



## Optimizing grain filling period of spring wheat in the warm and humid agro-climatic zone of northern Iran

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### ABSTRACT

To optimize the grain filling period of commercial wheat cultivars, an experiment was conducted at two agricultural research stations in the warm and humid agro-climatic zone of northern Iran. The experiment was conducted as a split plot with four replications. The main plots consisted of five sowing dates: 1 November (SD1), 16 November (SD2), 1 December (SD3), 16 December (SD4), and 31 December (SD5), and four spring wheat cultivars, namely Ehsan, Tirgan, Meraj, and Kalateh, were the subplots. The results indicated that the highest yield was obtained from SD3 (5892.2 kg ha<sup>-1</sup>). Despite the one-month difference between SD1 and SD3, the grain filling period remained unaffected, providing suitable conditions for plant height and resistance to lodging across the different cultivars. At SD3, optimal conditions were established for the wheat cultivars regarding temperature, day length (DL), relative humidity (RH), and energy use efficiency during the grain filling period. Both SD2 and SD3 exhibited the highest energy use efficiency. The grain yield at SD1 decreased due to severe plant lodging, while exposure to terminal heat and drought stresses, and shortened grain filling period reduced yield at SD4 and SD5. For the early anthesis cultivar, i.e., Kalateh, the grain yield was significantly higher than that of the other cultivars. The grain filling period for the early anthesis cultivar was not significantly different from the others, allowing the plant to escape terminal heat and drought stresses, thereby increasing energy use efficiency and, consequently the grain yield. Therefore, the early anthesis cultivar is highly suitable and recommended for cultivation in the studied zones where terminal heat and drought stresses are prevalent at optimal sowing dates.

### Highlights

- Highest wheat yield was 5892.2 kg/ha at Dec 1 sowing (SD3) in northern Iran.
- SD2 & SD3 optimize grain filling with max energy use efficiency.
- Early anthesis cv. Kalateh yields highest, escapes heat/drought stress.
- SD1 yield drops due to lodging; SD4 & SD5 suffer heat & short grain fill.
- Grain filling period stable at SD1-SD3, key to yield in humid zone.

### 1. Introduction

Wheat (*Triticum aestivum* L.), a globally significant crop, has the largest area (220.4 million hectares, 2023) under cultivation worldwide (FAO, 2025). In Iran, wheat is the most significant agricultural product in production and area under cultivation, playing a crucial role in both the economy and food security (Ghaffari, 2013). Climate change, particularly the increased greenhouse gases, has altered temperature and rainfall patterns (IPCC, 2018),

reducing crop yields, including wheat (Asseng et al., 2015). Nevertheless, climate change may even lead to an increase in yield in certain regions. Since 1980, the grain yield trends of the Azar-2 wheat variety, a widely cultivated type, have shown a kg ha<sup>-1</sup> increase in cold regions but a 14.4 kg ha<sup>-1</sup> decrease in warm and temperate regions (Deihimfard et al., 2023).

Terminal heat and drought stresses have been the primary causes of decreased wheat yield in many parts of

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the world, including Iran (Farooq et al., 2011). Environmental stresses during anthesis and the grain-filling period can lead to reduced fertility and a shortened grain filling period (Farooq et al., 2014). Aligning susceptible developmental stages with non-stress conditions during the growing season can help the plant escape environmental stresses (Farooq et al., 2014). Determining the appropriate sowing date to leverage optimal conditions is a key strategy to mitigate the adverse effects of terminal heat and drought stresses (Andarzian et al., 2015). Delayed planting, due to lower winter temperatures, affects emergence and leaf development and exposes critical stages such as anthesis and the grain filling period to terminal heat stress. This results in a substantial reduction in dry matter and shortens vegetative and reproductive periods. (Farooq et al., 2014). Conversely, early sowing dates lead to the accumulation of excessive growing degree days (GDD) during the vegetative period, resulting in lodging that negatively impacts grain yield (Gupta, 2017). Plant development is divided into several phenological stages to better understand its life cycle (Salazar-Gutierrez et al., 2013). The length of the growing season and the phenological stage are determinants of grain yield, with each plant requiring a certain amount of temperature to reach each phenological stage (Aslam, 2017). Any change during these stages can alter one or more yield components, ultimately affecting economic performance. Therefore, manipulating these stages can increase yield (Andarzian et al., 2015).

In addition to temperature, photoperiod (PPD) is a major environmental factor determining the anthesis period (Daba, 2016). Plant development is a function of both temperature and day length (DL) (Zhang et al., 2015), where the expression of wheat development genes is regulated in response to prevailing environmental conditions (Slafer, 2012). Agro-climatic indices such as

GDD, DL, PPD, photo-thermal unit (PTU), helio-thermal unit (HTU), hydro-thermal unit (HYTU), heat use efficiency (HUE), helio-thermal use efficiency (HTUE), photo-thermal use efficiency (PTUE), and hydro-thermal use efficiency (HYTUE) have been used to investigate plant phenology and its relationship with grain yield (Ahmad et al., 2017; Singh and Singh, 2014).

Under climate change conditions, these agro-climatic indices are also subject to change. Monitoring these indices allows for the assessment of crop response to climate change at different developmental stages (Parmesan et al., 2015). Developmental stages are estimated more accurately using GDD than calendar days. Therefore, GDD is recommended for studying the relationship between growth duration and temperature, based on a direct relationship between temperature and growth (Ahmad et al., 2017). Previous research on the effect of temperature on phenology has been conducted using cumulative GDD in wheat (Salazar-Gutierrez et al., 2013; Aslam et al., 2017, Li et al., 2012). This study aims to investigate the grain yield of spring bread wheat cultivars at different sowing dates to optimize the grain filling period based on the agro-climatic indices in the warm and humid agro-climatic zone of northern Iran.

## 2. Materials and methods

### 2.1. Field experiments

The experiments were conducted at two agricultural research stations in Gorgan and Gonbad, Golestan province, within the warm and humid agro-climatic zone of northern Iran, during the cropping seasons of 2017-2018 and 2018-2019. The geographical and meteorological characteristics of the two test stations over the two years of the experiment are presented in Table 1.

**Table 1. Meteorological data of two agricultural research stations during two years of the experiment (2017-19)**

Month	Location	Accumulated day length (hour)		Precipitation (mm)		Evaporation (mm)		Accumulated actual sunshine (hour)		Mean minimum temperature (°C)		Mean maximum temperature (°C)		Mean relative humidity (%)			
		2017-2018	2018-2019	2017-2018	2018-2019	2017-2018	2018-2019	2017-2018	2018-2019	2017-2018	2018-2019	2017-2018	2018-2019	2017-2018	2018-2019		
Nov	Gorgan <sup>‡</sup>	306.1	306.1	73.8	55.5	61.1	42.2	167.1	143.9	9.3	7.4	20.3	18.3	14.8	12.8	76.5	76.4
	Gonbad <sup>§</sup>	304.5	304.5	38.6	32.4	68.2	50.6	174.3	154.6	10.0	7.8	21.9	19.4	15.9	13.6	67.6	71.0
Dec	Gorgan	300.2	300.2	18.7	22.0	35.6	28.5	141.7	120.3	3.4	5.5	15.0	15.7	9.2	10.6	80.6	83.3
	Gonbad	298.0	298.0	19.5	57.0	42.4	39.5	153.8	125.8	4.7	6.8	17.3	16.1	11.0	11.4	72.2	78.9
Jan	Gorgan	309.2	309.2	70.2	156.6	27.9	36.9	129.0	156.2	3.2	2.4	12.3	14.9	7.8	8.6	82.7	80.8
	Gonbad	307.3	307.3	92.2	105.8	28.5	45.5	129.0	172.4	3.5	4.6	13.3	16.4	8.4	10.5	78.8	71.6
Feb	Gorgan	304.0	304.0	35.8	76.8	29.1	31.3	232.0	303.2	4.9	3.5	13.1	13.4	9.0	8.5	83.9	80.4
	Gonbad	303.0	303.0	44.2	121.6	41.8	37.9	233.2	338.8	5.6	3.9	14.2	15.1	9.9	9.5	80.3	77.2
Mar	Gorgan	371.4	371.4	28.7	209.9	61.7	65.2	125.3	166.6	8.0	6.6	20.0	17.8	14.0	12.2	80.0	77.6
	Gonbad	371.3	371.3	38.4	187.6	62.0	64.8	128.1	179.7	8.7	6.7	21.0	19.6	14.9	13.1	78.3	73.3
Apr	Gorgan	394.7	394.7	37.9	74.8	78.3	77.8	144.0	147.1	9.1	10.1	19.8	20.1	14.5	15.1	77.5	80.6
	Gonbad	395.6	395.6	42.5	62.3	75.5	68.7	139.7	152.8	9.2	10.6	20.1	22.0	14.6	16.0	77.0	76.3
May	Gorgan	438.5	438.5	5.2	2.7	172.0	169.9	235.3	238.4	14.8	16.6	30.8	30.3	22.8	23.4	64.8	68.8
	Gonbad	440.3	440.3	27.5	11.2	163.5	160.3	241.4	240.2	14.5	16.6	31.3	31.8	22.9	23.7	62.0	64.1

<sup>‡</sup>Gorgan: Latitude 36° 54' N; Longitude 54° 25' E; Altitude 6 m

<sup>§</sup>Gonbad: Latitude 37° 16' N; Longitude 55° 13' E; Altitude 45 m

## 2.2. Plant materials

The plant materials consisted of the latest wheat (*Triticum aestivum* L.) cultivars released for the region. These included four spring bread wheat cultivars: Ehsan (a predominant cultivar in the zone), Tirgan, Meraj, and Kalateh. The pedigree and characteristics of these cultivars are listed in Supplementary Tables 1 and 2. The cultivars were planted on five sowing dates as follows: SD1 (November 1), SD2 (November 16), SD3 (December 1), SD4 (December 16), and SD5 (December 31). Soil preparation practices included plowing and discing.

## 2.3. Experimental design

The experiment was conducted in a split-plot arrangement based on a randomized complete block design (RCBD) with four replications. The five sowing dates were randomly located in the main plots, while the four wheat cultivars were randomly placed in the subplots. Each cultivar was planted in 12-square-meter plots (1.2 m wide and 10 m long) using experimental plot seeders (Wintersteiger, Austria). The seeding rate for all plots was 350 seeds per square meter.

## 2.4. Crop protection

The amounts of chemical fertilizers were determined based on soil properties (Supplementary Table 3). Accordingly, all potash fertilizer, sourced from potassium sulfate, and all phosphate fertilizer, sourced from diammonium phosphate, were applied as base and topdressing. Urea, as the nitrogen source, was also applied as both base and topdressing. Additionally, chemical control of grassy and broadleaf weeds was achieved by mixing Granstar and Topic herbicides (at 20 g/ha and 1 L/ha, respectively). Throughout the growing period, agro-technical recommendations were uniformly applied to all treatments.

## 2.5. Phenological development and harvesting

During the experimental period, phenological stages such as emergence (Zadoks 11), heading (Zadoks 55), anthesis (Zadoks 65), and physiological maturity (Zadoks 90) were recorded. Days to reach each specific developmental stage was calculated based on when 50% of the plants in each plot reached that stage. The lodging score of the stem at the physiological maturity stage was calculated using Equation (1) (Fischer et al., 1987).

Lodging score = (% of plot area lodged × angle of lodging relative to the vertical / 90) × 100 (1)

At the end of the cropping seasons, the harvest was conducted using a small plot combine harvester (Wintersteiger, Austria), and then the grain yield and yield components of each plot were measured using a digital scale.

## 2.6. Agro-climatic indices

The agro-climatic indices at each phenological stage, such as DL, PPD, GDD, PTU, HTU, HYTU, HUE, HTUE, PTUE, and HYTUE, were calculated [14]. The calculation of PPD was performed using the data related to the DL

from the stage of emergence to anthesis, as shown in Equation (2) (Aslam et al., 2017):

$$PPD = 1 - 0.004 \times (20 - DL)^2 \quad (2)$$

For calculating GDD, Eq. (3) was used:

$$GDD = \sum (T_{min} + T_{max}) / 2 - T_{base} \quad (3)$$

The base temperature and maximum threshold temperature were considered to be zero and 35°C, respectively (Andarzian et al., 2015). To investigate the interaction between the bright period and temperature units, PTU and HTU indices were employed. PTU is the product of GDD and DL on any given day, while HTU is the product of GDD and actual bright sunshine hours on any given day (Ahmad et al., 2017).

$$PTU \text{ (degree-days hours)} = \sum (GDD \times DL) \quad (4)$$

HTU (degree-days hours) =  $\sum (GDD \times \text{No. of actual sunshine hours})$  (5)

HYTU was obtained by multiplying GDD by mean RH (Ahmad et al., 2017).

$$HYTU \text{ (degree-days percent)} = \sum (GDD \times \text{mean \%RH}) \quad (6)$$

The energy use efficiency indices, such as HUE, PTUE, HTUE, and HYTUE, were obtained by dividing the grain yield by the sum of units according to the relevant indices [Aslam et al., 2017].

$$HUE \text{ [(kg/ha)/(degree-days)]} = \text{Grain yield} / \text{Accumulated Heat Units} \quad (7)$$

$$PTUE \text{ [(kg/ha)/(degree-days)]} = \text{Grain yield} / \text{Accumulated PTU} \quad (8)$$

$$HTUE \text{ [(kg/ha)/(degree-days)]} = \text{Grain yield} / \text{Accumulated HTU} \quad (9)$$

$$HYTUE \text{ [(kg/ha)/(degree-days)]} = \text{Grain yield} / \text{Accumulated HYTU} \quad (10)$$

## 2.7. Statistical analysis

First, Bartlett's test was performed for the uniformity of error variances then the data analysis was performed using SAS 9.1.3 (SAS Institute Inc., Cary, NC, USA) with PROC GLM, and the comparison of means was carried out using least significant different (LSD) at the 5% probability level.

## 3. Results

### 3.1. Grain yield and yield components

The combined analysis of variance revealed a significant location effect on grain yield, 1000-grain weight, and spikes per square meter (Table 2). Both grain yield and spikes per square meter were significantly higher in Gorgan than in Gonbad (Table 3). The year effect on grain yield, biological yield, yield components, and plant height was also significant (Table 2). Notably, spikes per square meter, 1000-grain weight, and harvest index were significantly higher in the first year, while the biological yield, grains per spike, spike length, and plant height were higher in the second year (Table 3). Sowing date significantly affected biological yield, grain yield, yield components (except grains per spike), harvest index and plant height (Table 2). The highest grain yield was observed at SD3 (December 1), in the order of SD3 (5892.2 Kg/ha) > SD2 (5436.2 Kg/ha) > SD4 (5059 Kg/ha) > SD1

(4465.5 Kg/ha) > SD5 (4028.9 Kg/ha) (Table 3). However, the biological yield, spike length, and plant height decreased with delayed sowing date (Table 3). The combined analysis of variance confirmed significant differences between cultivars in terms of grain yield, yield components, and plant height (Table 2). The yield of the

Kalateh cultivar was significantly higher than the others. Additionally, spikes per square meter in the Kalateh and Tirgan cultivars were significantly higher than in the Ehsan and Meraj cultivars (Table 3). The height of the Kalateh cultivar was significantly shorter than the other cultivars, in the order of Ehsan > Meraj > Tirgan > Kalateh (Table 3).

**Table 2. Combined analysis of variance for grain yield, yield components, spike length and plant height in bread wheat cultivars at different sowing dates in two cropping seasons (2017-19)**

S.O.V	df	Biological yield	Spike m <sup>-2</sup>	Grain/spike	1000-Grain weight	Grain yield	Harvest index	Spike length	Plant height
Place (P)	1	26892863 <sup>ns</sup>	57111**	27.0 <sup>ns</sup>	87.2**	10240594**	308.11 <sup>ns</sup>	3.83 <sup>ns</sup>	409.7**
Year (Y)	1	154335957**	7097**	342.4*	1915.9**	3961613**	2442.05**	163.88**	8922.1**
P×Y	1	22630749 <sup>ns</sup>	2221*	73.2 <sup>ns</sup>	73.2*	1273989 <sup>ns</sup>	26.45 <sup>ns</sup>	0.08 <sup>ns</sup>	90.6*
Error1	12	10525286	414	44.6	8.3	3202467	106.91	0.39	17.0
Sowing Date (SD)	4	127721105**	34566**	42.6 <sup>ns</sup>	200.5**	35449683**	1501.20**	10.91**	798.0**
P×SD	4	3483033 <sup>ns</sup>	9104**	91.8*	107.8**	4860312**	376.18**	1.63**	18.5 <sup>ns</sup>
Y×SD	4	16563953**	31643**	78.6*	40.6**	2774509**	367.90**	2.86**	187.0**
P×Y×SD	4	8849635*	8732**	60.6 <sup>ns</sup>	48.6**	2253814**	158.85*	0.64 <sup>ns</sup>	29.7 <sup>ns</sup>
Error2	48	2821257	1186	30.5	5.2	373372	43.04	0.37	12.0
Cultivar (C)	3	1312091 <sup>ns</sup>	9737**	3173.1**	881.7*	9727177**	561.47**	46.44**	1014.9**
SD×C	12	2664889 <sup>ns</sup>	1585	38.4 <sup>ns</sup>	9.4 <sup>ns</sup>	157188 <sup>ns</sup>	33.37 <sup>ns</sup>	0.52 <sup>ns</sup>	13.6 <sup>ns</sup>
Y×C	3	17406259**	1904	147.8**	31.0**	1022383*	91.14*	8.58**	55.5**
P×C	3	10625052**	3776**	14.9 <sup>ns</sup>	21.4*	217524 <sup>ns</sup>	53.30 <sup>ns</sup>	1.62**	47.7**
P×Y×C	3	11821334**	6174**	6.0 <sup>ns</sup>	25.4**	455122 <sup>ns</sup>	46.21 <sup>ns</sup>	0.32 <sup>ns</sup>	29.8 <sup>ns</sup>
Y×SD×C	12	1642948 <sup>ns</sup>	1351 <sup>ns</sup>	89.0**	5.6 <sup>ns</sup>	162208 <sup>ns</sup>	17.83 <sup>ns</sup>	0.21 <sup>ns</sup>	8.2 <sup>ns</sup>
P×SD×C	12	1870394 <sup>ns</sup>	689 <sup>ns</sup>	30.1 <sup>ns</sup>	17.2**	252657 <sup>ns</sup>	41.62 <sup>ns</sup>	0.58 <sup>ns</sup>	10.3 <sup>ns</sup>
P×Y×SD×C	12	1666147 <sup>ns</sup>	972 <sup>ns</sup>	35.0 <sup>ns</sup>	12.2*	227934 <sup>ns</sup>	28.75 <sup>ns</sup>	0.54 <sup>ns</sup>	31.9**
Error3	180	2537527	936	27.48	6.0	326597	32.12	0.40	11.69
CV%		11.01	9.27	13.75	5.62	11.48	16.11	6.67	3.46

\* and \*\*: Significant at the 5% and 1% probability levels, respectively.  
ns: Non-significant.

**Table 3. Mean comparison for effect of location, cropping season, sowing date and cultivar on grain yield, yield components, spike length and plant height in four bread wheat cultivars.**

S.O.V	Biological yield	Spike m <sup>-2</sup>	Grain/spike	1000-Grain weight	Grain yield	Harvest index	Spike length	Plant height
<b>Place</b>								
Gorgan	14750.0a	343.33a	38.43a	43.10b	5155.2a	36.15a	9.63a	97.78a
Gonbad	14170.2a	316.61b	37.84a	44.14a	4797.5b	34.19a	9.41a	100.05a
<b>Cropping season</b>								
2017-2018	13765.6b	334.68a	37.10b	46.07a	5087.6a	37.93a	8.80b	93.63b
2018-2019	15154.6a	325.26b	39.17a	41.18b	4865.1b	32.41b	10.23a	104.20a
<b>Sowing date</b>								
SD1	15847.0a	352.53a	38.58a	45.58a	4465.5d	28.58d	10.08a	103.35a
SD2	15574.7a	330.91b	38.00a	45.31a	5436.2b	35.72b	9.79b	101.62b
SD3	14584.7b	342.09ab	38.98a	43.19b	5892.2a	41.75a	9.43c	98.40c
SD4	13969.6c	332.98b	36.83a	42.52b	5059.0c	36.72b	9.15d	96.26d
SD5	12324.5d	291.31c	38.28a	41.52c	4028.9e	33.08c	9.12d	94.97e
<b>Cultivar</b>								
Ehsan	14497.0a	318.55b	33.65b	47.45a	4675.04c	33.16c	10.51a	102.04a
Tirgan	14610.8a	338.26a	31.80c	45.24b	5102.06b	35.76b	9.60b	98.28b
Meraj	14427.6a	322.55b	43.89a	40.20d	4715.76c	33.08c	8.69c	101.21a
Kalateh	14305.0a	340.50a	43.20a	41.60c	5412.55a	38.68a	9.26b	94.15c

Means in each column, followed by at least one letter in common are not significantly different at the 5% probability level-using Tukey test.  
SD1 (1 November), SD2 (16 November), SD3 (1 December), SD4 (16 December) and SD5 (31 December).

**Table 4. Temperature and relative humidity during the grain filling period under different sowing dates of four bread wheat cultivars**

Sowing Date & Cultivar	Mean minimum temperature (°C)	Mean maximum temperature (°C)	Mean temperature (°C)	Mean minimum relative humidity (%)	Mean maximum relative humidity (%)	Mean relative humidity (%)
SD1	9.85e	21.18e	15.44e	58.90a	96.06a	77.48a
SD2	10.99d	23.13d	16.94d	55.00b	95.19b	75.10b
SD3	12.06c	25.21c	18.48c	50.42c	94.01c	72.22c
SD4	12.78b	26.63b	19.52b	46.80d	92.71d	69.75d
SD5	13.78a	28.36a	20.85a	43.98e	91.92e	67.95e
Ehsan	12.51a	26.01a	19.10a	48.70c	93.11c	70.90c
Tirgan	11.76b	24.71b	18.08c	51.34b	94.16b	72.75b
Meraj	11.85b	24.88b	18.21b	51.07b	94.05b	72.56b
Kalateh	11.44c	24.01c	17.59d	52.97a	94.58a	73.78a

Means in each column for each factor followed by at least one letter in common are not significantly different at the 5% probability level-using Duncan's multiple range test. § SD1 (1 November), SD2 (16 November), SD3 (1 December), SD4 (16 December) and SD5 (31 December)

### 3.2. Temperature and RH during the grain filling period

During the grain filling period, the minimum, maximum, and mean temperatures increased with a delay in sowing from SD1, While the minimum, maximum, and mean RH decreased with delayed sowing (Table 4). The grain filling period for the Kalateh cultivar occurred at milder temperatures and higher relative humidities compared with other cultivars (Table 4).

### 3.3. Period length and DL

The maximum and minimum lengths of the phenological period were obtained at SD1 and SD5,

respectively (Table 5). However, the three initial sowing dates were not significantly different concerning the grain filling period (Table 5). The Kalateh and Ehsan cultivars required the least and most time, respectively, to reach heading, anthesis, and physiological maturity. There was no significant difference among cultivars for grain filling duration (Table 5). At heading, anthesis, and maturity, the highest DL was obtained at SD1 and SD2. The accumulative DL at SD3 was significantly higher during the grain-filling period than the other sowing dates (Table 5). At all phenological stages, the highest and lowest DL was observed in the Ehsan and Kalateh cultivars, respectively. However, during the grain filling, there was no significant difference between cultivars (Table 5).

**Table 5. Mean comparison for effect of sowing date and cultivar on time period and day length of phenological stages in four bread wheat cultivars**

Sowing Date § Cultivar	Time (No. of days from sowing)				DL (h)			
	Heading (55)#	Anthesis (65)	Physiological Maturity (90)	Grain filling (65-90)	Heading (55)	Anthesis (65)	Physiological Maturity (90)	Grain filling (65-90)
SD1	137.02a	143.75e	184.22a	40.47a	1415.67a	1497.46a	2026.96a	529.50b
SD2	131.16b	137.14b	177.05b	39.91a	1370.97b	1445.90b	1980.46b	534.56b
SD3	123.27c	129.09c	169.72c	40.63a	1310.86c	1385.39c	1939.31c	553.92 a
SD4	116.08d	120.53d	157.69d	37.16b	1265.54d	1323.83d	1836.44d	512.60c
SD5	108.48e	112.47e	144.09e	31.63c	1216.94e	1272.26e	1712.70e	440.45d
Ehsan	125.83a	131.84a	169.66a	37.83a	1349.62a	1426.91a	1943.30a	516.39a
Tirgan	122.61c	127.98c	166.05c	38.08a	1308.44c	1376.87c	1892.27c	515.40a
Meraj	123.16b	128.61b	166.61b	38.00a	1315.32b	1385.00b	1899.87b	514.87a
Kalateh	121.20d	125.96d	163.89d	37.93a	1290.61d	1351.09d	1861.26d	510.18a

Means in each column for each factor followed by at least one letter in common are not significantly different at the 5% probability level-using Duncan's Multiple Range Test. # Zadoks growth scale. § SD1 (1 November), SD2 (16 November), SD3 (1 December), SD4 (16 December) and SD5 (31 December).

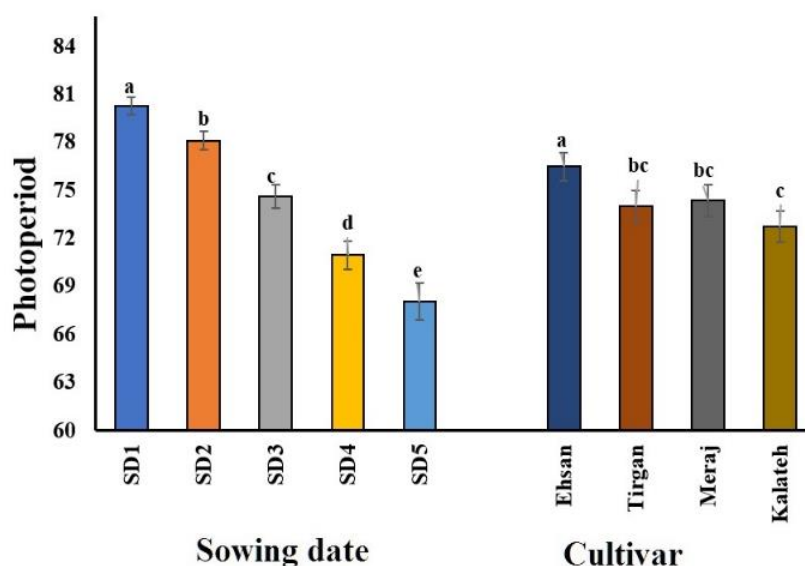
### 3.4. GDD

At heading, anthesis, and physiological maturity, SD1 significantly accumulated the highest GDD, which decreased significantly with a delay in sowing (Table 6). However, during the grain filling period, the highest GDD was recorded at SD3, followed by SD4, SD2, SD1, and SD5 (Table 6). At all phenological stages and during the grain filling period, the lowest and highest GDD was accumulated in the Kalateh and Ehsan cultivars,

respectively, in the order of Ehsan > Meraj > Tirgan > Kalateh (Table 6).

### 3.5. PPD

The results showed that SD1 had the highest PPD, while SD5 had the lowest PPD (Figure 1). Among the cultivars, Ehsan had the highest PPD, followed by Meraj, Tirgan, and Kalateh (Figure 1).



**Figure 1. Photoperiod under different sowing dates in bread wheat cultivars during two cropping seasons.**

For each factor, means followed by at least one letter in common are not significantly different at the 5% probability level using Tukey test. SD1 (1 November), SD2

(16 November), SD3 (1 December), SD4 (16 December) and SD5 (31 December).

**Table 6. Mean comparison of the agro-climatic indices at phenological stages and grain filling period in four bread wheat cultivars**

Sowing Date § Cultivar	GDD (degree-days)				HUE [(kg/ha)/(degree-days)]			
	Heading (55)#	Anthesis (65)	Physiological Maturity (90)	Grain filling (65-90)	Heading (55)	Anthesis (65)	Physiological Maturity (90)	Grain filling (65-90)
SD1	1520.82a	1609.76a	2236.65a	626.89e	2.97e	2.81e	2.01c	7.20b
SD2	1412.36b	1499.38b	2181.20b	681.83c	3.86c	3.63c	2.50b	8.06a
SD3	1315.97c	1402.62c	2157.53c	754.92a	4.53a	4.24a	2.74a	7.82a
SD4	1266.81d	1338.92d	2064.83d	725.91b	4.02b	3.79b	2.45b	7.00b
SD5	1227.39e	1287.58e	1945.58e	658.00d	3.32d	3.16d	2.07c	6.33c
Ehsan	1387.47a	1474.74a	2190.14a	715.40a	3.44c	3.23c	2.16c	6.64c
Tirgan	1340.29c	1418.70c	2105.83c	687.13b	3.85b	3.63b	2.42b	7.49b
Meraj	1347.72b	1427.75b	2118.00b	690.24b	3.51c	3.31c	2.21c	6.81c
Kalateh	1319.20d	1389.41d	2054.66d	665.25c	4.15a	3.93a	2.64a	8.18a
PTU (degree-days hours)				PTUE [(kg/ha)/(degree-days)]				
SD1	15778.63a	16860.62a	25089.38b	8228.76d	0.29c	0.27c	0.18d	0.55c
SD2	14867.86b	15957.29b	25129.12b	9171.83c	0.37b	0.34b	0.22b	0.60a
SD3	14170.48c	15278.62c	25626.72a	10348.10a	0.42a	0.39a	0.23a	0.57b
SD4	14053.79d	14997.43d	25060.12b	10062.69b	0.36b	0.34b	0.20c	0.51d
SD5	14090.80d	14888.80e	24086.26c	9197.46c	0.29c	0.27c	0.17e	0.45e
Ehsan	15086.74a	16206.89a	16206.89a	26036.83a	0.32c	0.29c	0.18c	0.48c
Tirgan	14485.30c	15480.15c	15480.15c	24836.86c	0.36b	0.33b	0.21b	0.55b
Meraj	14578.49b	15595.76b	15595.76b	25009.02b	0.32c	0.30c	0.19c	0.50c
Kalateh	14218.71d	15103.41d	15103.41d	24110.57d	0.38a	0.36a	0.22a	0.61a
HTU (degree-days hours)				HTUE [(kg/ha)/(degree-days)]				
SD1	7422.21a	7825.93a	11223.39b	3397.46d	0.62e	0.58e	0.40d	1.34a
SD2	6807.23b	7231.42b	11246.05b	4014.63c	0.81c	0.76c	0.49b	1.38a
SD3	6140.97c	6486.88c	11397.52a	4910.63b	1.00a	0.94a	0.53a	1.23b
SD4	5939.34d	6299.64d	11377.36a	5077.72a	0.88b	0.82b	0.45c	1.02c
SD5	5816.00e	6173.87e	11118.93c	4945.06b	0.73d	0.69d	0.36e	0.84d
Ehsan	6634.02a	7023.83a	11897.75a	4873.92a	0.74c	0.70c	0.40d	1.00d
Tirgan	6384.49c	6752.54c	11181.24c	4428.70b	0.83b	0.78b	0.46b	1.20b
Meraj	6408.64b	6811.04b	11282.64b	4471.60b	0.76c	0.71c	0.42c	1.08c
Kalateh	6273.47d	6626.78d	10728.97d	4102.18c	0.90a	0.85a	0.51a	1.37a
HYTU (degree-days percent)				HYTUE [(kg/ha)/(degree-days)]				
SD1	114865.5a	121863.0a	169720.4a	47857.3c	0.039d	0.037d	0.026d	0.094c
SD2	107498.5b	114561.4b	164827.8b	50266.4b	0.051b	0.048b	0.033b	0.109a
SD3	101879.4c	109023.2c	162474.5c	53451.3a	0.058a	0.054a	0.036a	0.110a
SD4	98383.7d	104029.5d	153986.6d	49957.1b	0.051b	0.049b	0.033b	0.101b
SD5	95439.4e	99891.7e	143893.4e	44001.7d	0.042c	0.040c	0.028c	0.094c
Ehsan	106635.3a	113532.6a	163540.8a	50008.2a	0.044c	0.042c	0.029c	0.095c
Tirgan	102948.2c	109211.7c	158266.0c	49054.3b	0.050b	0.047b	0.032b	0.105b
Meraj	103550.0b	109905.5b	159034.3b	49128.8b	0.045c	0.043c	0.029c	0.095c
Kalateh	101319.6d	106845.3d	155081.1d	48235.9c	0.054a	0.051a	0.035a	0.113a

Means in each column for each factor, followed by at least one letter in common are not significantly different at the 5% probability level-using Duncan's multiple range test. # Zadoks growth scale. § SD1 (1 November), SD2 (16 November), SD3 (1 December), SD4 (16 December) and SD5 (31 December).

### 3.6. PTU and HTU

In the heading and anthesis stages, the highest values of PTU and HTU were accumulated in SD1 and SD2. During the grain filling period, the highest PTU was obtained in SD3, followed by SD4, SD5, SD2 and SD1, whereas the highest HTU accumulated in SD4 followed by SD5, SD3, SD2 and SD1 (Table 6). The results confirmed that in the phenological stages and also in the grain filling period, the highest PTU and HTU were observed in Ehsan and Kalateh cultivars, respectively, in the order of Ehsan> Meraj> Tirgan> Kalateh (Table 6).

### 3.7. HYTU

The HYTU in the phenological stages decreased in the order of the sowing date: SD1> SD2> SD3> SD4> SD5. However, during the grain filling period, SD3 and SD2 accumulated the highest HYTU, respectively, in the

following order: SD3> SD2> SD4> SD1> SD5 (Table 6). Similar to the mentioned agro-climatic indices (PPD, GDD, PTU, HTU and HYTU), the highest HYTU was obtained in Ehsan, followed by Meraj, Tirgan and Kalateh, respectively, in all phenological stages and during the grain filling period (Table 6).

### 3.8. Energy use efficiency

HUE, PTUE, HTUE and HYTUE indicated that the energy use efficiency at heading, anthesis and physiological maturity at SD3 and SD4 were significantly higher than at other sowing dates (Table 6). In the grain filling period, the highest HUE, HTUE, PTUE and HYTUE were observed at SD2 and SD3 (Table 6). In all phenological stages and the grain filling period, the Kalateh and Ehsan cultivars had the highest and lowest energy use efficiency, respectively (Table 6).

#### 4. Discussion

Climate change represents an important research challenge for plant scientists. The rise in greenhouse gas emissions and the impact of increased carbon dioxide levels have led to changes in temperature and precipitation patterns (IPCC, 2018), resulting in reduced yields for many crops, including wheat (Lobell et al., 2011; Asseng et al., 2015). Identifying the optimal planting date is a vital strategy for mitigating the effects of heat stress and drought at the terminal cropping season (Amrawat et al., 2013).

The decrease in fertile spikes and 1000-grain weight at late sowing dates was due to warm and dry weather and the reduced grain-filling period (Andarzian et al., 2015). Delayed sowing dates exposed the grain-filling period to

higher temperatures and lower relative humidity (Table 4). The reduction in fertile spikes could be attributed to the decreased duration of stem elongation at late sowing (Slafer, 2012). High temperatures negatively affected the biological yield, grain yield, and some yield components (Farooq et al., 2011). It should be noted that the biological yield is directly related to the length of the growing period, with temperature being the most important factor influencing the development and growth of plants (Liu et al., 2016). As such, the biological yield decreased in the order of sowing dates: SD1 > SD2 > SD3 > SD4 > SD5 (Table 3). There was a significant and positive correlation between the biological yield and growing period (Figure 2a).

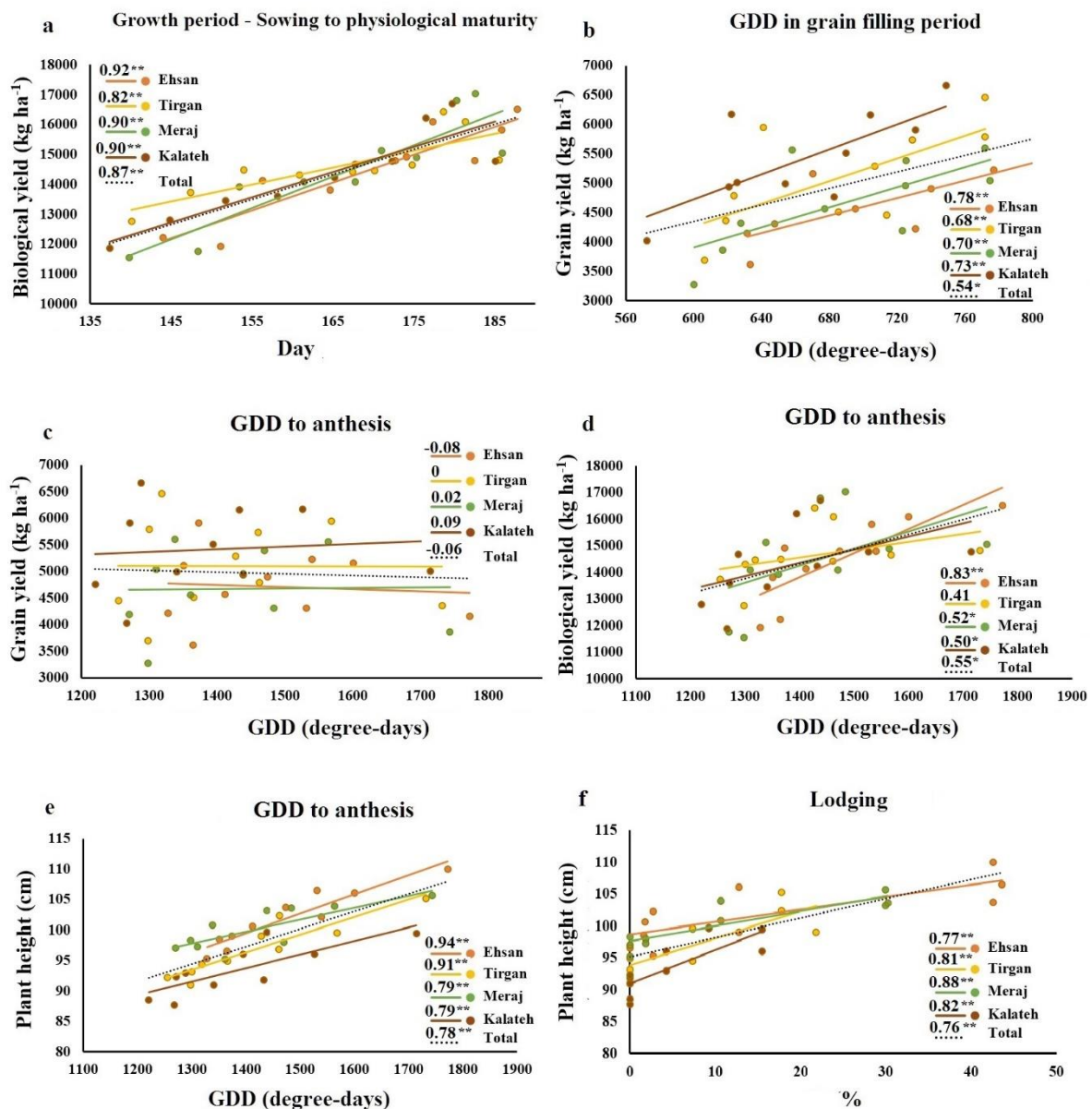


Figure 2. Regression between some of the traits. Growth period and biological yield (a), GDD in grain filling and grain yield (b), growing degree days (GDD) to anthesis and grain yield (c), GDD to anthesis and biological yield (d), GDD to anthesis and plant height (e), lodging and plant height (f).

The grain yield and spikes per square meter in the Kalateh cultivar were higher than in the other cultivars

(Table 3). Kalateh is an early-anthesis cultivar (Table 5), and its anthesis occurred at milder temperatures (Table 4);

thus, producing more fertile spikes was plausible. Climate change and global warming have altered and accelerated the phenological stages of plants, thereby reducing yield performance (Asseng et al., 2015; Zhang et al., 2015). The ability to control the length of phenological stages is crucial for adapting to specific environmental conditions and determining breeding strategies based on them (Mkhabela et al., 2016). In the warm and humid agro-climatic zone of northern Iran, the grain-filling period occurs in April and May. A comparison of the two-year climatic parameters of the experiment with the long-term weather data showed that in April and May of the two years of the experiment, the mean minimum, mean maximum, and daily mean temperatures increased. Moreover, the mean relative humidity increased in April and decreased in May (Table 7). An increase of one degree Celsius in world temperature has reduced wheat yield by 4.1-6.1% (Liu et al., 2014). A two-month difference between SD1 and SD5 resulted in a reduction in the phenological period of the crop at different stages, with the number of days to heading, anthesis, and physiological maturity decreasing by 28.54, 31.28, and 40.13 days, respectively (Table 5). The reduction in growing period might be attributed to higher temperatures at late sowing dates (Asseng et al., 2015). In this study, the differences in phenological stages were due to variability in the climatic parameters at the different sowing dates (Aslam et al., 2017) Meanwhile, the reduction in days to maturity and other phenological stages of wheat has been reported to have a direct relationship with higher temperatures (Andarzian et al., 2015; Salazar-Gutierrez et al., 2013; Aslam et al., 2017). Therefore, yield reduction due to temperature changes in delayed sowing dates can be expected because of the reduction in the length of developmental stages of wheat (Andarzian et al., 2015). Adjusting the sowing date to minimize the effects of terminal heat and drought stresses effectively maintains yield performance (Sylvester-Bradley et al., 2012). The control of plant phenology through the sowing date is very important to prepare optimal conditions for assimilate transport and partitioning during the grain-filling period (Reynolds et al., 2012).

Despite the one-month difference between SD1 and SD3, the grain filling period was not affected. However, in the two final sowing dates (SD4 and SD5), the grain filling period decreased significantly due to the increase in temperature and decrease in humidity (Table 5). It is well known that crops require the accumulation of a certain

amount of heat to grow and reach each of the phenological stages (Ahmad et al., 2017). The ability to predict the phenological stages leads to improved control and management of pests and weeds, and facilitates the selection of appropriate breeding strategies (Mkhabela et al., 2016). In terms of GDD, SD1 had significantly the highest value at heading, anthesis, and physiological maturity. However, during the grain filling period, the highest GDD was observed in SD3, which was significantly higher than other sowing dates (Table 6). During the grain filling, a positive and significant correlation was observed between GDD and the grain yield of different cultivars (Figure 2b). However, at anthesis, no significant correlation was observed between GDD and grain yield (Figure 2c). Moreover, at anthesis, the high and positive correlation of GDD with the biological yield and plant height caused severe lodging in plants, especially in the two initial sowing dates (Figure 2d,e). The early anthesis cultivar, Kalateh, had a lower lodging percentage than other cultivars in the first three sowing dates, which did not lodge even at the last three sowing dates. This could be attributed to lower GDD and plant height in the Kalateh cultivar (Figure 2e,f). The late anthesis cultivar, Ehsan, had higher lodging than that of other cultivars because of the accumulation of more GDD and higher plant height (Figure 2f). Based on the results, SD2 and SD3 provided the optimal conditions for sufficient GDD accumulation, plant height, and yield performance in the different cultivars.

Under normal conditions, where biotic and abiotic stresses are unlikely to occur and the plant does not lodge, longer phenological stages such as more days to anthesis and physiological maturity can produce higher yield (Camargo et al., 2016). At heading, anthesis, and maturity, the highest DL was obtained in SD1 and SD2 (Table 5). It is worth mentioning that during the grain filling period at SD3, accumulated DL was significantly higher than those of the other sowing dates (Table 5). In the grain filling period, a positive and significant correlation was observed between DL and grain yield in different cultivars (Figure 3a). However, there was no significant correlation between DL and the grain yield at anthesis (Figure 3b). In the phenological stages, the highest and lowest DL was observed in the late anthesis cultivar (Ehsan) and the early anthesis cultivar (Kalateh), respectively. However, during the grain filling, there was no significant difference between cultivars (Table 5).

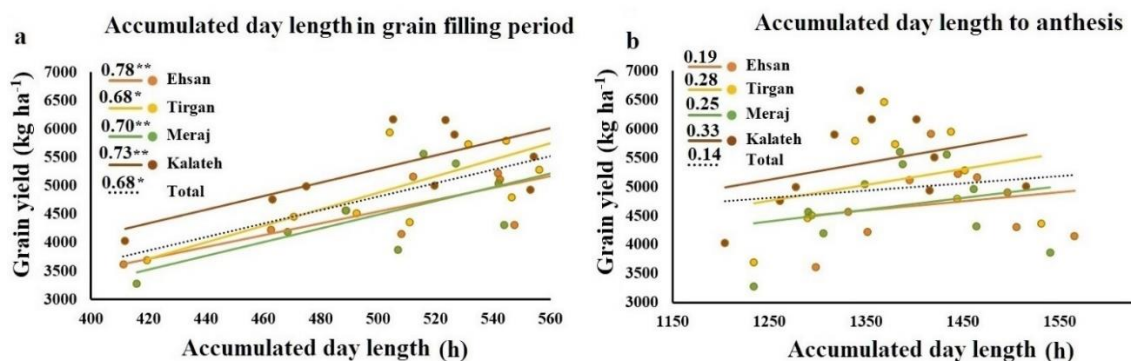


Figure 3. Regression between grain yield and accumulated day length in grain filling period (a) and anthesis (b).

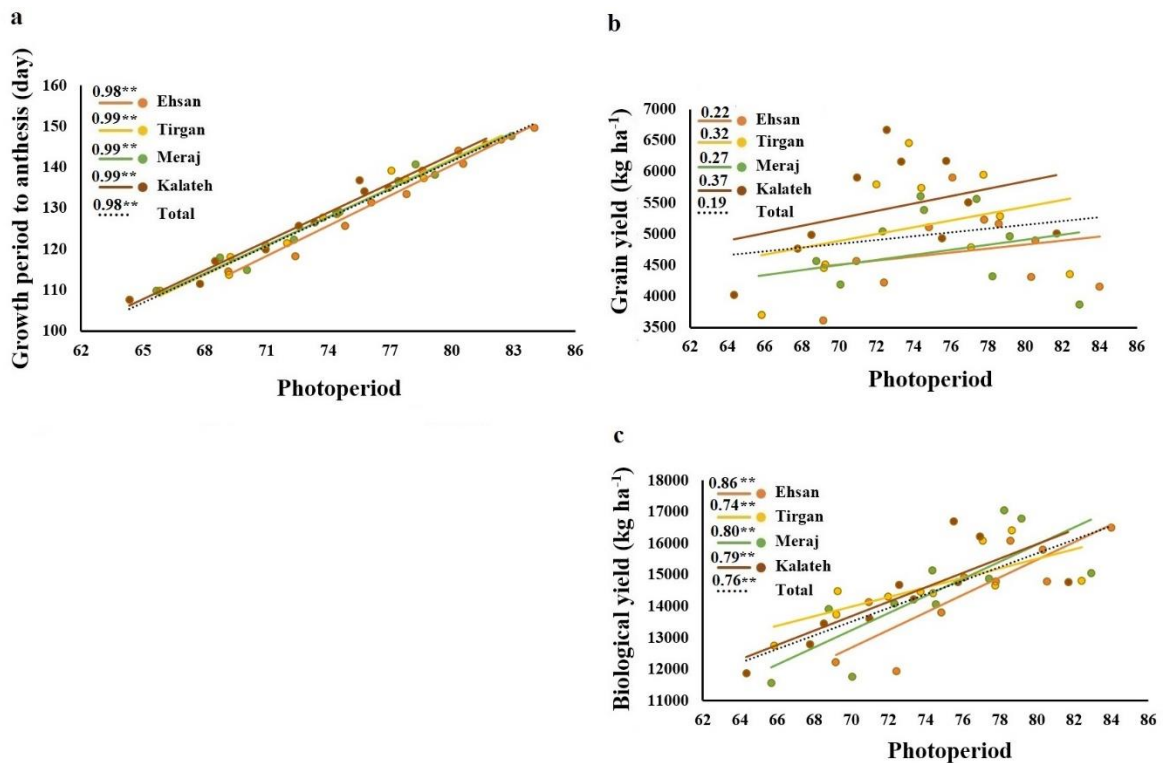


Figure 4. Regression between photoperiod with days to anthesis (a), grain yield (b), and biological yield (c).

In wheat, emergence to the beginning of anthesis, in addition to temperature, is also affected by the PPD (Ahmad et al., 2017). Thus, wheat anthesis is sensitive to both PPD and DL (Zhang et al., 2015). The developmental response of plants sensitive to PPD begins and reaches a maximum during a certain day and accelerates the development of long-day plants such as wheat (Perez-Gianmarco et al., 2018). Here, the results showed that SD1 had the highest PPD values, whereas SD5 had the lowest PPD values (Figure 1). The highest and lowest PPD values were related to the late anthesis cultivar (Ehsan) and the early anthesis cultivar (Kalateh), respectively (Figure 1). There was a very strong positive correlation between PPD and days to anthesis in different cultivars (Figure 4a). Furthermore, no significant correlation was observed between PPD and the grain yield in any cultivars, while the correlation between PPD and the biological yield was positive and significant (Figure 4b,c).

As the beginning and end of each phenological stage occur due to the effect of temperature and the length of the bright period, the PTU and the HTU must be used to predict the exact stages of both anthesis and maturity (Singh and Singh, 2014). Overall, PTU is the product of GDD and the potential sunshine hours, while HTU is the product of GDD and actual sunshine hours (Ahmad et al., 2017). In the phenological stages, the highest PTU and HTU were observed in SD1 and SD2. During the grain filling period, the highest PTU was related to SD3, while SD1 accumulated the lowest value (Table 6). Thus, SD3 provided the optimal conditions for the cultivars regarding temperature, potential sunshine hours and actual sunshine hours during the grain filling period. Other researchers reported receiving more PTU on the early sowing dates

than the delayed ones (Singh and Sing, 2014). In the grain filling period, a positive and significant correlation was observed between PTU and the grain yield in different cultivars (Figure 5b). Nevertheless, at anthesis, the correlation between PTU and grain yield was not statistically significant for different cultivars (Figure 5a). The early sowing date accumulated lower HTU during the grain filling period, which reduced the yield performance at SD1 (Tables 3 and 6). On the other hand, higher HTU in SD4 and SD5, despite a significant reduction in the grain filling period, was attributed to the overlap of high temperatures and maximum sunshine hours during the grain filling period. As a result, no significant relationship was observed between HTU and the grain yield at anthesis and the grain filling period (Figure 5c,d). The reduction of HTU in different stages of wheat development has also been attributed by other researchers to delay in sowing (Amrawat et al., 2013).

The HYTU in the phenological stages decreased in the order of the sowing date: SD1 > SD2 > SD3 > SD4 > SD5. However, SD3 and SD2 accumulated the highest HYTU during the grain-filling period, respectively (Table 6). Here, it should be noted that as the minimum, maximum, and mean relative humidity decreased during the grain filling period (Table 4), the maximum HYTU in SD3 and SD2 indicated the optimal conditions to employ humidity and heat in the grain filling period, which has played an essential role in the final grain yield (Gudadhe et al., 2013). In this regard, a positive and significant correlation was observed between the HYTU and the grain yield in different cultivars during the grain filling period (Figure 5f).

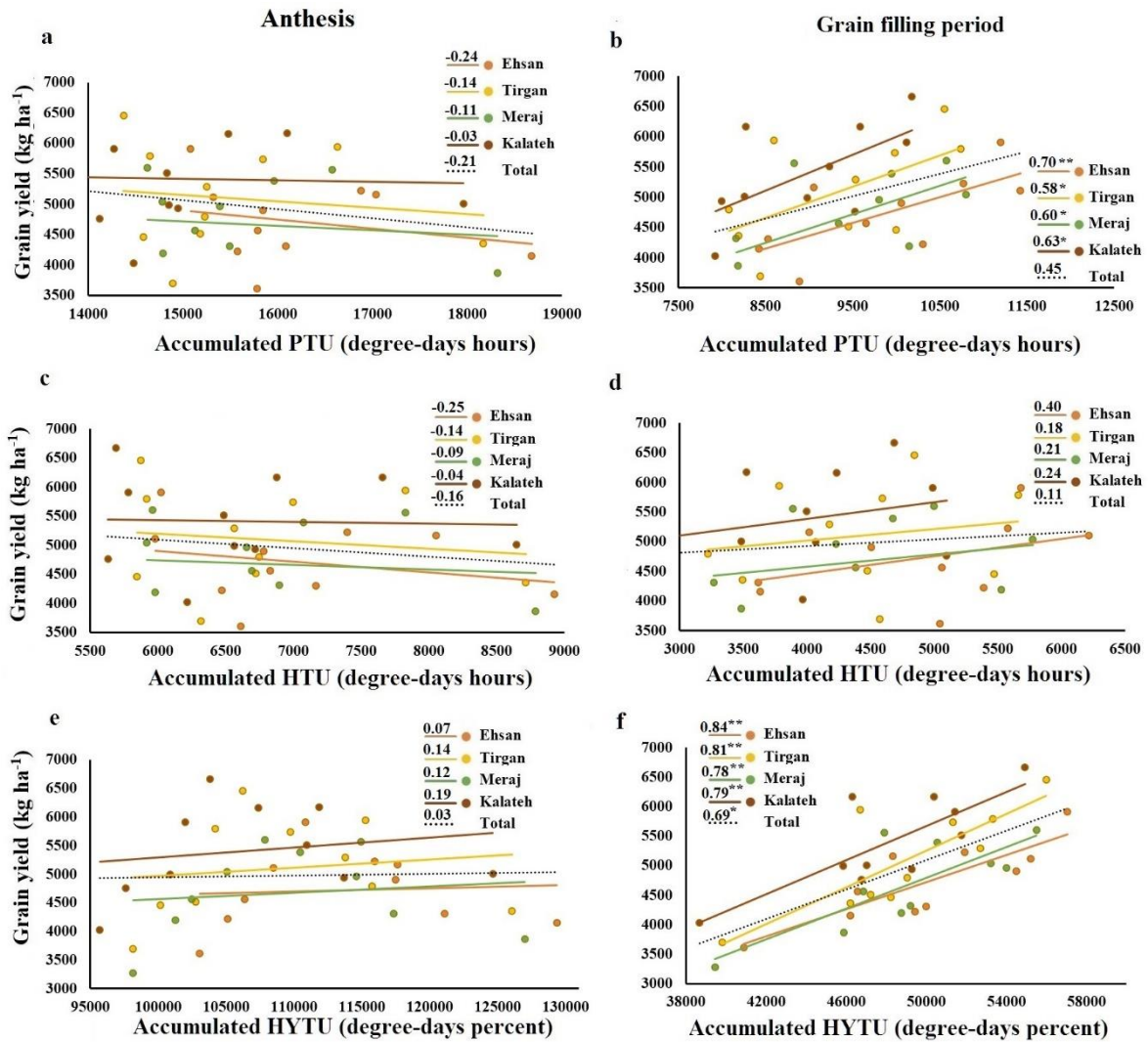


Figure 5. Regression between the agro-climatic indices at anthesis and grain filling period with grain yield.

The results confirmed that in the phenological stages and also in the grain filling period, the highest and lowest agro-climatic indices such as GDD, PTU, HTU, and HYTU were observed in the late anthesis cultivar (Ehsan) and the early anthesis cultivar (Kalateh), respectively (Table 6).

The accumulation of the mentioned indices was directly related to the growth period, so that a positive and significant correlation was observed between these agro-climatic indices and the days to anthesis (Figure 6a-d). Accordingly, the higher values of the agro-climatic indices in the Ehsan cultivar and the lower values in the Kalateh cultivar were due to the differences in their late and early anthesis and maturity, respectively (Table 5). Therefore, days to anthesis was higher in the Ehsan cultivar compared to the Kalateh cultivar; 6.2, 6, 6.4, 5, and 7 days to anthesis in SD1, SD2, SD3, SD4, and SD5, respectively (data not displayed). There was no significant difference between Ehsan and Kalateh for the grain filling period at different sowing dates. The decrease in the agro-climatic indices during the grain filling period in the early anthesis cultivar (Kalateh resulted from the coincidence of the grain filling period with mild weather conditions. So, the minimum, maximum, and mean daily temperature during the grain

filling in the early anthesis cultivar (Kalateh) was less than that of the late anthesis cultivar (Ehsan). Conversely, in the same period, the relative humidity in the early anthesis cultivar was higher than in the late anthesis cultivar (Table 4).

Energy efficiency is a function of genetic factors that regulate plant phenological stages by selecting an appropriate sowing date (Singh et al., 2016). The energy use efficiency indices (HUE, PTUE, HTUE, and HYTUE) in the phenological stages were significantly higher at SD3 and SD4 (Table 6). While in the grain filling period, the highest energy use efficiency was observed in SD2 and SD3 (Table 6).

The early sowing date prevents the plant from utilizing the maximum GDD during the grain filling period, in contrast in the late sowing date, the plant receives less GDD due to a shortening of the phenological stages and consequently, the grain yield and energy efficiency are reduced (Gupta et al., 2017). In all phenological stages and the grain filling period, the early anthesis cultivar (Kalateh) and the late anthesis cultivar (Ehsan) had the highest and lowest energy use efficiency, respectively (Table 6). In different cultivars, a positive and significant correlation

could be observed between HUE, HTUE, PTUE, and HYTUE with the grain yield during anthesis and the grain filling period (Figure 7). These results showed that selecting an appropriate sowing date for wheat is crucial for

managing the climatic conditions, which could lead to achieving the maximum energy efficiency and grain yield (Solanki et al., 2017).

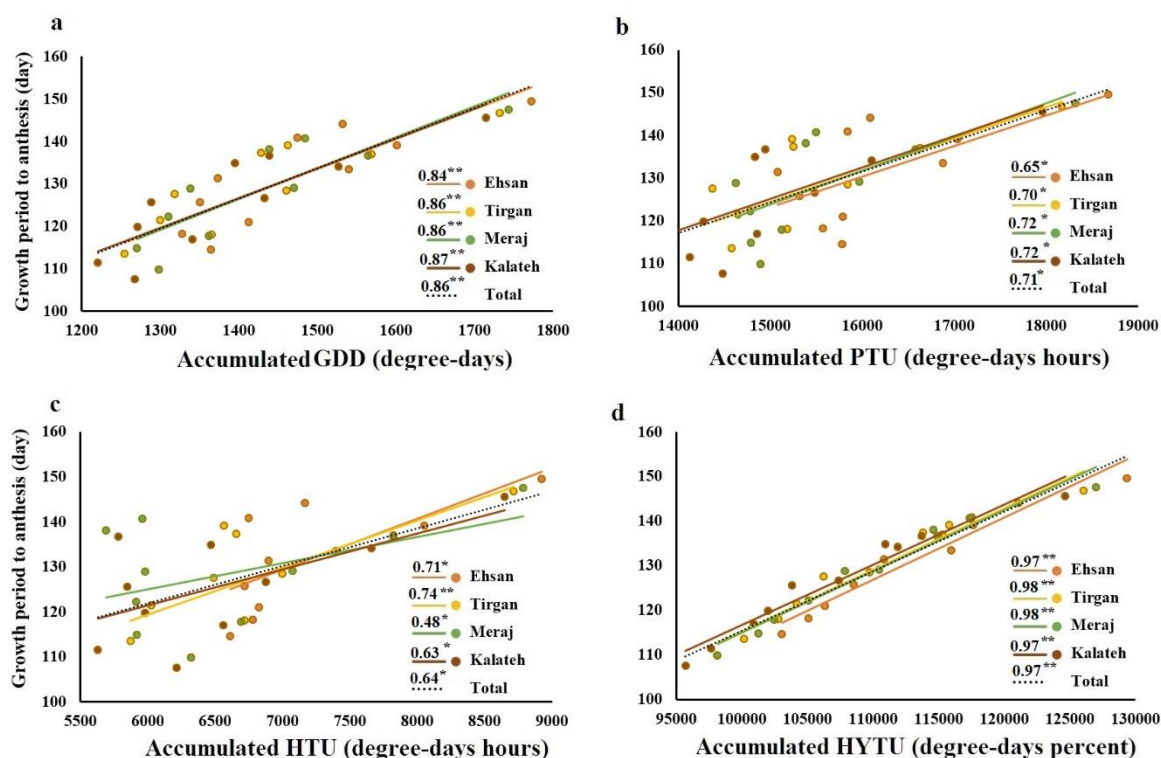


Figure 6. Regression between the agro-climatic indices and growth period at anthesis.

Table 7. Mean comparison of the climate parameters during two years of experiment with long-term average in April and May.

Parameter	Location	Long-term average (34 years)		Average experiment (2 years)	
		April	May	April	May
Mean minimum temperature (°C)	Gorgan	8.8	13.8	9.8	14.0
	Gonbad	8.8	13.7	9.8	13.3
Average maximum temperature (°C)	Gorgan	19.7	25.0	20.3	27.0
	Gonbad	20.9	26.6	21.4	27.9
Mean temperature (°C)	Gorgan	14.2	19.4	15.1	20.5
	Gonbad	14.8	20.2	15.6	20.6
Mean minimum relative humidity (%)	Gorgan	57.3	52.9	63.8	46.5
	Gonbad	56.6	50.3	58.5	43.5
Mean maximum relative humidity (%)	Gorgan	91.1	89.5	94.8	86.9
	Gonbad	91.8	89.1	95.5	92.5
Mean relative humidity (%)	Gorgan	74.2	71.2	79.3	66.7
	Gonbad	74.2	69.7	77.0	67.5
Precipitation (mm)	Gorgan	50.6	43.3	55.1	37.4
	Gonbad	52.1	40.0	46.3	41.0
Evaporation (mm)	Gorgan	85.1	124.6	71.0	132.7
	Gonbad	75.6	120.9	71.1	124.5

Meteorological data for Gorgan and Gonbad weather stations from its inception (1984).

## 5. Conclusion

The SD2 and SD3 provided suitable conditions for plant height and resistance to lodging in different cultivars. Also, these two sowing dates provided optimal conditions for different cultivars in terms of climatic parameters and energy use efficiency during the grain filling period. The grain yield decreased due to severe plant lodging at SD1, exposure to terminal heat and drought stresses, and a reduced grain filling period at SD4 and SD5. In addition to determining the optimal sowing date, the release of new

commercial cultivars adapted to the climatic conditions also plays an important role in increasing yield. The grain filling period of the early anthesis cultivar, Kalateh, was not significantly different from other cultivars. Nevertheless, the grain filling period in the early anthesis cultivar, Kalateh, occurred sooner than other cultivars. This helped the crop escape terminal heat and drought stresses, increased energy use efficiency, and consequently increased grain yield. Therefore, the early anthesis cultivar is suitable and advisable for cultivating in the studied zones where terminal heat and drought stresses are common at optimal sowing dates.

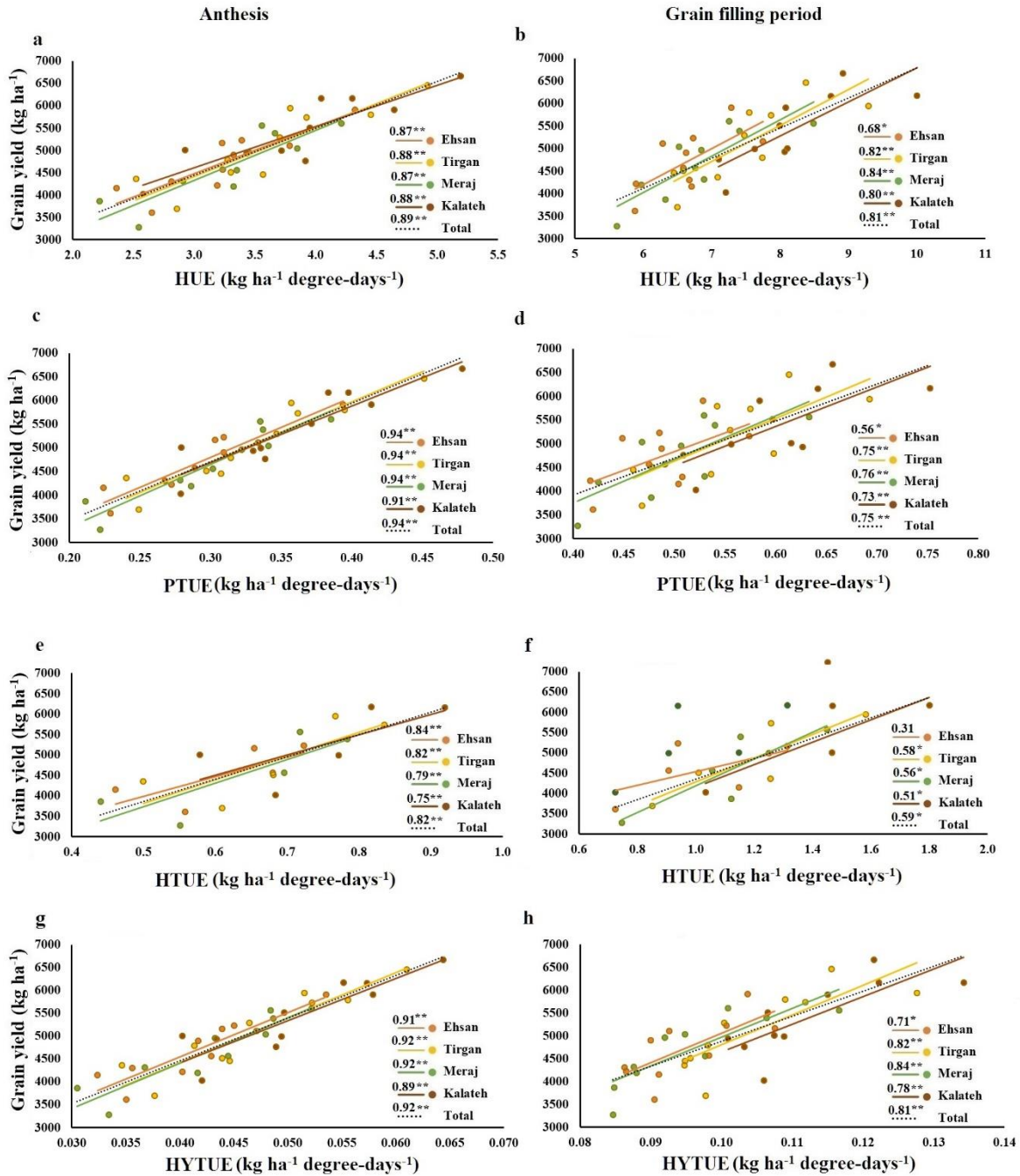


Figure 7. Regression between energy use efficiency in agro-climatic indices and grain yield.

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