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Growing environments and cultivar selection limits wheat growth and yield potential in Punjab

Jatinderpal Singh[1], Barun Biswas[2*] & Lakhvir Kaur Dhaliwal[1]

[1]Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University, Ludhiana 141 004, Punjab, India
[2]Punjab Agricultural University, Regional Research Station, Gurdaspur 143 521, Punjab, India

*Email: bbiswasgsp@pau.edu

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Abstract

Selecting a suitable sowing time and cultivar can play a pivotal role in sustaining wheat productivity in north India while mitigating the influence of climate extremes. Field experiments were conducted in two distinct climatic regions (Ludhiana and Gurdaspur), of Punjab, India to assess the influence of different sowing environments and cultivars on wheat growth and yield. The crop was sown on three dates (early-5 November, mid-20 November and late-5 December) with two popularly grown wheat cultivars (PBW725 and PBW677). The results indicated that mid and late sowing significantly shortened phenological phases compared to early sowing at both study sites. Wheat sown on 5 November accumulated more thermal time, exhibited a greater leaf area index (LAI), intercepted more photosynthetically active radiation (IPAR), and demonstrated superior radiation use efficiency (RUE). Early-sown wheat also produced higher biological yield (BY), grain yield (GY), irrigation water use efficiency and heat use efficiency compared to delayed sowing at both sites. The wheat cultivar PBW725 outperformed PBW677 in terms of phenological duration, yield, thermal time accumulation, IPAR, LAI and RUE at both sites. IPAR and RUE exhibited a strong positive correlation and regression with the periodic dry matter accumulation of wheat. Linear regression revealed that LAI_{max} (maximum LAI) and ΣLAI (accumulated LAI) were the best determinants of BY of wheat. These findings highlight the significance of optimizing growing environments and cultivar selection in mitigating climate extremes and sustaining wheat production in the diverse agro-climatic conditions of Punjab.

Keywords

PAR interception; phenology; radiation use efficiency; sowing time; wheat; yield attributes

Introduction

Wheat (*Triticum aestivum* L.) is a globally cultivated cereal crop, and a staple food. In Punjab, India, wheat is the second most important cereal crop after rice, covering an area of 3.52 million hectares, producing 18.2 thousand million tonnes, and an average yield of 5188 kg ha^{-1} (1). Punjab covers 12% of the wheat growing area and contributes about 17.6% of the wheat grain production of India (1). Wheat yield in Punjab has increased significantly over the past few decades, primarily due to the adoption of improved technologies that have increased significantly the potential yield. However, sustaining or increasing potential wheat yield under changing climatic conditions in the region remains a major challenge for scientists.

Climate change-induced terminal heat stress significantly influences wheat growth and yield due to high temperatures during critical growth phases like flowering and grain filling. Conversely, low temperatures during early vegetative stages adversely affect germination and tillering, resulting in poor plant establishment and reduced yield potential. Appropriate management practices, particularly optimizing sowing time and selecting suitable cultivar, are pivotal for mitigating undesirable climatic conditions' impact on sensitive crop stages (2). These are key factors to avoid unfavorable environmental conditions at sensitive phenophases (3). Crops sown under optimal conditions avoid heat stress during reproductive phase, and the timely sown crop has a longer crop duration, facilitating the plant to accumulate higher biomass, and grain yields (4). The late sowing of wheat is often exposed to a suboptimal temperature at the early vegetative phase, adversely affecting germination and tillering capacity and leading to a poor plant population (5). Subsequently, the reproductive phases, such as flowering and grain-filling, of late-sown wheat are exposed to supra-optimal temperatures, which may shorten the crop cycle, hence decreasing grain yield (6–8). Furthermore, the selection of appropriate cultivars is crucial for resilience against environmental challenges. Many studies have highlighted the importance of selecting cultivars with traits capable of withstanding adverse conditions and also stressed the importance of aligning cultivar traits with local environmental conditions, which can lead to better crop performance and reduced susceptibility to extreme weather conditions. (9–10).

Changes in the growing environment directly affect many plant canopy traits and can significantly alter crop growth and yield responses. Leaf area index (LAI), a measure of leaf area per unit ground area that reflects plant's ability to capture sunlight, significantly influences crop growth by altering source to sink ratio. A reduced LAI due to adverse weather conditions would eventually decrease absorbed or intercepted photosynthetically active radiation (IPAR), the fraction of sunlight intercepted by the crop, influencing photosynthesis and growth. Subsequently, the ability of a plant to convert intercepted sunlight into biomass, i.e., radiation use efficiency (RUE), would decrease, resulting in reduced crop yield. Therefore, these plant traits are critical for enduring adverse climatic conditions. Sowing time and cultivar selection greatly affect these parameters by altering thermal environments computed by growing degree days (GDD), photothermal units (PTU), and helio-thermal units (HTU).

Earlier studies conducted in the wheat-growing areas of northwest India reported that sowing time significantly affects wheat yield and the thermal environment (11–12). Crop canopy parameters extensively used for crop growth monitoring are highly sensitive to these factors and thus serve as an important indicator for potential grain yield (13). Adjusting the sowing date can also change daily IPAR by altering the radiation regime to which the crop is exposed (14). In central Punjab, wheat sowing windows critically influence wheat LAI, IPAR and RUE (15). These studies did not illuminate the complex relationship of sowing time and cultivar selection with the above plant traits. Conversely, coupled water and terminal heat stresses alter wheat seasonal IPAR forcing screening genotypes for characteristics that increase the ratio of radiation productivity to water productivity can boost wheat productivity (16). However, in Punjab, the delayed harvesting of monsoon season paddy crop often compels farmers to defer wheat sowing in the winter season from the recommended sowing window of early November.

Despite advancements, comprehensive studies examining the combined effects of sowing time and cultivar choice on wheat growth and yield in Punjab remain lacking. Addressing this gap is essential for developing strategies to sustain and enhance wheat production under changing climatic conditions. It was hypothesized that optimal sowing times would improve wheat yield by avoiding heat stress during critical growth phases through LAI, thermal environment, IPAR and RUE variations. Additionally, selecting cultivars with traits adapted to local conditions could enhance climate resilience and yield. This study aimed to (i) demonstrate the influence of different sowing environments and cultivar selection on wheat yield, as well as water and heat use efficiency, (ii) explore the impact of growing environments on wheat phenology, thermal environment, growth and development traits and radiation usage efficiency in Punjab, India.

Materials and Methods

Study area, weather and soil:

The field experiments were conducted at two agro-climatically distinct sites in Punjab, India. One set of experiments was conducted at the Punjab Agricultural University Regional Research Station, Gurdaspur (32°03' N, 75°25' E; msl 261 m) located in the sub-mountainous undulating zone (17). Another set of experiments was performed at Punjab Agricultural University (PAU), Ludhiana (30°54' N, 75°56' E; msl 247 m) under central plain zone of Punjab. The normal mean maximum and minimum temperature during the wheat season (November to April) in Gurdaspur remains 21.3 °C and 7.4 °C, respectively and in Ludhiana stands 26.2°C and 8.3°C, respectively. However, 34% and 32% of annual normal precipitation of Gurdaspur (980 mm) and Ludhiana (740 mm), respectively, occur during the crop season. The north-western part of India gets substantial precipitation during the winter wheat season due to sub-tropical climatic phenomenon called western disturbances (WD).

Daily records on meteorological parameters were collected from the surface agrometeorological observatory installed near the respective experimental sites to compute thermal indices, intercepted photosynthetically active radiation (IPAR) and radiation use efficiency (RUE). Solar radiation data were computed daily by Ångström–Prescott equation (18, 19) from actual bright sunshine (BSS) duration recorded with Campbell-Strokes sunshine recorder. The average monthly weather conditions the study sites are depicted in Fig. 1. The soils

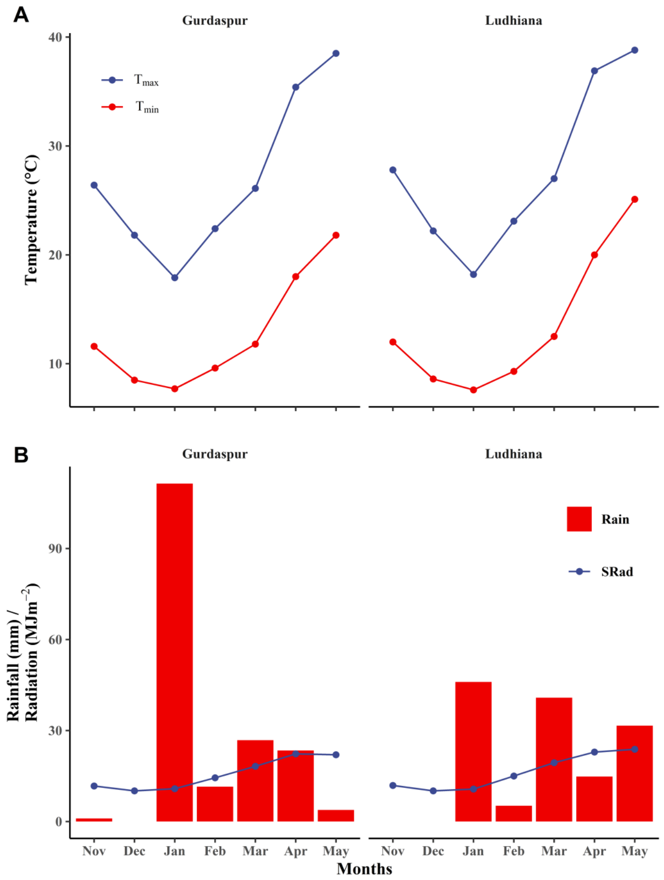

Fig. 1. Mean monthly weather summary (A: Maximum Temperature-T_{max}, Minimum Temperature-T_{min}; B: Rainfall-Rain, Solar Radiation- SRad) during wheat growing period in Ludhiana and Gurdaspur.

at Ludhiana and Gurdaspur study sites are classified as *Ustochrepts* and *Udic Haplustalf* as per (United State Department of Agriculture (USDA) classification criteria, respectively. The soil texture was determined as sandy loam and silt loam for Ludhiana and Gurdaspur, respectively. The soils at the Ludhiana and Gurdaspur experimental site contained low organic matter (0.38 and 0.51%), and available nitrogen (225 and 229 kg ha^{-1}), respectively.

Experimental details:

The field experiment was conducted with two factors at each site i.e., sowing environments (DOS): three [Early-season – 5 November (SD_1), Mid-season – 20 November (SD_2) and Late-season – 5 December (SD_3)] and wheat cultivars (WC): two (PBW 725 – WC_1 and PBW 677 – WC_2) during *rabi* (winter) seasons for two years. The factorial arrangement of the above treatment combinations was laid out in a randomized complete block design (RCBD) with four replications in 24 plots (plot size = 5 m × 5 m). The crop was raised following identical crop husbandry at Gurdaspur and Ludhiana following recommendations in the package of practices (20). Line sowing of wheat at 22 cm apart was done using a manual drill with a seed rate of 100 kg ha^{-1}. The crop was fertilized with 60 kg N, 25 kg P, and 25 kg K per hectare at sowing, and the remaining 60 kg N was fertilized after the first irrigation. Four to six recommended irrigations were applied, using 70 mm of water each, depending on the sowing time. No significant incidences of diseases or insect attacks were observed in any plot. At maturity, a net area of 16 m^2 (4 m × 4 m) was manually harvested from each plot after excluding 0.5 m border on each side to record yield and related attributes data as described under 'Agronomic traits.'

Field measurements and data collection:

Agronomic traits

The phenological stages were determined from emergence to physiological maturity to Zadok's scale (21) and five key stages [tillering (GS2), flag leaf (GS4), anthesis (GS6), milking (GS7)] and physiological maturity (GS9) were selected for recording periodic plant growth data. The plants in each plot were regularly observed for phenological changes, and when 50% of the plants in each plot reached a particular developmental stage, data was recorded for that growth stage. Grain yield and biological yield (total above ground biomass) of each plot were determined after threshing net plot area. Simultaneously, plants within one-meter row length were harvested separately from each plot and threshed manually to measure related yield attributes, such as the number of grains per spike (GN) and 1000-grain weight (TW). The harvest index (HI) of wheat was calculated as the ratio of grain yield to biological yield. Irrigation water use efficiency (IWUE) was calculated as the ratio of biological yield or grain yield to the total applied irrigation water and seasonal rainfall (22).

Thermal index

Daily growing degree days (GDD) were computed using the following equation (23):

$$GDD = \frac{(T_{max}+T_{min})}{2} - T_{base} \qquad [1]$$

Where, T_{max} and T_{min} are daily maximum and minimum temperature (°C), T_{base} is the minimum threshold/base 5°C temperature for wheat (24).

The GDD on a daily scale, starting from sowing to maturity of the crop, was multiplied by the corresponding daylength (N) and actual sunshine hours (n) to compute photothermal Units (PTU) and helio-thermal nits (HTU), respectively (24, 25). Heat use efficiency (HUE) represents the heat units utilized by crop plants to produce a unit of dry matter or grain yield. It was computed by dividing total biomass recorded at physiological maturity by cumulative heat units or GDD of the corresponding period.

Leaf area index:

Leaf area index (LAI) was recorded at five developmental stages (tillering, booting, anthesis, milk development and physiological maturity) during the entire crop season within the four replications of each treatment by SS1-SunScan canopy analyzer (Delta-T Company, Britain) (13). The SunScan probe was placed horizontally across the rows near the soil surface, and three consecutive readings of LAI were recorded to calculate a mean value.

Periodic dry matter:

Five plants from each plot were harvested randomly to obtain dry matter accumulation. The plant samples were manually collected by cutting at ground level at five phenological stages, from tillering to physiological maturity (2). The samples at each stage were oven-dried at 70°C for 72 hours to a constant weight, then weighed using a digital analytical balance to determine the dry weight. The dry weight of 5 plants were converted into dry matter per square meter by multiplying by the plant population factor.

Computation of canopy light extinction coefficient (k), intercepted photosynthetically active radiation (IPAR) and radiation use efficiency (RUE):

The RUE of the wheat crop under different treatments was calculated as the ratio of above-ground dry matter produced at different phenophases and the total accumulated intercepted PAR (ΣIPAR) during that particular phase by the crop.

$$RUE = \frac{DM(g\ m^{-2})}{\sum IPAR\ (MJ\ m^{-2})} \quad [2]$$

Where, DM was dry matter accumulated during a particular growing phase, and ΣIPAR was estimated by aggregating calculated daily IPAR using Beer-Lambert's law (26).

$$IPAR = PAR_{int}(1 - e^{-k \times LAI}) \quad [3]$$

Where, PAR_{int} is the daily incident photosynthetically active radiation (MJ m^{-2}) which was estimated from global insolation (derived from BSS) using following relation (27):

PAR_{int} = 0.5 x global solar radiation (MJ m^{-2}) [4]

Additionally *k* represents canopy light extinction coefficient. In the present study, *k* was estimated by the

$$k = -\ln\left(\frac{PAR_{bot}}{PAR_{top}}\right)/LAI \quad [5]$$

Where, PAR_{bot} is the transmitted fraction of PAR (measured below the canopy), and PAR_{top} is the incident PAR (measured at the top of the canopy). LAI is the leaf area index. LAI values measured at different phenophases were extrapolated to compute daily IPAR values using the regression techniques (29, 30).

Statistical Analysis

The normality of response variables (BY, GY, TW, GN, HI, IWUE, HUE, phenology days, thermal indices, LAI, dry matter, IPAR and RUE) was evaluated with the Shapiro-Wilk normality test to carry out further parametric statistical tests to compare treatment effects i.e., location (LOC), date of sowing (DOS) and wheat cultivar (WC) used in the present study. A pooled ANOVA was performed for the response variables, with replications nested within locations as random effects, DOS, WC, and their interactions as fixed effects. In the case of significant LOC×DOS interactions, separate two-way ANOVA were performed for each study location to analyze the mean difference in response variables influenced by DOS and WC and their interactions. Statistical analysis and the subsequent preparation of figures were performed using R programming with functions available in various packages (31). The packages were available through CRAN (https://cran.r-project.org). The statistical significance was reported at $p \leq 0.5$ to compare means using the 'Least Significance Difference (LSD)' test.

Results

Yield and yield attributing traits:

The pooled ANOVA of field experiments conducted at two locations (Table 1) revealed that location (LOC), sowing time (DOS) and wheat cultivars (WC) had a highly significant effect on biological yield (BY), grain yield (GY) and related traits, such as 1000-grain weight, grain number spike^{-1}, Harvest Index (HI), Heat (HUE) and Irrigation Water Use Efficiency (IWUE). Additionally, the location and treatment interactions (LOC×DOS) also showed significant *p*-values for most of the traits. As a result, mean comparisons were conducted within each location to identify significant differences among DOS and WC treatments and their impact on wheat BY, GY, TW, GN, HI, IWUE and HUE.

The influence of sowing dates on BY, GY, and related yield characteristics of wheat in Ludhiana was evident from the decreasing values of the parameters as the sowing window advanced (Table 1). GY was 5.8% and 10.7% greater in the 5 November (SD_1) seeded crop compared to the 20 November (SD_2) and 5 December (SD_3) sown crops, respectively. Other yield-related traits, such as TW, GN, HI, IWUE and HUE were also varied significantly across sowing environments, as follows: $SD_1 > SD_2 > SD_3$. Wheat sown earlier in the season attained significantly higher HI and IWUE compared to crops sown later in the season. SD_3 recorded a 3.9% decrease in HI as compared to SD_1. For heat use efficiency (HUE), no definite trend was observed. Compared to wheat cultivar WC_2, WC_1 produced superior 1000-grain weight (7.4%), grain number spike^{-1} (5.3%), and GY (4.4%) in Ludhiana. WC_1 also showed superior results for HI and other resource use efficiency measures compared to WC_2 under Ludhiana conditions (Table 1). However, WC_2 produced 3.6% higher biomass (BY) than WC_1 in Ludhiana.

In Gurdaspur, the highest and lowest BY and GY were obtained for 5 November and 5 December sowing, respectively (Table 1). Consequently, remaining yield-attributing traits (TW, GN, HI, IWUE and HUE) significantly differed among the sowing date treatments as follows: $SD_1 > SD_2 > SD_3$. The early season sowing contributed positively to BY (5.5% and 18.5%) and GY (6.6% and 24.1%) compared to mid-season and late-season sowing under Gurdaspur conditions. With a one month's advancement in the sowing date (5 November to 5 December), the 1000-grain weight and spike^{-1} grain number also decreased by 16.3% and 16%, respectively. In contrast to Ludhiana, the three sowing dates influenced the wheat crop's harvest index (HI) differently in the Gurdaspur environment, with statistically similar values for the 5 November, and 20 November sown crops, and the lowest value recorded for the 5 December seeded crop (Table 1). The decrease was 4.4% when comparing HI under SD_1 with that of the SD_3 sown crop. Consequently, the growing environments also significantly influenced the water use efficiency ($IWUE_B$ and $IWUE_G$) and heat use efficiency (HUE_B and HUE_G) of wheat in Gurdaspur. For IWUE, the results followed the trend $SD_1 > SD_2 > SD_3$ and for HUE, the value trend was observed as $SD_2 > SD_1 > SD_3$. Comparing early and late season sowing of wheat, an increase of 19.3% for $IWUE_B$, and 24.8% for $IWUE_G$ was observed on this site. In Gurdaspur, WC_1 significantly outperformed WC_2 in terms of yield and related characteristics, except for BY and HUE_B (Table 1).

Phenology and thermal indices:

In Ludhiana, the duration of all major phenophases (GS2 – GS9) of the wheat crop was longer under early-season (SD_1) sowing and decreased under subsequent sowing windows (Fig. 2). The mid-season (SD_2) and late-season (SD_3) sown crops matured in significantly less time (11 days and 21 days, respectively) compared to the early-season crop. Due to the primary dependency on phenology duration, thermal indices showed significant differences among sowing environments ($SD_1 > SD_2 > SD_3$) except for HTU. In Ludhiana, WC_1 had a significantly longer crop duration, GDD, PTU and HTU as compared to WC_2.

Wheat crops grown in the Gurdaspur environment under various seeding time treatments had a longer crop duration and consumed more GDD and PTU than those grown at the Ludhiana site (Fig. 2). Early-season and mid-season wheat crops completed their crop cycles 24 and 12 days earlier, respectively, than late-season wheat crops. Growing days, GDD and PTU were also significantly affected by DOS in all phenophases (GS2-GS9; $SD_1 > SD_2 > SD_3$). However, HTU for reproductive stages of the crop were not significantly different in Gurdaspur.

Growth parameters:

Leaf area index

The early-season sowing (5 November) achieved the maximum LAI at each phenological stage in Ludhiana (Fig. 3). The results revealed that sowing dates and cultivars significantly influenced the LAI_{max} at both study sites. LAI production declined as sowing time was extended and was lowest during the late-season crop. The tillering stage showed the greatest reduction in LAI under SD_3 (54%), compared to the SD_1 crop. Wheat produced the highest LAI in Ludhiana during the anthesis stage under all sowing scenarios, which then decreased in the following growth

Table 1. Effect of different sowing dates and cultivars on yield and related traits in Ludhiana and Gurdaspur

Treatments	BY (Mg ha^{-1})	GY (Mg ha^{-1})	TW (g)	GN (n)	HI	$IWUE_B$	$IWUE_G$	HUE_B	HUE_G
Ludhiana									
DOS									
SD_1	14.60a	5.26a	52.50a	59.13a	0.372a	3.26a	1.18a	7.82b	2.82b
SD_2	13.89b	4.97b	48.88b	55.63b	0.360b	3.10b	1.11b	8.05a	2.88a
SD_3	12.78c	4.75c	46.00c	49.13c	0.358c	2.85c	1.06c	7.77b	2.89a
LSD (p<0.05)	0.05	0.06	1.56	0.94	0.006	0.01	0.01	0.05	0.04
WC									
WC_1	13.64b	5.10a	50.75a	56.08a	0.374a	3.04b	1.14a	7.92a	2.96a
WC_2	13.88a	4.89b	47.50b	53.17b	0.353b	3.10a	1.09b	7.84b	2.77b
LSD (p<0.05)	0.04	0.05	0.94	0.77	0.005	0.01	0.01	0.04	0.03
Gurdaspur									
DOS									
SD_1	14.86a	5.62a	53.50a	65.13a	0.379a	3.35a	1.27a	7.54b	2.86b
SD_2	14.09b	5.27b	48.75b	61.63b	0.375a	3.19b	1.19b	7.71a	2.88a
SD_3	12.54c	4.53c	46.00c	56.13c	0.363b	2.81c	1.02c	7.26c	2.62c
LSD (p<0.05)	0.06	0.05	0.79	0.94	0.005	0.01	0.01	0.05	0.03
WC									
WC_1	13.71b	5.24a	50.67a	62.42a	0.383a	3.10b	1.18a	7.57a	2.89a
WC_2	13.95a	5.05b	48.17b	59.50b	0.360b	3.14a	1.14b	7.45b	2.69b
LSD (p<0.05)	0.05	0.04	0.64	0.77	0.004	0.01	0.01	0.04	0.03
POOLED ANOVA									
LOC	***	***	***	***	***	***	***	***	***
DOS	***	***	***	***	***	***	***	***	***
WC	***	***	***	***	***	***	***	***	***
LOC X DOS	***	***	NS	***	***	***	***	***	***
LOC X WC	NS	NS	***	NS	NS	NS	NS	NS	NS
DOS X WC	NS	NS	NS	NS	NS	NS	NS	***	NS
LOC X DOS X VAR	NS	NS	NS	NS	NS	NS	NS	NS	NS

BY, Biological Yield; GY, Grain Yield; TW, 1000-Grain Weight; GN, Grain Number Spike^{-1}; HI, Harvest Index; $IWUE_B$, Irrigation water use efficiency for BY; $IWUE_G$, Irrigation water use efficiency for GY; HUE_B, Heat use efficiency for BY; HUE_G, Heat use efficiency for GY; LOC, Locations of experiment; DOS, Date of Sowing; SD_1, 5 November; SD_2, 20 November; SD_3, 5 December; WC, Wheat cultivar; WC_1, PBW 725; WC_2, PBW 677; LSD, Least significant difference; separate letters indicate significant different among mean values; Significance codes: '***' – p≤0.001, '**' – p≤0.01, '*' – p≤0.05, 'NS' – Non-Significant (p>0.05)

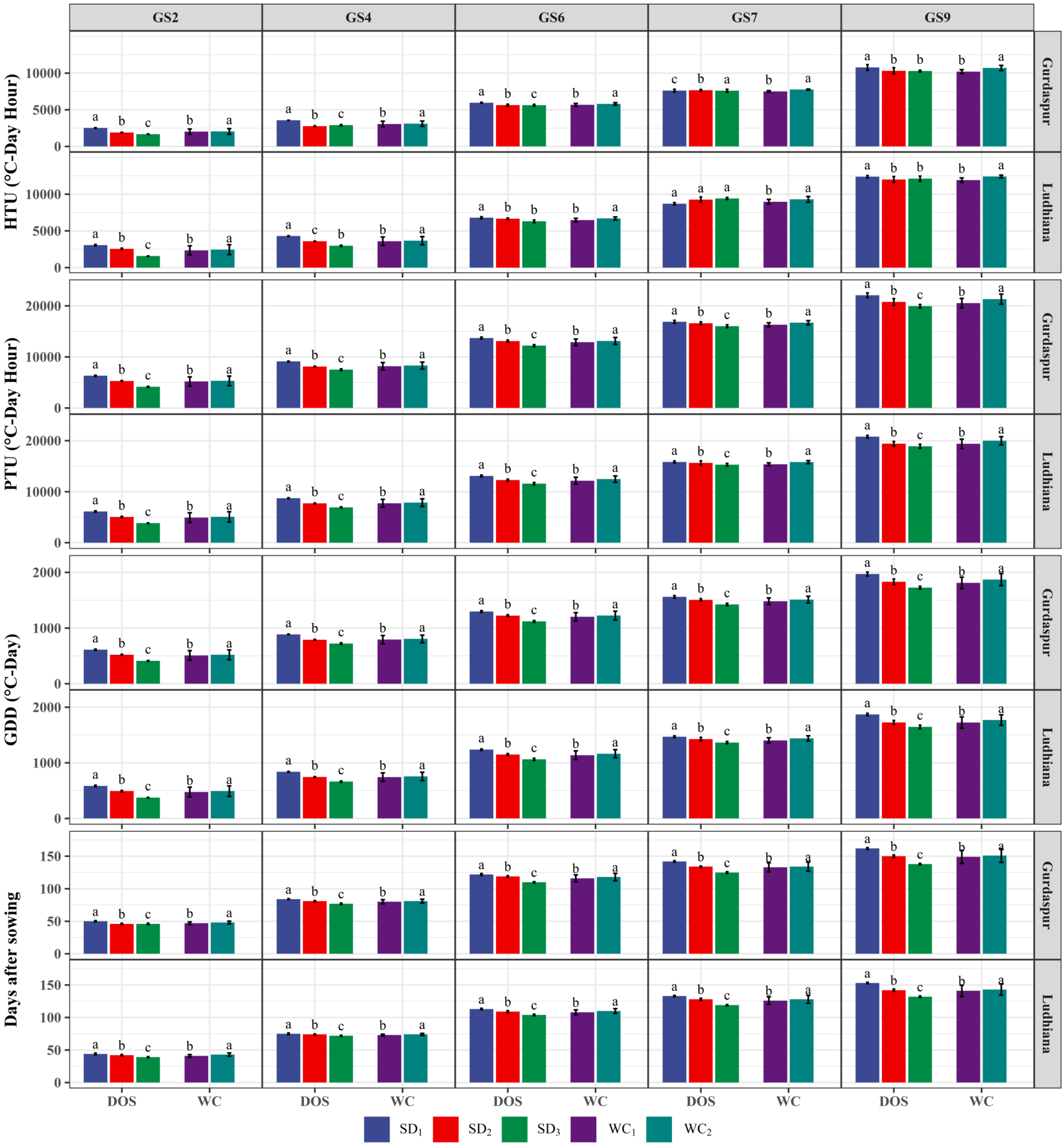

Fig. 2. Effect of different sowing dates (DOS; SD_1, 5 November; SD_2, 20 November; SD_3, 5 December) and wheat cultivars (WC; WC_1, PBW 725; WC_2, PBW 677) on phenology (tillering (GS2), flag leaf (GS4), anthesis (GS6), milking (GS7), physiological maturity (GS9)) days and periodic thermal indices (GDD, growing degree days; PTU, Pheno-thermal unit; HTU, Helio-thermal unit) consumed in Ludhiana and Gurdaspur; separate letters indicate significant different among mean values of parameters within each location.

phases. Across all phenophases, wheat cultivar WC_1 produced more LAI than WC_2.

Subsequently, Fig. 3 illustrates that the LAI decreased significantly at all major phenophases when sowing was delayed by two and four weeks from 5 November in Gurdaspur. Under the climatic conditions of Gurdaspur, the highest LAI_{max} was achieved for the seeds sown on 5 November followed by 20 November and 5 December sowing. Compared to the SD_1-sown crop, LAI_{max} decreased by 12% under SD_2 and 22% under SD_3. The LAI of cultivar WC_1 was significantly higher (15.5%, 13.7%, 10.2%, 6.6%, and 6.8% at tillering, flag leaf, anthesis, milking and physiological maturity, respectively) than that of the WC_2 cultivar at critical phenological stages.

Periodic dry matter

The sowing environment of wheat had a significant impact on dry matter accumulation in Ludhiana and Gurdaspur (Fig. 3). However, wheat cultivars significantly affected biomass accumulation during early growth. Interactions between DOS and WC showed no evidence of a beneficial effect on biomass accumulation.

Compared to early wheat sowing (SD_1), a two-week delay in seeding reduced dry matter by 6%, while a four-week delay in sowing resulted in a 16% reduction in biomass accumulation at maturity (GS9) in Ludhiana. Additionally,

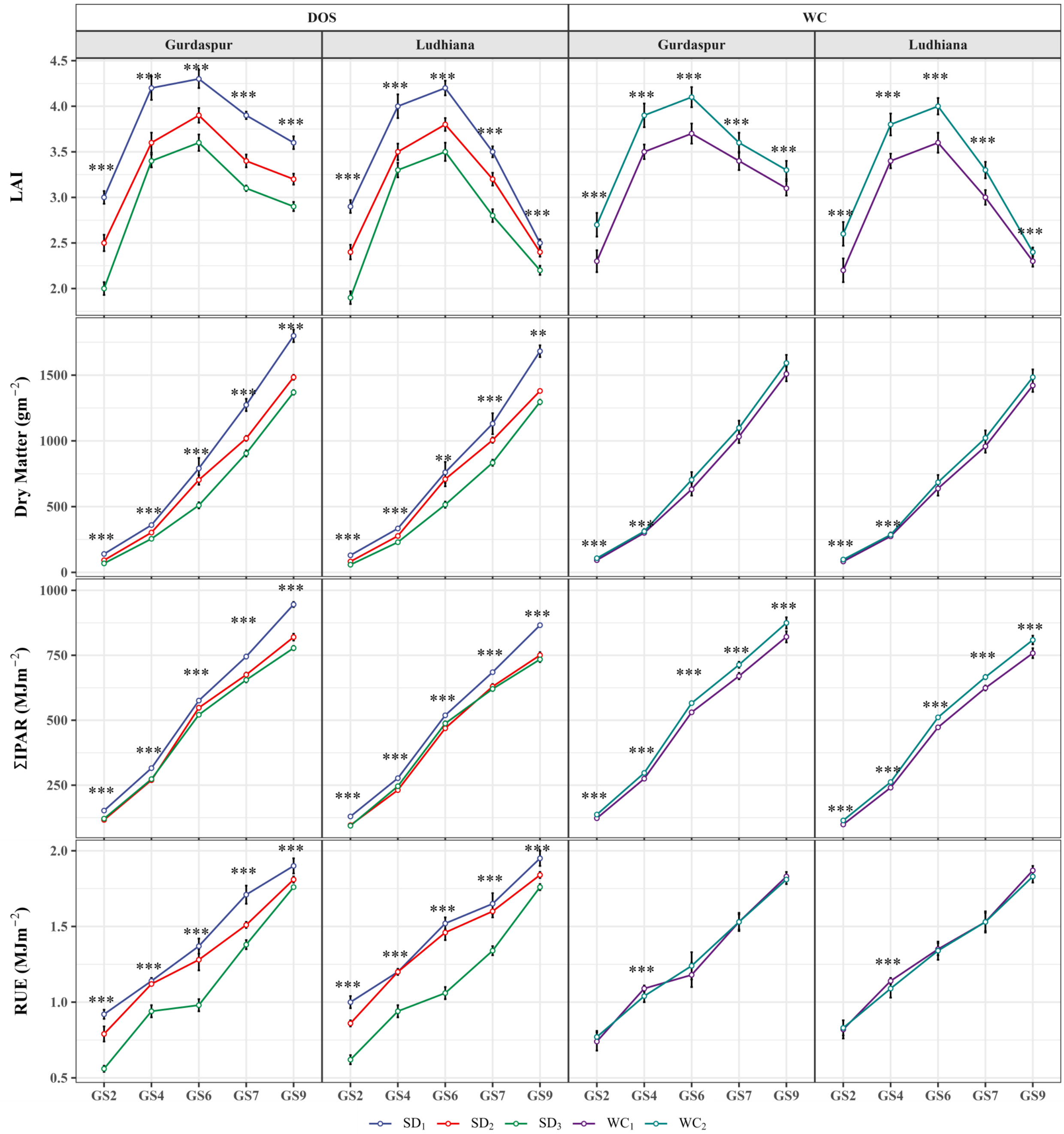

Fig. 3. Effect of different sowing dates (DOS; SD$_1$, 5 November; SD$_2$, 20 November; SD$_3$, 5th Dec) and wheat cultivars (WC; WC$_1$, PBW 725; WC$_2$, PBW 677) on periodic growth parameters and ΣIPAR (Accumulated Intercepted PAR) and RUE (Radiation use efficiency) in Ludhiana and Gurdaspur; Significance codes: '***' – *p*≤0.001, '**' – *p*≤0.01, '*' – *p*≤0.05, 'NS' – Non-Significant (*p*>0.05).

Fig. 3 demonstrated that regardless of phenophases, early -season wheat seeding significantly contributed to dry matter accumulation in Ludhiana, which was reduced with delayed sowing in the following order: SD$_1$ > SD$_2$ > SD$_3$. The greatest loss in biomass accumulation (123%) due to a one -month delay in wheat sowing from 5 November occurred during the tillering stage, followed by the anthesis stage (48%). WC$_1$ accumulated 7% more dry mass than WC$_2$ in Ludhiana, but statistically their performances were equal.

Similar outcomes were observed in Gurdaspur across all treatments, as shown in Fig. 3. The SD$_1$ crop produced the greatest amount of biomass per square meter, followed by the SD$_2$, and SD$_3$ crops at all growth stages. However, dry matter accumulation was equivalent at anthesis (GS 6) and milking (GS7) for SD$_1$ and SD$_2$ seeded wheat crops, followed by the SD$_3$ crop. The early wheat sowing (SD$_1$) accumulated 10% and 18% higher biomass compared to the SD$_2$ and SD$_3$ sowings. In Gurdaspur, WC$_1$ produced statistically higher dry biomass than WC$_2$ till flag leaf stage.

Total Intercepted PAR (ΣIPAR):

The temporal variations in wheat's total intercepted PAR (ΣIPAR) along with the ANOVA results are depicted in Fig. 3. At both study sites, the two treatment groups (DOS and WC), and their interactions had a highly significant ($p<0.001$) effect on the accumulated intercepted PAR. Regardless of the sowing dates, the ΣIPAR of wheat in Ludhiana ranged from 93.9 MJ m^{-2} to 865.7 MJ m^{-2} at key phenological stages. At maturity, ΣIPAR was highest for the SD$_1$ crop, and significantly lower for the subsequent SD$_2$ (13.3%) and SD$_3$ (15.2%) sown crops. When comparing the two cultivars, PBW677 (WC$_2$) registered a 6.3% lower ΣIPAR as compared to PBW725 (WC$_1$).

The radiation intercepted by the wheat crop at all phenophases was higher in Gurdaspur than in Ludhiana (Fig. 3). At all phenophases, the early-sowing ΣIPAR was significantly higher, and at reproductive phases, it followed the trend $SD_1 > SD_2 > SD_3$. However, late-season sown crops accumulated more IPAR during the vegetative phases than mid-season sown crops. More IPAR was captured by the canopy of WC_1 (6.8%) than WC_2.

Radiation use efficiency (RUE):

The seasonal variation in RUE due to different sowing environments at two study sites is presented in Fig. 3. Radiation use efficiency, which measures relative dry matter accumulation per unit of radiation captured by the canopy, was significantly affected by DOS at both the study sites. However, the effect of cultivars was non-significant in determining the RUE of the wheat crop except GS4 in both study locations. The available results indicate that RUE was quite inconsistent across phenological stages at all study sites. However, the early-season seeded crop expressed significantly higher RUE at maturity than the other two subsequent sowing treatments (SD_2 and SD_3). The RUE of wheat at GS9 decreased by 0.16 gMJ^{-1} and 0.07 gMJ^{-1} in the SD_3 sown crop compared to the SD_1 and SD_2 sown crops, respectively, at Ludhiana. RUE was 7.9% and 3.3% lower at maturity in the Gurdaspur environment when SD_3 crops were compared to SD_1 and SD_2 crops.

Determinants of dry matter accumulation, above ground biomass, grain yield and radiation use efficiency in wheat:

The periodic dry matter accusation of wheat showed a positive association in terms of correlation and regression with ΣIPAR and RUE irrespective of seeding date treatments and study locations (Fig. 4). The correlation coefficient between DM and ΣIPAR ranged from 0.96 to 0.98 ($p<0.05$), and the coefficient of determination (R^2) varies from 0.87 to 0.97 (Fig. 4A). Consequently, the regression between DM and RUE exhibited a positive slope and a significant R^2 value (0.92 to 0.98) and a correlation coefficient ranging from 0.94 to 0.99 ($p<0.05$) (Fig. 4B).

Above-ground biomass production (BY) of wheat showed a significant positive association with LAI_{max}, LAI_{mean}, ΣLAI, Σ (LAI × IPAR) and ΣGDD at Ludhiana and Gurdaspur (Fig. 5A-E). All of the above parameters had a greater correlation coefficient (r, $p<0.05$) with BY in Gurdaspur conditions, with the exception of LAI_{max} (0.86–0.96), when compared to the Ludhiana location (0.85–0.95). At Ludhiana, regression using ΣLAI (R^2 = 0.88), Σ(LAI × IPAR) (R^2 = 0.81) augmented relationships with BY as compared to LAI_{max} (R^2 = 0.71), LAI_{mean} (R^2 = 0.79) and ΣGDD (R^2 = 0.76) and thus provides a superior estimator of wheat biomass. The best predictor for BY at Gurdaspur was ΣLAI (R^2 = 0.84), followed by ΣGDD (R^2 = 0.82) > LAI_{mean} (R^2 = 0.80) > Σ (LAI × IPAR) (R^2 = 0.79) > LAI_{max} (R^2 = 0.63). Consequently, grain yield (GY) of wheat was also positively correlated with the above factors (Fig. 5F-J) for both the experimental sites. The significant ($p<0.05$) correlation coefficient with GY for the Ludhiana environment varied from 0.56 (LAI_{max}) to 0.72 (ΣGDD), whereas the r value ranged from 0.62 (LAI_{max}) to 0.81 (ΣLAI and Σ(LAI x IPAR)) for Gurdaspur conditions. The linear regression of GY with the five determinants above had a positive trend, and the most effective estimator of GY was ΣGDD for both locations.

Fig. 5 (K-O) illustrates the relationship between RUE and LAI_{max}, LAI_{mean}, ΣLAI, Σ(LAI × IPAR), and GDD at two study sites. The plots revealed a positive relation (correlation and regression) between the above variables and wheat RUE. On the other hand, RUE had no significant correlation ($p<0.05$) with LAI_{max} and Σ(LAI × IPAR) in Ludhiana, and with LAI_{max} and LAI_{mean} in Gurdaspur. The linear regressions had poor fits for all the variables (R^2: 0.23 – 0.36) to estimate the RUE of wheat.

Discussion

Yield and yield attributing traits:

The results indicate that early-season sowing of wheat is likely to be beneficial, and result in a grain yield advantage over delayed sowing (Table 1). This might be attributed to more favourable climatic conditions, which lead to longer crop duration, higher accumulated intercepted radiation, more sunshine hours, and greater thermal time, all

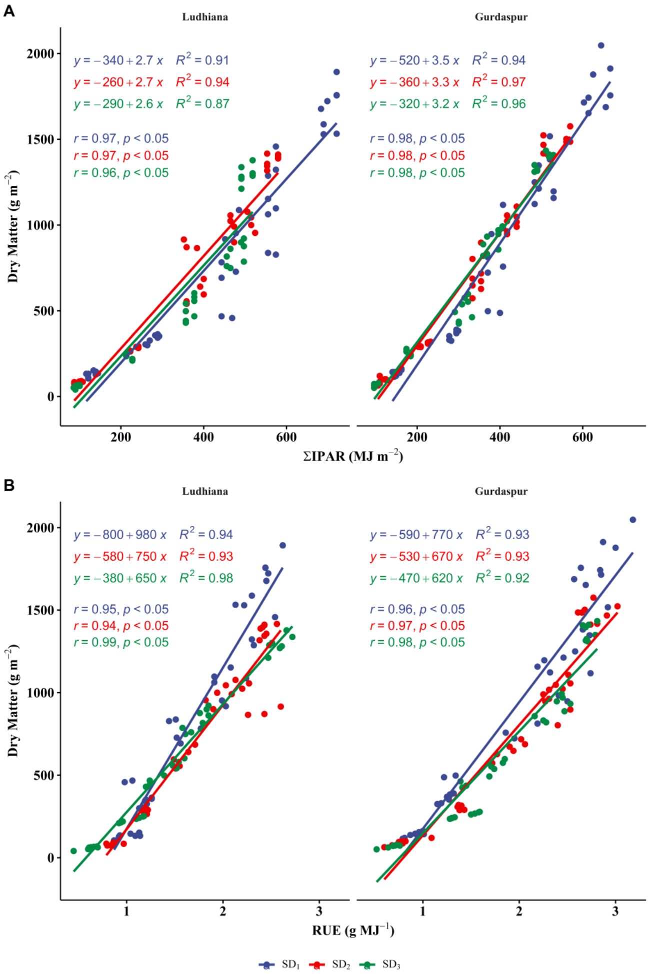

Fig. 4. Relationship of wheat dry matter accumulation with ΣIPAR (Accumulated Intercepted PAR) and RUE (Radiation use efficiency) under three sowing environments in Ludhiana and Gurdaspur.

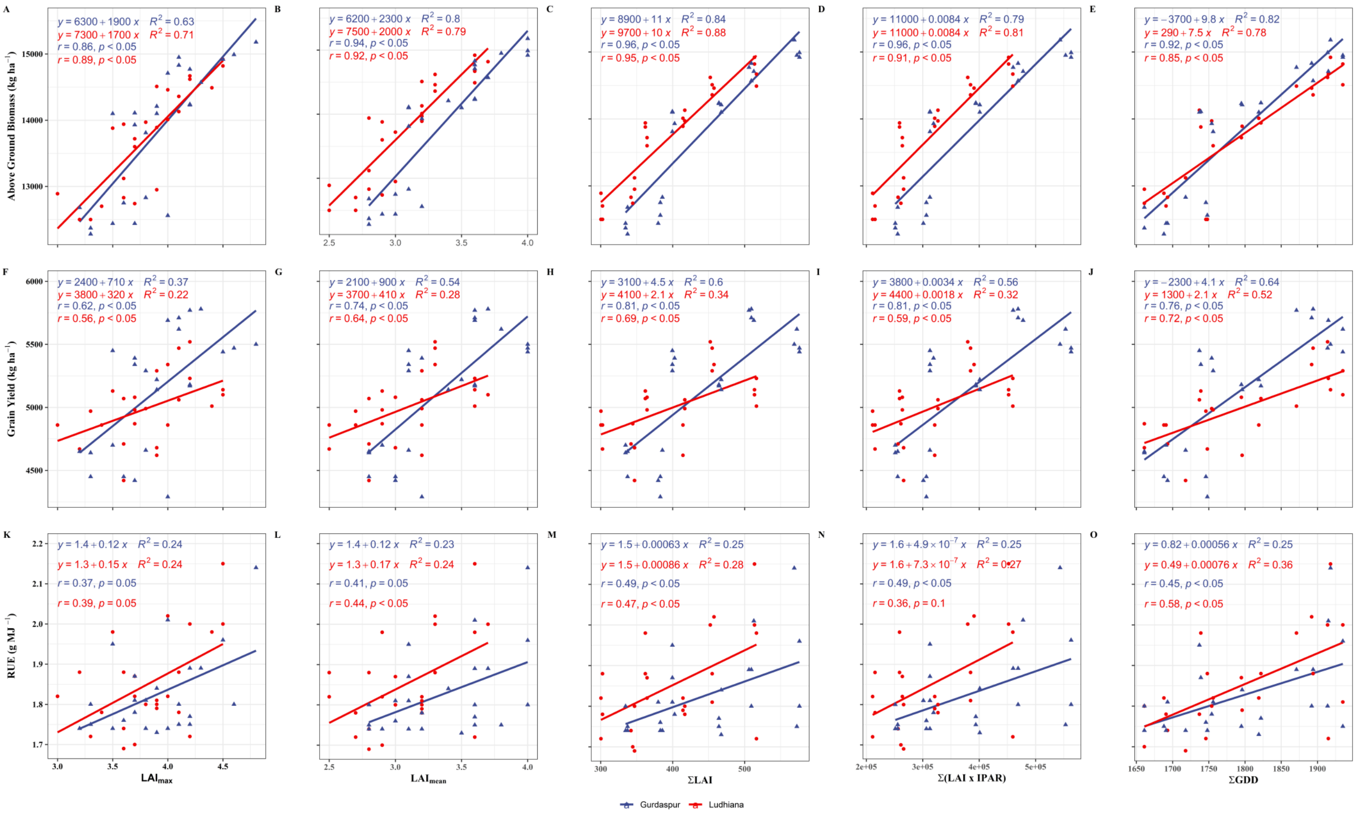

Fig. 5. Relationship of above ground biomass, grain yield and radiation use efficiency with LAI_{max}, LAI_{mean}, ∑LAI, ∑ (LAI x IPAR) and ∑GDD in Ludhiana and Gurdaspur.

contributing to higher yield, and improved IWUE (32). In contrast to IWUE, superior heat use efficiency (HUE) was expressed by the mid-season sown crop as a result of shorter crop duration, and higher air temperature during crop maturity compared to early sown crop (Table 1). As the sowing date was delayed, the crop plants confronted adverse weather conditions during the vegetative and reproductive phases (33). Delayed sowing exposes the plants to sub-optimal temperature during the early vegetative stage, resulting in poor seedling emergence and tiller development and consequently, reduced biomass production (34). Supra-optimal temperatures during later stages can trigger earlier anthesis and shorten grain-filling duration (35). Due to this, relatively short time is available for plants to transport photosynthate to sink and biomass assimilation, reducing spike length, fewer grains per spike and lower 1000-grain weight, ultimately decreasing final grain dry matter (36). These inconsistencies in dry matter allocation likely explain the diminishing harvest index observed in delayed sowings (Table 1). A decrease in harvest index following a delay in sowing has been reported by various researchers (37, 38). The similar trend in grain and biomass production has been documented previously (39). Research has shown that delayed sowing from the optimum period results in grain yield reduction of 32 $kgha^{-1}d^{-1}$ and 0.7-1.5% per day (40). Under late sowing conditions, studies have reported a 51% depletion in overall biomass production (41). The above yield dynamics are closely linked to wheat's phenological development and thermal indices, which was significantly influenced by the sowing time and cultivar selection.

Phenology and thermal indices:

Changes in sowing time led to variations in the thermal environment of crops, affecting different growth stages, and ultimately the completion of the crop life cycle (42). The present study found that the plant phenological development becomes faster due to increasing temperature in a delayed sowing environment, as presented in Fig. 2. Furthermore, this possibly reduces the number of days to attain different phenophases and accumulates a relatively lower heat unit, leading to shorter crop duration (43). Prolonged vegetative phase accompanied by shorter reproductive phases observed under delayed sowing. The number of days from sowing to flag leaf stage advanced by 3 days and 7 days and from flag leaf to maturity by 17 days under late sowing at Ludhiana and Gurdaspur, respectively, relative to early season sowing (Fig. 2). This shrinkage in phenology might be due to the post-planting phase encountered with lower temperature and the reproductive phase subjected to the higher temperature. Previous studies showed that the crop growing cycle is likely reduced under delayed sowing conditions (11, 44). Regardless of location, the cultivar WC_1 exhibits a longer growing season and accumulates more heat units than the WC_2. This variation in growing duration might be due to the genetic potential of the cultivars. Therefore, variability in phenology duration and the thermal environment highlights the importance of understanding growth parameters under different growing environments.

Growth parameters:

The variability in periodic dry matter and leaf area index of wheat in three different sowing environments is presented in Fig. 3. Periodic dry matter production and LAI reduced with delayed in sowing. Previous research has also confirmed that warm weather during the vegetative stage boosts plant growth to attain the largest foliar surface (45). Conversely, delay in wheat sowing exposes it to lower temperatures in early vegetative stages and higher temperatures during reproductive phases (46), which induces rapid leaf senescence, thus, reduces vegetative growth. Research has shown that a plant's ability and the size of its photosynthetic area determine dry matter production (47). Reduced radiation interception under delayed sowing conditions is linked to lower dry matter production and leaf area index (LAI) (2, 48). The variations in dry matter production and LAI influenced by different sowing dates have a direct impact on the amount of intercepted photosynthetically active radiation and the overall efficiency of radiation usage. This relationship is further discussed in the following sections.

Intercepted PAR and radiation use efficiency (RUE):

The radiation interception is a crucial determinant of crop production, primarily governed by canopy growth, also determined by leaf production and expansion. Under field conditions, a larger crop canopy intercepts a sufficient amount of incoming PAR, leading to higher biomass production, hence higher RUE (49). In the present study, the radiation interception in different treatments varied due to differences in LAI development (Fig. 3). The correlation and regression analysis of dry matter with IPAR and RUE showed strong positive and linear relation (Fig. 4). The early season sowing intercepted more incoming PAR and delivered higher RUE across the growing stages in relation to mid and late season sowing (Fig. 3). This is explained as profuse growth and higher LAI, consequently, improved canopy light capture (50).

Furthermore, the large canopy improves photosynthesis rate, and partitioning of accumulates to leaves (51). The conversion of IPAR to biomass, RUE is determined by optimum temperature. The lower IPAR in later sowing dates due to the short growing season lower vegetative growth, hence, much lower foliar surface (Fig. 3). Previous study has demonstrated that early-sown crops with fully developed canopies achieve maximum interception of incoming PAR, while delayed sowing results in reduced IPAR due to compromised canopy development (52). Quantitative analyses have shown that delayed wheat planting leads to a 25.4% reduction in RUE, attributed to decreased LAI, diminished radiation interception and subsequently lower biomass accumulation (43). These findings align with comparable observations documented in a study on mustard (53). Therefore, interactions between the growth parameters and radiation utilization indicators by the crop under varying growing conditions.

Interaction of growth and yield parameters:

The regression analysis of above-ground biomass, grain yield, and RUE against LAI_{max}, LAI mean, ∑LAI, ∑ (LAI×IPAR), and ∑GDD showed a positive linear relationship as shown in Fig. 5. The lower temperature enhances the growth duration of crops, which is more closely related to environmental conditions during the growing season (54). Higher growth duration leads to profuse crop canopy growth with higher LAI and captures greater solar radiation, consequently, higher dry matter accumulation, grain yield, and RUE. Statistical analyses presented in previous research reported a strong positive correlation between above-ground dry matter and LAI_{mean}, LAI_{max}, ∑LAI, and ∑ (LAI×IPAR) (28). The significant relationship between above-ground dry weight and IPAR has also been corroborated through previous research investigation (55).

Many researchers have highlighted that climate change would significantly influence wheat productivity. High temperatures during critical wheat growth phases, such as flowering and grain filling, negatively affect wheat yield by accelerating phenological development and reducing grain size and weight (54). Developing heat-tolerant wheat varieties can help maintain yield stability at higher temperatures. Traits such as early maturity, stay-green, heat shock protein expression, and deep root systems are beneficial (56). The wheat cultivars PBW 725 and PBW 677 mature between 155-157 days after sowing. Therefore, under timely sowing conditions, these cultivars can escape terminal heat stress conditions usually triggered in Punjab during the second fortnight of April. Reduced rainfall and increased evapotranspiration due to climate change can cause water deficits, adversely impacting photosynthesis, nutrient uptake, and grain development (57). Drought-resistant varieties with traits like early maturation and efficient water use can better withstand water deficits (58). Climate change can modify the distribution and virulence of pests and diseases, presenting new threats to wheat productivity. For instance, warmer temperatures and increased humidity can heighten the prevalence of rust diseases (59). Cultivars with disease resistance are crucial for mitigating climate change's impact on wheat health. The wheat cultivars used in the study are resistant to all prevailing stripe rust pathogen races in Punjab.

Conclusion

Wheat grown under two different weather conditions exhibited that sowing environments and cultivars significantly affected the crop's phenology, canopy growth, amount of radiation absorption, biomass conversion, and resource use efficiency. Early sowing (SD_1) of wheat produced a higher number of grains per spike, 1000-grain weight and harvest index, resulting in maximum BY and GY production than delayed sowing. Increased wheat growth, yield, water productivity (IWUEs) and heat use efficiency (HUE) under early-season sowing can also be attributed to increased GDD, PTU, HTU and RUE as a result of a longer growing period and increased PAR interception due to superior LAI production compared to SD_2 and SD_3 crops. In delayed sowing, stressed growing conditions like higher air temperature shortened the reproductive span, significantly decreasing grain yield and RUE. The wheat cultivar WC_1 out-yielded the WC_2 due to longer growth, higher GDD consumed, and RUE across locations during early, mid and late-season sowing. To summarize, sowing dates and cultivar selection were critical for maximizing wheat growth and yield in the Punjab plains. The study's findings will have significant implications for wheat production in northwest India, particularly under inevitable global warming. Wheat productivity can be significantly enhanced through early sowing and strategic cultivar selection by optimizing growth duration, thermal time accumulation, and radiation use efficiency. These strategies lead to higher grain yield, better water productivity, and improved heat use efficiency sustaining wheat production under varying climatic conditions.

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Authors' Contributions

Methodology, investigation, analysis, and writing were carried out by JS and BB. Field experiment layout, periodic data collection, final yield data were performed by JS, BB and LKD. All authors read and approved the final manuscript.

Compliance with Ethical Standards

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

Ethical issues: None

References

1. Statistical abstract of Punjab 2022. Department of planning, Government of Punjab. Publication [Internet]. 2023;(956):709. Available from: www.esopb.gov.in
2. Fischer RA. The effect of duration of the vegetative phase in irrigated semi-dwarf spring wheat on phenology, growth and potential yield across sowing dates at low latitude. Field Crop Res. 2016;198:188-99. https://doi.org/10.1016/j.fcr.2016.06.019
3. Tester M, Langridge P. Breeding technologies to increase crop production in a changing world. Science. 2010;327:818-22. https://doi.org/10.1126/science.1183700
4. Alghabari F, Lukac M, Jones HE, Gooding MJ. Effect of Rht alleles on the tolerance of wheat grain set to high temperature and drought stress during booting and anthesis. J Agro Crop Sci. 2014;200(1):36-45. https://doi.wiley.com/10.1111/jac.12038
5. Dreccer MF, Barnes LR, Meder R. Quantitative dynamics of stem water soluble carbohydrates in wheat can be monitored in the field using hyperspectral reflectance. Field Crop Res. 2013;159:70-80. https://doi.org/10.1016/j.fcr.2014.01.001
6. Farooq M, Bramley H, Palta JA, Siddique KHM. Heat stress in wheat during reproductive and grain-filling phases. Crit Rev Plant Sci. 2011;30(6):491-5077. https://doi.org/10.1080/07352689.2011.615687
7. Padovan G, Martre P, Semenov MA, Masoni A, Bregaglio S, Ventrella D, et al. Understanding effects of genotype × environment × sowing window interactions for durum wheat in the Mediterranean basin. Field Crop Res. 2020;259:107969. https://doi.org/10.1016/j.fcr.2020.107969
8. Zheng B, Chenu K, Dreccer FM, Chapman SC. Breeding for the future: What are the potential impacts of future frost and heat events on sowing and flowering time requirements for Australian bread wheat (*Triticum aestivium*) varieties? Glob Change Biol. 2012;18(9):2899-14. https://doi.org/10.1111/j.1365-2486.2012.02724.x
9. Montemurro F, Maiorana M. Agronomic practices at low environmental impact for durum wheat in mediterranean conditions. J Plant Nutr. 2015;38:624-38. https://doi.org/10.1080/01904167.2014.988356
10. Iwańska M, Oleksy A, Dacko M, Skowera B, Oleksiak T, Wójcik-Gront E. Use of classification and regression trees (CART) for analyzing determinants of winter wheat yield variation among fields in Poland. Biom Lett. 2018;55:197-214. https://doi.org/10.2478/bile-2018-0013
11. Ram H, Singh G, Mavi GS, Sohu VS. Accumulated heat unit requirement and yield of irrigated wheat (*Triticum aestivum* L.) varieties under different crop growing environment in central Punjab. J Agrometeorol. 2012;14(2):147-53. https://doi.org/10.54386/jam.v14i2.1414
12. Singh H, Kingra PK, Pal RK, Singh S. Improving heat use efficiency of wheat (*Triticum aestivum* L.) under abiotic stresses in semi-arid and arid agroclimatic conditions of Punjab. Mausam. 2021;72(3):673-80. https://doi.org/10.54302/mausam.v72i3.1319
13. Honnaiah PA, Sridhara S, Gopakkali P, Ramesh N, Mahmoud EA, Abdelmohsen SAM, et al. Influence of sowing windows and genotypes on growth, radiation interception, conversion efficiency and yield of guar. Saudi J Biol Sci. 2021;28(6):3453-60. https://doi.org/10.1016/j.sjbs.2021.03.010
14. Adak T, Chakravarty NVK, Muthukumar M, Deshmukh PS, Joshi HC, Katiyar RK. Evaluation of biomass and thermal energy utilization efficiency of oilseed Brassica (*Brassica juncea*) under altered microenvironments. Biomass Bioenergy. 2011;35(5):2254-67. https://doi.org/10.1016/j.biombioe.2011.02.035
15. Mehta P, Dhaliwal LK. Radiation interception, growth dynamics and agroclimatic indices of wheat under different sowing dates. J Agrometeorol. 2022;24(3):312-15. https://doi.org/10.54386/jam.v24i3.1650
16. Dhakar R, Nagar S, Sehgal VK, Jha PK, Singh MP, Chakraborty D, et al. Balancing water and radiation productivity suggests a clue for improving yields in wheat under combined water deficit and terminal heat stress. Front Plant Sci. 2023;14:1171479. https://doi.org/10.3389/fpls.2023.1171479
17. Mavi HS, Tiwana DS, Grewal SS, Singh R, Singh B, Singh NT, et al. Agroclimatic regions of Punjab. Research Bulletin. 1979.
18. Angstrom A. Solar and terrestrial radiation: Report to the international commission for solar research on actinometric investigations of solar and atmospheric radiation. QJR Meteorol Soc. 1924;50(210):121-26. https://doi.org/10.1002/qj.49705021008
19. Prescott JA. Evaporation from water surface in relation to solar radiation. Trans Roy Soc S Aust. 1940;64:114-18.
20. Anonymous. Package of practices for the crops of Punjab. Vol. 32. Ludhiana: Punjab Agricultural University. 2016; p.18-21.
21. Zadoks JC, Chang TT, Konzak CF. A decimal code for the growth stages of cereals. Weed Res. 1974;14(6):415-21. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x
22. Saab TMA, Sellami MH, Giorio P, Basile A, Bonfante A, Rouphael Y, et al. Assessing the potential of cereal production systems to adapt to contrasting weather conditions in the Mediterranean

region. Agronomy. 2019;9(393):1-21. https://doi.org/10.3390/agronomy9070393

23. Nuttonson MY. Wheat climatic relationship and use of phenology in ascertaining the thermal and photothermal requirements of wheat. In: American Institute of Crop Ecology Washington DC; 1955. p. 388. https://doi.org/10.2307/1292056
24. Sastry PSN, Chakravarty NVK. Energy summation indices for wheat crop in India. Agric Meteorol. 1982;27(1-2):45-48. https://doi.org/10.1016/0002-1571(82)90018-8
25. McMaster GS, Smika DE. Estimation and evaluation of winter wheat phenology in the central Great Plains. Agric For Meteorol. 1988;43(1):1-18. https://doi.org/10.1016/0168-1923(88)90002-0
26. Hirose T. Development of the Monsi-Saeki theory on canopy structure and function. Ann Bot. 2004;95(3):483-94. https://doi.org/10.1093/aob/mci047
27. Szeicz G. Solar radiation for plant growth. J Appl Ecol. 1974;11(2):617. https://doi.org/10.2307/2402214
28. Tripathi A, Pohanková E, Fischer M, Orság M, Trnka M, Klem K, et al. The evaluation of radiation use efficiency and leaf area index development for the estimation of biomass accumulation in short rotation poplar and annual field crops. Forests. 2018;9(4):168. https://doi.org/10.3390/f9040168
29. Saha S, Sehgal VK, Nagarajan S, Pal M. Impact of elevated atmospheric CO_2 on radiation utilization and related plant biophysical properties in pigeon pea (*Cajanus cajan* L.). Agric For Meteorol. 2012;(158-159):63-70. https://doi.org/10.1016/j.agrformet.2012.02.003
30. Pradhan S, Sehgal VK, Bandyopadhyay KK, Panigrahi P, Parihar CM, Jat SL. Radiation interception, extinction coefficient and use efficiency of wheat crop at various irrigation and nitrogen levels in a semi-arid location. Ind J Plant Physiol. 2018;23(3):416-25. https://doi.org/10.1007/s40502-018-0400-x
31. R core team. R: A language and environment for statistical computing. R Foundation for Statistical Computing [Internet]. Vienna, Austria; 2023. Available from: https://www.R-project.org/
32. Coventry DR, Gupta RK, Yadav A, Poswal RS, Chhokar RS, Sharma RK, et al. Wheat quality and productivity as affected by varieties and sowing time in Haryana, India. Field Crop Res. 2011;123(3):214-25. https://doi.org/10.1016/j.fcr.2011.05.017
33. Kaur P, Hundal SS. Effect of temperature rise on growth and yield of wheat: A simulation study. Agric Res J. 2007;44(1):6-8.
34. Tahir S, Ahmad A, Khaliq T, Jehanzeb M, Cheema M. Evaluating the impact of seed rate and sowing dates on wheat productivity in semi-arid environment. Int J Agric Biol. 2018;22:57-64. https://doi.org/10.17957/IJAB/15.1033
35. Ferrise R, Triossi A, Stratonovitch P, Bindi M, Martre P. Sowing date and nitrogen fertilisation effects on dry matter and nitrogen dynamics for durum wheat: An experimental and simulation study. Field Crop Res. 2010;117(2-3):245-57.
36. Borràs-Gelonch G, Rebetzke GJ, Richards RA, Romagosa I. Genetic control of duration of pre-anthesis phases in wheat (*Triticum aestivum* L.) and relationships to leaf appearance, tillering and dry matter accumulation. J Exp Bot. 2012;63(1):69-89. https://doi.org/10.1093/jxb/err230
37. Roy D, Vashisth A, Krishnan P, Mukherjee J, Meena MC, Biswakarma N, et al. Delayed sowing and its ramifications: Biophysical, yield and quality analysis of wheat cultivars in the northwest Indo-Gangetic plains. J Sci Food Agric. 2024;104(11):6831-43. https://doi.org/10.1002/jsfa.13512
38. Sun H, Zhang X, Chen S, Pei D, Liu C. Effects of harvest and sowing time on the performance of the rotation of winter wheat–summer maize in the North China plain. Ind Crop and Prod. 2007;25(3):239-47. https://doi.org/10.1016/j.indcrop.2006.12.003
39. Shah F, Coulter A, Ye C, Wu W. Yield penalty due to delayed sowing of winter wheat and the mitigatory role of increased seeding rate. Eur J Agron. 2020;119:126120. https://doi.org/10.1016/j.eja.2020.126120
40. Tripathi SC, Mongia AD, Sharma RK, Kharub AS, Chhokar RS. Wheat productivity at different sowing dates in various agroclimatic zones of India. SAARC J Agric. 2005;3:191-201.
41. Hocking PJ, Stapper M. Effects of sowing time and nitrogen fertiliser on canola and wheat and nitrogen fertiliser on Indian mustard. I. Dry matter production, grain yield and yield components. Aust J Agric Res. 2001;52(6):623. https://doi.org/10.1071/AR00113
42. Hatfield JL, Prueger JH. Temperature extremes: Effect on plant growth and development. Weather Clim Extrem. 2015;10:4-10. https://doi.org/10.1016/j.wace.2015.08.001
43. Fayed TB, El-Sarag EI, Hassanein MK, Magdy A. Evaluation and prediction of some wheat cultivars productivity in relation to different sowing dates under North Sinai region conditions. Ann Agric Sci. 2015;60(1):11-20. https://doi.org/10.1016/j.aoas.2014.12.001
44. Gill KK, Babuta R, Kaur N, Kaur P, Sandhu SS. Thermal requirement of wheat crop in different agroclimatic regions of Punjab under climate change scenarios. Mausam. 2014;65(3):417-24. https://doi.org/10.54302/mausam.v65i3.1052
45. Maresma A, Chamberlain L, Tagarakis A, Kharel T, Godwin G, Czymmek KJ, et al. Accuracy of NDVI-derived corn yield predictions is impacted by time of sensing. Computer Electron Agric. 2020;169:105236. https://doi.org/10.1016/j.compag.2020.105236
46. Domingos IFN, Bilsborrow PE. The effect of variety and sowing date on the growth, development, yield and quality of common buckwheat (*Fagopyrum esculentum* Moench). Eur J Agron. 2021;126:126264. https://doi.org/10.1016/j.eja.2021.126264
47. Reddy AA. Pulses production technology: Status and way forward. Econ Polit Wkly. 2009;44:73-80. https://doi.org/10.2139/ssrn.1537540
48. Sun H, Shao L, Chen Y, Zhang X. Effects of sowing time and rate on crop growth and radiation use efficiency of winter wheat in the North China plain. Int J Plant Prod. 2013;7(1):117-38. https://doi.org/10.22069/IJPP.2012.925
49. Zeleke K, Nendel C. Growth and yield response of faba bean to soil moisture regimes and sowing dates: Field experiment and modelling study. Agric Water Manage. 2019;213:1063-77. https://dx.doi.org/10.1016/j.agwat.2018.12.023
50. Hamzei J, Soltani J. Deficit irrigation of rapeseed for water-saving: Effects on biomass accumulation, light interception and radiation use efficiency under different N rates. Agric Ecosyst Environ. 2012;155:153-60. https://doi.org/10.1016/j.agee.2012.04.003
51. Mondani F, Khani K, Honarmand SJ, Saeidi M. Evaluating effects of plant growth-promoting rhizobacteria on the radiation use efficiency and yield of soybean (*Glycine max*) under water deficit stress condition. Agric Water Manage. 2019;213:707-13. https://doi.org/10.1016/j.agwat.2018.11.004
52. Confalone A, Lizaso JI, Ruiz-Nogueira B, López-Cedrón FX, Sau F. Growth, PAR use efficiency, and yield components of field-grown *Vicia faba* L. under different temperature and photoperiod regimes. Field Crop Res. 2010;115(2):140-48. https://doi.org/10.1016/j.fcr.2009.10.014
53. Pradhan S, Sehgal VK, Das DK, Jain AK, Bandyopadhyay KK, Singh R, et al. Effect of weather on seed yield and radiation and water use efficiency of mustard cultivars in a semi-arid environment. Agric Water Manage. 2014;139:43-52. https://doi.org/10.1016/j.agwat.2014.03.005

54. Asseng S, Foster I, Turner NC. The impact of temperature variability on wheat yields. Glob Chang Biol. 2011;17(3):997-1012. https://doi.org/10.1111/j.1365-2486.2010.02262.x

55. Singh R, Singh D, Biswas B, Mani JK. Radiation interception and radiation use efficiency in barley. J Agrometeorol. 2012;14:358-62.

56. Reynolds MP, Pierre CS, Saad ASI, Vargas M, Condon AG. Evaluating potential genetic gains in wheat associated with stress-adaptive traits under drought and heat stress. Crop Sci. 2007;47(S3):172-89. https://doi.org/10.2135/cropsci2007.10.0022IPBS

57. Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA. Plant drought stress: Effects, mechanisms and management. Agron Sustain Dev. 2009;29(1):185-212. https://dx.doi.org/10.1051/agro:2008021

58. Blum A. Drought resistance - Is it really a complex trait? Funct Plant Biol. 2011;38(10):753-57. https://doi.org/10.1071/FP11101

59. Bebber DP, Ramotowski MAT, Gurr SJ. Crop pests and pathogens move polewards in a warming world. Nat Clim Change. 2013;3(11):985-88. https://doi.org/10.1038/nclimate1990