HTU values in early-sown crops. This effect is particularly noticeable in crops planted on 25th October, when extended exposure to favourable sunlight and temperature promoted increased biomass buildup and photosynthetic activity. On the other hand, shorter day lengths and lower solar incidence were experienced by late sowings, especially those on 10th December, which limited HTU accumulation and accelerated up phenological development (41). The dynamics of HTU were greatly impacted by irrigation treatments. Longer vegetative and reproductive development stages were made possible by the steady soil moisture provided by the Penman-Monteith and 3 irrigation techniques. Higher HTU buildup resulted from the crop's increased ability to use available radiation and heat over a longer period (42, 43). On the other hand, moisture stress brought about by rainfed and limited irrigation treatments accelerated crop maturity and shortened the effective period of radiation and heat absorption, resulting in lower HTU values (44, 45).

Like HTUs, photo thermal units (PTU) showed patterns, with larger values seen in wheat that was seeded early and under conditions of maximal irrigation. Increased PTU accumulation

throughout all growth phases was facilitated by the 25th October planting date, which coincided with ideal sun radiation and temperatures (46). Conversely, delayed sowings saw shorter photoperiods and lower radiation levels, which led to lower PTU values, especially during the grain-filling stage. The Penman-Monteith and 3 irrigation treatments had the greatest PTU values, demonstrating how important sufficient water availability is for coordinating crop development with environmental signals. By optimising the use of thermal and photothermal resources, this alignment enabled crops to sustain active leaf area and photosynthetic capacity for extended periods of time (47, 48). However, rainfed circumstances reduced PTU buildup, limited radiation use efficiency and hastened crop maturity owing to water shortage stress. Yield potential was negatively impacted by the resulting decrease in dry matter partitioning to grain. Sowing date and irrigation method work together to modulate HTU and PTU, which in turn affect wheat phenology, biomass production and grain yield under different agroclimatic conditions.

Grain yield and straw yield

Because of favourable radiation and temperature regimes throughout crop growth, the 25th October planting date consistently yielded the maximum grain yield. Due to lower grain size, fewer grain-filling days and decreased radiation usage efficiency, late seeding (December 10th) dramatically decreased yields by up to 47.4 and 35.8 % over the course of the 2 years (49–51). In the end, delayed planting reduces the number of grains per spike by limiting photosynthetic duration and spikelet fertility (52, 53). Penman-Monteith and 3 irrigation regimens improved water and nutrient absorption, better assimilate partitioning and extended photosynthetic activity, all of which increased grain production (54, 55). In line with research showing that irrigation at key points boosts production and lessens terminal drought stress, rainfed crops displayed lower yields because of moisture stress (56).

The production of straw was significantly impacted by timely seeding. Longer vegetative periods and ideal temperature and radiation regimes helped crops seeded on 25th October accumulate more biomass and produce more straw (56). In comparison to timely planting, delayed sowing until 10th December shortened the crop's vegetative development period, which reduced dry matter production and significantly decreased straw yield (up to 19.39 % in 2022–2023) (57, 58).

Irrigation treatments also had a major impact on straw output. 3 irrigation treatments were linked to the highest straw production, suggesting that increased biomass buildup is encouraged by ideal moisture availability. These results are in line with earlier research that shown that at crucial development phases, 4 irrigations produced more straw than restricted irrigation (59). Due to increasing moisture stress throughout critical phenophases, rainfed conditions consistently produced the lowest straw yields.

The relationship between irrigation technique and planting timing emphasises how crucial integrated crop management is to increase biomass production. While planned irrigation scheduling, like the Penman-Monteith system, guarantees effective water utilisation and constant crop production, early planting helps reduce terminal heat stress. To increase climate resilience and production in wheat-based systems, these findings are consistent with policy suggestions that call for early planting, better irrigation infrastructure and the distribution of real-time weather alerts (60). Similar patterns

have been seen in a variety of agroecological zones, supporting the results resilience under a range of environmental circumstances.

Conclusion

The study unequivocally shows that the phenological development, thermal indices and resource use efficiency of wheat are significantly influenced by both the date of sowing and the application of scientifically informed irrigation regimens. Due to increased real sunshine hours for several plant physiological processes, which improved growing degree days, heliothermal units, heat use efficiency, photo-thermal units and photo-thermal index, wheat grown on 25th October under mid-hill sub-temperate agroclimatic conditions demonstrated a significantly greater grain yield. Farmers may utilise Penman-Monteith modified irrigation and 3 irrigations for irrigation scheduling since it yields more grains than rainfed farming. Like this, weather-model-based irrigation schedules-particularly the Penman-Monteith technique (14) and the 3 irrigation schedule (13)-supported improved thermal environment usage, improving crop production and phenological advancement. These results highlight the agronomic benefit of enhancing wheat performance in a range of climates by combining early planting with model-based irrigation control. Reduced heat build-up, accelerated crop maturity and decreased HUE were linked to late planting and inadequate watering, which ultimately limited yield potential. For greater and more consistent wheat yields, it is therefore essential to optimise the planting window and irrigation techniques.

Overall, early sowing combined with weather-based irrigation models, particularly the Penman-Monteith and spatial ET methods, improved wheat phenology, thermal efficiency and yield performance. By conserving water and adjusting to climate change, these methods promote sustainable wheat production.

Acknowledgements

The authors gratefully acknowledge the facilities provided by CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur.

Authors' contributions

BP, RSR, SM, NK and NR contributed to conceptualisation, methodology, investigation, data curation, formal analysis and original draft writing. NP contributed to supervision, visualisation and review and editing of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language editing, grammatical corrections and formatting of references. After using this tool, the authors carefully reviewed and edited the content to ensure accuracy and scientific integrity. The authors take full responsibility for the content of this publication.

References

- Mir SA, Farooq M, Naseem Z, Mugabi R. Techno-functional, nutritional, antioxidant and prebiotic potential of underutilized buckwheat flour from Western Himalayas of Jammu and Kashmir. *Applied Food Research*. 2025;100723. <https://doi.org/10.1016/j.afres.2025.100723>
- Suri D, Sharma RP, Sankhyan NK, Manuja S, Singh J, Sharma T. Five decadal nutrient management effects on productivity, sustainability and soil properties in a maize-wheat system on Alfisols of north-western Himalayas. *New Zealand Journal of Crop and Horticultural Science*. 2025. <https://doi.org/10.1080/01140671.2025.2467101>
- Bhartiya A, Dev R, Kant L. Genetic enhancement in local food systems in north-western Himalayan hills. *Indian Journal of Plant Genetic Resources*. 2025;38(1):11–23.
- Kumar A, Kumar S. Impact of climate change on Himalayan ecosystem and traditional crops. In: *Climate Change Impact on Himalayan Biodiversity*. Cham: Springer Nature Switzerland; 2025. https://doi.org/10.1007/978-3-031-77149-1_18
- Kaira P, Tamta N, Pant NC, Joshi J, Deepak. Impact of climate change adaptation on millet crops as climate resilient and sustainable crops of Uttarakhand Himalaya. In: *Climate Change Impact on Himalayan Biodiversity*. Cham: Springer Nature Switzerland; 2025. https://doi.org/10.1007/978-3-031-77149-1_15
- Giri G, Upreti H, Singhal GD. Soil moisture extraction patterns for wheat crop under different drip and flood irrigated treatments. *ISH Journal of Hydraulic Engineering*. 2025. <https://doi.org/10.1080/09715010.2025.2471338>
- Pareek B, Rana RS, Rana N, Manuja S, Kumar N, Pareek N. Wheat productivity and profitability under different sowing window and irrigation scheduling based on weather model and spatial data in north-western Himalayas. *Journal of Soil and Water Conservation*. 2023;22(2):186–92. <https://doi.org/10.5958/2455-7145.2023.00025.5>
- Naderi N, Mohammadi A. Investigating the effect of water use management on wheat yield and water productivity using the rain-flat sprinkler irrigation method. *Irrigation and Drainage Structures Engineering Research*. 2025.
- Tafteh A, Emdad MR, Sedaghat A. Improving irrigation management in wheat farms through the combined use of the AquaCrop and WinSRFR models. *Journal of Arid Land*. 2025;17(2):245–58. <https://doi.org/10.1007/s40333-025-0005-y>
- Ajaz A, Taghvaeian S, Lollato R, Alderman PD, Gowda PH. Gridded drought response assessment of winter wheat in Oklahoma using big data and AquaCrop-OS. *Science of the Total Environment*. 2025;959:178206. <https://doi.org/10.1016/j.scitotenv.2024.178206>
- Chakraborty C, Hazra S. Rainfall variability and irrigation scheduling for paddy cultivation in the Kankai irrigation system, Eastern Nepal. In: *Geographies of the Indian Subcontinent: Cutting-Edge Methods in 21st Century Research*. Cham: Springer Nature Switzerland; 2025. https://doi.org/10.1007/978-3-031-74813-4_13
- Yu J, Rezaei EE, Reckling M, Nendel C. Winter wheat–soybean relay intercropping with a shift in sowing dates as a climate change adaptation strategy for crop production in Germany. *Field Crops Research*. 2025;322:109695. <https://doi.org/10.1016/j.fcr.2024.109695>
- Garofalo P, Cammerino ARB. Modeling the performance of a continuous durum wheat cropping system in a Mediterranean environment: carbon and water footprint at different sowing dates under rainfed and irrigated regimes. *Agriculture*. 2025;15(3):259. <https://doi.org/10.3390/agriculture15030259>
- Chen G, Yu W, Zheng Y, Zhang L, Si J, Zhao K, et al. Optimizing sowing time and density can synergistically improve productivity and quality of strong-gluten wheat in different ecological regions of Shandong Province. *Plants*. 2025;14(3):372. <https://doi.org/10.3390/plants14030372>
- Nuttonson MY. Wheat-climate relationships and the use of phenology in ascertaining the thermal and photo-thermal requirements of wheat. Washington DC; 1955.
- Chakravarty NVK, Sastry PSN. Some aspects of crop weather interaction in wheat cultivars. *International Journal of Ecology and Environmental Sciences*. 1985;11.
- Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed. New York: Wiley-Interscience; 1984.
- Howell TA, Evett SR. The Penman-Monteith method. Washington DC: USDA Agricultural Research Service; 2004.
- Piper CS. Soil and plant analysis. Adelaide: University of Adelaide; 1944.
- Jackson ML. Soil chemical analysis. Englewood Cliffs: Prentice Hall; 1967.
- Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science*. 1934;37(1):29–38. <https://doi.org/10.1097/00010694-193401000-00003>
- Subbiah BV, Asija GL. A rapid procedure for determination of available nitrogen in soils. *Current Science*. 1956;25:259–60.
- Olsen SR, Cole CV, Watanabe FS, Dean LA. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Washington DC: USDA Circular 939; 1954.
- AOAC. Official methods of analysis. Washington DC: Association of Official Analytical Chemists; 1970.
- Debnath M, Sarma AK. Assessment of climate change impact on irrigation water demand for food security in rice-fallow cropland areas using an integrated modeling technique. *Theoretical and Applied Climatology*. 2025;156(2):1–19. <https://doi.org/10.1007/s00704-024-05246-5>
- Haile MM, Gelalcha AT. Assessment of land suitability and crop water requirements for irrigated sugarcane in the Kuraz irrigation scheme, Lower Omo Basin, Ethiopia. *Geology, Ecology and Landscapes*. 2025;1–19. <https://doi.org/10.1080/24749508.2025.2451448>
- Singh G, Singh A, Bindra AD, Saini A, Manuja S, Fayeizadeh MR. Assessment of sowing environment for wheat cultivars and evaluation of growing degree days for phenological stages in the north-west Himalayan region of Himachal Pradesh. *Discover Applied Sciences*. 2024;6(11):1–16. <https://doi.org/10.1007/s42452-024-06290-6>
- Zheng J, Zhang S. Decomposing the total uncertainty in wheat modeling: An analysis of model structure, parameters, weather data inputs and squared bias contributions. *Agricultural Systems*. 2025;224:104215. <https://doi.org/10.1016/j.agsy.2024.104215>
- Liu L, Chen X. Estimation of the impact of climate warming on spring wheat phenology from observations and modelling in the arid region of northwest China. *Journal of Agronomy and Crop Science*. 2025;211(1):e70011. <https://doi.org/10.1111/jac.70011>
- Liu Z, Cammarano D, Liu X, Tian Y, Zhu Y, Cao W, et al. Winter wheat yield responses to growing degree days: Long-term trends and adaptability in major producing areas of China. *Ecological Indicators*. 2025;170:113058. <https://doi.org/10.1016/j.ecolind.2024.113058>
- Nadi M, Shamgani Mashhadi B. Investigating the impact of climate change on the phenological stages of autumn wheat in Mazandaran province, Iran. *Iran Agricultural Research*. 2025;1–23.
- Yu F, Noor H, Seleiman MF, Noor F. Effects of different winter wheat varieties addressing agriculture-climate interactions in temperature regions of yield. *Atmosphere*. 2025;16(2):189. <https://doi.org/10.3390/atmos16020189>
- Wojtacki M, Żuk-Gołaszewska K, Gołaszewski J. Modeling the effects of agronomic factors and climatic parameters on grain yield of oats. *European Journal of Agronomy*. 2025;162:127425. <https://doi.org/10.1016/j.eja.2024.127425>

34. Lal D, Kumar R, Ahmed I, Mishra M, Shekhar M, Patil C, et al. Intraseasonal variability of monsoon extremes and its impact on kharif crops in the western plains of India. *Theoretical and Applied Climatology*. 2025;156(3):1–22. <https://doi.org/10.1007/s00704-025-05396-0>
35. Ji W, Osman R, Ma J, Jiang X, Wang L, Xiao L, et al. Improving process-based modelling to simulate the effects of low-temperature stress during pre-anthesis on wheat grain quality. *Plant Cell and Environment*. 2025;48(2):1574–93. <https://doi.org/10.1111/pce.15217>
36. Mutanda M, Shimelis H, Chaplot V, Madala NE, Figlan S. Association between agronomic traits and metabolite profiles on yield response and water use efficiency in newly developed wheat populations under drought stress conditions. *Acta Agriculturae Scandinavica Section B Soil and Plant Science*. 2025;75(1):2454389. <https://doi.org/10.1080/09064710.2025.2454389>
37. Guo G, Tang Y, Yan Z, Zhang J, Zhang Y, Ren X. Liquid mulch improves yield and water use efficiency of summer maize planted in rainwater harvesting systems. *Journal of Agronomy and Crop Science*. 2025;211(1):e70003. <https://doi.org/10.1111/jac.70003>
38. Wang K, Liu H, Zhou X, Tang X. Comprehensive mega-data analysis of water use efficiency in winter wheat and its influencing factors. *Water*. 2025;17(4):564. <https://doi.org/10.3390/w17040564>
39. Wang N, Chu X, Li J, Luo X, Ding D, Siddique KHM, et al. Understanding increased grain yield and water use efficiency by plastic mulch for dryland maize in China's Loess Plateau. *European Journal of Agronomy*. 2025;162:127402. <https://doi.org/10.1016/j.eja.2024.127402>
40. Engonopoulos V, Papastylianou P, Kakabouki I, Bilalis D. Agro-meteorological indices in relation to cotton yield in a Mediterranean environment. *Notulae Scientia Biologicae*. 2025;17(1):12330. <https://doi.org/10.55779/nsb17112330>
41. Mohapatra AKB, Parhi C, Priyadarshi D, Nanda A, Yetgin A, Srivastava RK. Effect of varying agronomic management on agro-meteorological indices of rice in eastern India. In: *Mitigation and Adaptation Strategies Against Climate Change in Natural Systems*. Cham: Springer Nature Switzerland; 2025:51–69. https://doi.org/10.1007/978-3-031-75968-0_3
42. Nalli D, Nath S, Biswas T. Effect of sowing dates and nitrogen management on thermal time requirement and heat use efficiency of rabi maize in Odisha. *Journal of Agrometeorology*. 2025;27(1):43–48. <https://doi.org/10.54386/jam.v27i1.2707>
43. Liu L, Liu Y, Zhou X, Tietz F, Grüner D, Yang T, et al. Nominal lanthanum niobate as a versatile additive for reducing grain boundary resistance in conductive ceramics. *Advanced Energy Materials*. 2025. <https://doi.org/10.1002/aenm.202404985>
44. Dierner M, Landes M, Will J, Ziegler A, Hübner S, Przybilla T, et al. Influence of substrate polarity on thermal stability and grain growth of Au thin films on ZnO surfaces. *Acta Materialia*. 2025;284:120531. <https://doi.org/10.1016/j.actamat.2024.120531>
45. Vercellino RB, Fanna I, Mortarini M, Pérez Polo A, Ureta S, Fernández P, et al. Radiation and photothermal coefficient as determinants of grain yield and oil content in sunflower under different sowing dates. *International Journal of Plant Production*. 2025;19(1):83–97. <https://doi.org/10.1007/s42106-024-00321-3>
46. Biswas S, Das R, Nwe LL, Dutta D. Influence of integrated nutrient management on agro-meteorological indices in soybean cultivation. *Discover Plants*. 2025;2(1):1–24. <https://doi.org/10.1007/s44372-025-00105-7>
47. Chauhdary JN, Li H, Pan X, Zaman M, Anjum SA, Yang F, et al. Modeling effects of climate change on crop phenology and yield of wheat-maize cropping system. *Journal of the Science of Food and Agriculture*. 2025. <https://doi.org/10.1002/jsfa.14134>
48. Singh T, Singh C, Kumar R, Nandeesh CV. Assessing the efficacy of foliar sprays in alleviating terminal heat stress in late-sown wheat. *Functional Plant Biology*. 2025;52(1). <https://doi.org/10.1071/FP24184>
49. Liu Q, Li Y, Cao J, Yue J, Hu X, Wang Y, et al. Photothermal catalytic oxidation performance of cerium-based perovskite catalyst CeBO3 under full spectrum radiation. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2025;705:135693. <https://doi.org/10.1016/j.colsurfa.2024.135693>
50. Bora S, Kingra P, Pal RK, Mangshatabam A. Simulation of biophysical parameters and yield of wheat under projected climate during mid-century. *Journal of Agrometeorology*. 2025;27(1):96–99. <https://doi.org/10.54386/jam.v27i1.2850>
51. Zakir I, Ahmad S, Saleem MS, Hussain S, Nawaz H, Ahmed T, et al. Insights on sowing time and cultivar selection of sweet corn for optimal yield under agro-climatic conditions of Multan. *International Journal of Plant Production*. 2025. <https://doi.org/10.1007/s42106-025-00329-3>
52. Wang X, Li Z, Chen Y, Zhu J, Wang C, Wang J, et al. Impact of extreme weather events on crop yields in the Tarim River Basin, China. *Journal of Arid Land*. 2025;17(2):200–23. <https://doi.org/10.1007/s40333-025-0094-7>
53. Raza MAS, Muhammad F, Farooq M, Aslam MU, Akhter N, Toleikienė M, et al. ZnO nanoparticles and stage-based drought tolerance in wheat: Effects on morpho-physiology and yield. *Scientific Reports*. 2025;15(1):5309. <https://doi.org/10.1038/s41598-025-89718-2>
54. Christian MM, Shimelis H, Laing MD, Tsilo TJ. Association of yield and yield components among bread wheat genotypes under silicon fertilization and drought conditions. *Journal of Agronomy and Crop Science*. 2025. <https://doi.org/10.1111/jac.70020>
55. Tripathi SC, Kumar N, Venkatesh K. Nano-urea environmental and economic efficacy in boosting wheat yield across Indian agro-climates. *Scientific Reports*. 2025;15:3598. <https://doi.org/10.1038/s41598-024-83616-9>
56. Sultonov K, Kholmurodova G, Eshonkulov J, Allanov K, Sindarov O, Khayitov K, et al. Effect of integrative NPK soil and foliar nutrition on winter wheat productivity in irrigated arid lands. *Frontiers in Sustainable Food Systems*. 2025;8:1508913. <https://doi.org/10.3389/fsufs.2024.1508913>
57. Nouman M, Hayat MK, Aslam Z, Anjum S, Usman M, Saeed MS. Interactive effects of gibberellic acid and water regimes on wheat grain yield. *World News of Natural Sciences*. 2025;59:267–93.
58. Sellami W, Daoui K, Ibriz M, Bendidi A. Effect of no-till and phosphorus fertilizer on wheat yield under rainfed conditions in Morocco. *Journal of Soil Science and Plant Nutrition*. 2025. <https://doi.org/10.1007/s42729-024-02206-w>
59. Zhang Z, Yan J, Gao X, Zheng Z, Xu L, Zhu Z, et al. Effects of wheat straw mulching and wet treatment on soil improvement and vegetable yield. *Horticultural Plant Journal*. 2025.
60. Hou P, Gao L, Jiang P, Yu J, Liu X, Jiang D, et al. Straw return amplifies the stimulated impact of night warming on N₂O emissions from wheat fields in a rice-wheat rotation system. *Field Crops Research*. 2025;320:109652. <https://doi.org/10.1016/j.fcr.2024.109652>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc

See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.