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Evaluation of physiological indices and grain yield of wheat (*Triticum aestivum*) cultivars under different sowing schedules

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ABSTRACT

Environmental variations significantly impact crop productivity, highlighting the need for optimised planting dates and cultivar selection. This study, conducted during 2020–22 in Mobarakeh, Iran, aimed to assess the effects of planting dates and cultivars on physiological indices and grain yield of wheat (*Triticum aestivum* L.). The experiment followed a split-plot design (SPD) with three replications having planting dates (early: October 20, normal: November 20, late: December 20) as a main factor and six wheat cultivars [Zare and Heydari (winter type), Pishgam and Alvand (intermediate type) and Sirvan and Pishtaz (spring type)] were considered as the sub-factor. The results indicated that delayed planting (December 20) significantly decreased leaf nitrogen (by 12% approx.) and phosphorus content. Physiological assessments, including leaf relative water content (RWC) measured by the standard fresh/turgid/dry weight method, revealed that delayed planting significantly decreased RWC (from about 77% to 69%) and radiation use efficiency (by 25–27%), while increasing ion leakage (up to 38.8% in winter types) and light extinction coefficient. Photosynthetic rates were highest in winter cultivars when sown early (up to 7.22 μmol/m^2/sec) but spring cultivars (Sirvan and Pishtaz) performed better under late sowing (up to 6.10 μmol/m^2/sec). As a result, grain yield was significantly reduced by late sowing. Winter and intermediate cultivars had the highest yields when sown early (up to 6,535 kg/ha), while spring types showed more adaptability to late planting, maintaining relatively stable yields. Therefore, early sowing (October 20) is recommended for maximising grain yield, particularly for winter and intermediate wheat cultivars. For scenarios where late planting is unavoidable, the use of spring-type cultivars (Sirvan and Pishtaz) is suggested as a practical strategy to mitigate yield losses and enhance the resilience of wheat production systems under variable climatic conditions.

Keywords: Chlorophyll content, Growth type, Harvest index, Seed yield

Maintaining agricultural productivity alongside environmental sustainability is a paramount concern, especially within the context of climate change and a growing global population (Shah and Wu 2019). Among the most effective approaches to address this challenge is bolstering genetic diversity and refining crop management strategies to enhance resilience to environmental stressers (Kahiluoto *et al.* 2019). Studies demonstrate that climate variability profoundly influences plant development, presenting substantial obstacles to sustainable food production systems (Ur Rahman *et al.* 2019). As a result, investigating the interactive effects of climate change, agronomic practices and genotype selection has emerged as a critical research focus (Gray *et al.* 2016).

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Among the numerous factors that govern crop yield, selecting an optimal sowing window is crucial for maximising final productivity. Postponed planting often leads to diminished yield potential, as crops become more vulnerable to unfavourable weather conditions, especially variations in temperature and water scarcity (Shah *et al.* 2020). Thus, pinpointing the ideal sowing period is essential for unlocking the growth and yield capacity of diverse wheat cultivars (Kamara *et al.* 2009). Due to the heterogeneity of climatic patterns across regions, identifying the most appropriate sowing time is indispensable for achieving consistent wheat output (Wu *et al.* 2017).

Wheat (*Triticum aestivum* L.) is one of the most widely grown crops worldwide, cultivated on approximately 216 mha. It achieves an average global yield of 3.5 t/ha, contributing to an annual production of 765 mt (FAOSTAT 2019). Adopting enhanced agronomic strategies such as optimised sowing timetables, use of stress-tolerant varieties, judicious fertiliser application and effective water management can help counter these setbacks (Hatfield

and Dold 2018). Assessing physiological reactions across varying sowing environments remains vital for refining wheat output (Flohr *et al.* 2018). In recent decades, breeding initiatives have prioritised creating high-yielding varieties capable of thriving under diverse environmental stresses (Hunt 2017). Research affirms that sowing date substantially affects both yield quantity and quality, underscoring the importance of location-specific planting recommendations (Kamara *et al.* 2009).

Given the significant impact of planting date on wheat yield, it is essential to examine how various cultivars perform under different sowing schedules. This study evaluates the physiological traits and grain yield of wheat cultivars with distinct growth habits across multiple planting dates. By identifying cultivar-specific optimal sowing times, this research aims to offer actionable strategies to enhance wheat productivity under diverse environmental conditions.

MATERIALS AND METHODS

Experimental site, design and treatments: The experiment was conducted during two successive growing seasons (2020–21 and 2021–22) in Mobarakeh (32°34′N, 51°49′E; 1,680m amsl), Iran. The experimental site has a semi-arid climate with hot summers and cold winters. The experimental trial was laid out in a split-plot design with three replications. The main plot factor comprised of three sowing dates i.e. early (October 20), normal (November 20) and late (December 20). The sub-plot factor involved six wheat cultivars exhibiting distinct growth habits: *'Zare'* and *'Heydari'* (winter types), *'Pishgam'* and *'Alvand'* (intermediate types) and *'Sirvan'* and *'Pishtaz'* (spring types).

Field preparation and agronomic practices: The experimental field had silty loam soil with *p*H 7.8, EC was 1.3 and 1.2 dS/m, organic carbon was 0.87% and 0.91%, total neutralizing value was 28% and 30%, nitrogen content was 0.09% and 0.06% as well as 9.3 and 10.2 mg/kg phosphorous, 168 and 182 mg/kg potassium, 4.1 and 3.6 mg/kg manganese, 5.4 and 4.7 mg/kg iron, 2.1 and 1.6 mg/kg copper and 1.9 and 2.2 mg/kg zinc during 2020–21 and 2021–22, respectively. Field preparation involved ploughing using a reversible plough and subsequent leveling operations. Fertiliser application was done according to the results of soil analysis and included 100 kg/ha of triple superphosphate, 100 kg/ha of potassium sulfate and 100 kg/ha of urea prior to planting. Supplemental urea fertilisation (200 kg/ha) was administered during both stem elongation and anthesis growth stages. Micronutrients (iron, zinc and manganese) were delivered via foliar spraying at a 0.2% concentration during early stem elongation and heading phases (Attarzadeh *et al.* 2019). The meteorological conditions during the two growing seasons (2020–21 and 2021–22) were obtained from the Mobarakeh synoptic station (Table 1).

Individual experimental units measured 5 m × 2 m, each containing eight parallel planting rows with 25 cm inter-row spacing. A 50 cm isolation buffer was maintained between subplots, with 1 m separations between main plots. Seeding rates were calibrated according to the 1,000 kernel weight of each cultivar to achieve a uniform density of 400 seeds/m^2. Post-sowing irrigation was applied immediately and standardised agronomic management protocols, encompassing pest, disease and weed control, were consistently implemented throughout the trial. To reduce potential edge effects, border rows and a 50 cm perimeter from each plot's edges were excluded during data collection. Following parameters were measured during the course of experimentation:

Leaf nutrient content: Leaf nutrient analysis for nitrogen, phosphorus and potassium began by sampling foliar tissues. The samples were washed with deionised water and dried at 70°C for 48 h. Following this, 1g portions of the dried material were ashed at 500°C and then extracted. Phosphorus was quantified using the molybdate-vanadate colorimetric protocol with absorbance measured at 420nm. Potassium was determined using flame photometry and nitrogen content was assessed using the standardised Kjeldahl methodology (Attarzadeh *et al.* 2019).

Physiological traits: Ion leakage was evaluated according to the protocol established by Sairam *et al.* (2009). For leaf relative water content (RWC) determination, three fully expanded young leaves were selected per treatment before sunrise. Initial fresh weight (FW) was recorded, followed by a 12 h saturation period in distilled water at 25°C to establish turgid weight (TW). Samples were then oven-dried at 70°C for 24 h to determine dry weight (DW). RWC was calculated according to Weatherley (1950) using the formula:

$$\text{RWC (\%)} = \frac{\text{FW} - \text{DW}}{\text{TW} - \text{DW}} \times 100$$

Where RWC, Relative water content; FW, Initial fresh weight; DW, Dry weight; TW, Turgid weight.

Photosynthetically active radiation (PAR) was quantified at flowering stage using a LI-191SA quantum sensor. The light extinction coefficient was derived through the Monsi and Saeki (1953) methodology. Daily solar radiation was estimated via the Angstrom equation, with the photosynthetically active component calculated as 48% of total solar radiation (Monteith 1972, Pradhan *et al.* 2014). Photosynthetic rates were measured at anthesis between 10:00 AM and 02:00 PM using an LCA4-002 photosynthesis system on the youngest fully expanded leaves.

Growth and yield components: Leaf area index (LAI) was measured using a CI-202 leaf area meter and calculated as the ratio of total leaf surface area to ground area (Arshad *et al.* 2016). Biomass yield was assessed by harvesting all plants within a designated 1 m^2 sampling area and grain yield was determined after adjusting to a standardised 12% moisture content.

Statistical analysis: Statistical analysis was conducted using SAS software (version 9.1). Treatment effects were evaluated through analysis of variance (ANOVA) and mean comparisons were conducted using Duncan's multiple range test at the 5% significance level.

Table 1 Monthly meteorological data during the wheat growing seasons (2020–21 and 2021–22) at Mobarakeh station

Month	Year 2020–21				Year 2021–22			
	T max (°C)	T min (°C)	T mean (°C)	Precipitation (mm)	T max (°C)	T min (°C)	T mean (°C)	Precipitation (mm)
October	28.3	7.3	17.8	0.0	28.3	7.3	17.8	0.0
November	22.6	3.4	13.0	0.0	22.6	3.4	13.0	0.0
December	14.3	-2.5	5.9	6.6	14.3	-2.5	5.9	6.6
January	14.2	-2.9	5.6	3.2	14.2	-2.9	5.6	3.2
February	14.8	-1.4	6.7	14.9	14.8	-1.4	6.7	14.9
March	19.1	3.6	11.3	11.2	19.1	3.6	11.3	11.2
April	24.5	10.5	17.5	26.8	24.5	10.5	17.5	26.8
May	33.2	16.6	24.9	8.4	33.2	16.6	24.9	8.4
June	33.2	16.6	24.9	0.0	33.2	16.6	24.9	0.0

T min, Minimum temperature; T mean, Mean value of the temperature; T max, Maximum temperature. Data extracted from synoptic station of Mobarakeh, Iran.

Table 2 Analysis of variance for the effects of planting date and cultivar on the amount leaf elements, ion leakage and relative water content of wheat

Year	Source of variation	df	Leaf N	Leaf P	Leaf K	Ion leakage (%)	Relative water content (%)
2020–21	Replication	2	0.146^{ns}	0.0002^{ns}	0.237^{ns}	7.28^{ns}	108.63^{ns}
	Planting date	2	0.260^{*}	0.001^{*}	0.033^{ns}	101.22^{**}	361.98^{*}
	Error 1	4	0.053	0.0002	0.010	3.76	40.78
	Cultivar	5	0.000^{ns}	0.0001^{ns}	0.025^{ns}	7.38^{**}	19.86^{ns}
	Interaction	10	0.000^{ns}	0.0001^{ns}	0.005^{ns}	20.54^{**}	11.85^{ns}
	Error 2	30	0.031	0.0001	0.015	1.03	23.37
	CV (%)		9.00	5.62	9.49	13.59	6.54
2021–22	Replication	2	0.036^{ns}	0.000005^{ns}	0.203^{ns}	13.35^{ns}	90.01^{ns}
	Planting date	2	0.394^{*}	0.001^{*}	0.075^{ns}	317.55^{**}	302.19^{*}
	Error 1	4	0.079	0.00009	0.117	15.14	16.87
	Cultivar	5	0.003^{ns}	0.0001^{ns}	0.043^{ns}	11.02^{**}	21.10^{ns}
	Interaction	10	0.012^{ns}	0.00005^{ns}	0.021^{ns}	13.35^{**}	15.53^{ns}
	Error 2	30	0.021	0.0001	0.038	2.38	14.44
	CV (%)		7.46	5.73	15.62	15.02	5.17

*, Significant at 5% error probability; **, Significant at 1% error probability; ns, Non significant.

RESULTS AND DISCUSSION

Leaf nutrient content and water status: Delayed planting led to a marked decrease in leaf nitrogen and phosphorus content (Table 2), likely due to shortened vegetative growth and limited root development under cooler soil temperatures, which restricted nutrient uptake (Bagheri and Balouchi 2013, Mohammadghasemi *et al.* 2021). The highest nitrogen and phosphorus levels were recorded in the October 20 planting, with no significant difference between October 20 and November 20. In contrast, potassium content remained unaffected across planting dates or cultivar types, indicating that potassium dynamics were less sensitive to planting date variations (Table 2).

Water status indicators showed a similar trend. Relative water content was significantly higher in early-sown plants and declined as planting was delayed. Leaf relative water content decreased with delayed planting. The highest water retention was seen in plants sown on October 20, while those planted on December 20 had the lowest values. There were no significant differences between October 20 and November 20 in terms of water content (Table 3). Simultaneously, ion leakage increased with delayed sowing,

Table 3 Comparison of mean interactions of planting date on leaf N, leaf P, relative water content and radiation use efficiency of wheat (2020–21 and 2021–22)

Planting dates	Leaf N (%)		Leaf P (%)		Relative water content (%)		Radiation use efficiency (g/MJ)	
	2021–22	2020–21	2021–22	2020–21	2021–22	2020–21	2021–22	2020–21
October 20	0.415^{a}	0.410^{a}	76.20^{a}	77.43^{a}	0.197^{a}	0.200^{a}	2.13^{a}	2.10^{a}
November 20	0.382^{a}	0.354^{b}	75.44^{a}	75.45^{a}	0.190^{ab}	0.197^{a}	1.94^{ab}	1.97^{ab}
December 20	0.310^{b}	0.298^{c}	68.75^{b}	68 86^{b}	0.182^{b}	0.181^{b}	1.83^{b}	1.86^{b}

Means followed by the same letters in each column are not significantly different by Duncan test at 5% probability level.

reflecting increased damage to cell membranes. The lowest leakage was observed in winter and intermediate cultivars (*'Zare', 'Heydari', 'Pishgam'* and *'Alvand'*) under early sowing, whereas spring cultivars (*'Sirvan'* and *'Pishtaz'*) exhibited higher leakage levels under the same conditions. However, in the December 20 planting, spring cultivars showed relatively lower leakage than winter types (Table 4). These observations are consistent with Kamaei *et al.* (2019), who reported greater cellular stability under optimal planting times and confirm that early sowing enhances plant water balance and membrane integrity (Khichar and Niwas 2006).

Light interception and photosynthesis efficiency: Planting date significantly affected canopy light absorption characteristics. The extinction coefficient increased with delayed sowing, especially in winter and intermediate cultivars under the December 20 planting (Table 5). In the November 20 treatment, the lowest extinction coefficient was recorded in the *'Pishtaz'* cultivar. These findings suggest that canopy architecture becomes less efficient in intercepting light as planting is delayed, which is consistent with previous findings by Lake and Sadras (2017).

Radiation use efficiency (RUE) declined under late sowing conditions. Compared to the October 20 planting, RUE dropped by approximately 27% in 2020–21 and

Table 4 Comparison of mean interactions of planting date and cultivar on ion leakage, radiation extinction coefficient, photosynthetic rate and leaf area index of wheat

Planting date	Cultivar	Ion leakage (%)		Radiation extinction coefficient		Photosynthetic rate (µmol/m^2/sec)		Leaf area index	
		2021–22	2020–21	2021–22	2020–21	2021–22	2020–21	2021–22	2020–21
October 20	*Zare*	3.05^{a}	3.11^{a}	6.75^{a}	7.20^{a}	0.530^{e}	0.527^{f}	27.8^{c}	26.0^{ef}
	Heidari	3.02^{a}	3.10^{a}	6.78^{a}	7.22^{a}	0.525^{e}	0.540^{f}	28.4^{bc}	26.7^{ef}
	Pishgam	3.00^{a}	3.01^{ab}	6.67^{a-c}	7.10^{a}	0.529^{e}	0.536^{f}	27.7^{c}	26.2^{ef}
	Alvand	3.02^{a}	3.05^{ab}	6.67^{a-c}	7.06^{a}	0.518^{e}	0.526^{f}	27.8^{c}	25.6^{f}
	Sirvan	3.00^{a}	2.98^{b}	6.68^{ab}	6.82^{ab}	0.516^{e}	0.536^{f}	28.6^{bc}	29.0^{cd}
	Pishtaz	3.03^{a}	2.98^{b}	6.67^{a-c}	6.83^{ab}	0.532^{e}	0.527^{f}	28.7^{bc}	29.6^{c}
November 20	*Zare*	2.77^{b}	2.87^{c}	6.14^{de}	6.44^{a-c}	0.621^{d}	0.625^{d}	28.3^{bc}	27.2^{d-f}
	Heidari	2.75^{b}	2.83^{c}	6.28^{d}	6.48^{a-c}	0.616^{d}	0.627^{d}	29.0^{bc}	26.7^{ef}
	Pishgam	2.78^{b}	2.88^{c}	6.34^{b-d}	6.48^{a-c}	0.618^{d}	0.629^{d}	28.6^{bc}	26.6^{ef}
	Alvand	2.78^{b}	2.80^{c}	6.32^{cd}	6.53^{a-c}	0.613^{d}	0.624^{d}	27.9^{c}	26.3^{ef}
	Sirvan	2.74^{bc}	2.77^{cd}	6.30^{d}	6.9^{a-c}	0.619^{d}	0.609^{de}	28.2^{bc}	26.0^{ef}
	Pishtaz	2.75^{bc}	2.79^{c}	6.34^{b-d}	6.47^{a-c}	0.624^{d}	0.590^{e}	28.4^{bc}	27.4^{d-f}
December 20	*Zare*	2.52^{e}	2.40^{h}	5.18^{g}	5.09^{e}	0.729^{ab}	0.747^{a}	38.8^{a}	35.0^{a}
	Heidari	2.52^{e}	2.40^{h}	5.27^{g}	5.13^{e}	0.735^{a}	0.741^{ab}	38.6^{a}	35.2^{a}
	Pishgam	2.64^{d}	2.58^{fg}	5.69^{f}	5.84^{c-e}	0.705^{b}	0.712^{bc}	36.4^{a}	30.3^{bc}
	Alvand	2.64^{d}	2.55^{g}	5.73^{f}	5.85^{c-e}	0.704^{b}	0.703^{c}	37.2^{a}	31.4^{b}
	Sirvan	2.67^{cd}	2.67^{ef}	5.93^{ef}	6.09^{b-d}	0.660^{c}	0.641^{d}	31.2^{b}	27.7^{d-f}
	Pishtaz	2.64^{d}	2.68^{de}	5.69^{de}	6.10^{b-d}	0.660^{c}	0.643^{d}	31.2^{b}	26.5^{ef}

Means followed by the same letters in each column are not significantly different by Duncan test at 5% probability level.

Table 5 Analysis of variance for the effects of planting date and cultivar on the physiological and yield indices of wheat

Year	Source of variation	df	Radiation extinction coefficient	Radiation use efficiency (g/MJ)	Photosynthetic rate (μmol/m^2/sec)	Leaf area index	Biological yield (kg/ha)	Seed yield (kg/ha)
2020–21	Replication	2	0.004*	0.010 ^{ns}	0.292 ^{ns}	0.026 ^{ns}	1.12**	0.04**
	Planting date	2	0.123**	0.056*	8.280*	1.047*	0.16**	0.05**
	Error 1	4	0.0003	0.003	0.802	0.085	0.007	0.001
	Cultivar	5	0.003**	0.0002 ^{ns}	0.179 ^{ns}	0.003 ^{ns}	0.023ns	0.019**
	Interaction	10	0.001**	0.0006 ^{ns}	0.523*	0.026*	0.037**	0.008**
	Error 2	30	0.0003	0.0003	0.198	0.003	0.011	0.002
	CV (%)		9.08	5.45	7.02	12.03	8.83	9.89
2021–22	Replication	2	0.001 ^{ns}	0.004 ^{ns}	0.189 ^{ns}	0.047 ^{ns}	0.019^{ns}	0.002^{ns}
	Planting date	2	0.136**	0.014*	4.838*	0.078**	0.038*	0.021**
	Error 1	4	0.002	0.004	0.293	0.016	0.01	0.006
	Cultivar	5	0.001**	0.001 ^{ns}	0.195 **	0.003 ^{ns}	0.025*	0.004ns
	Interaction	10	0.001**	0.002 ^{ns}	0.150**	0.005**	0.018*	0.006*
	Error 2	30	0.0002	0.0005	0.035	0.001	0.009	0.002
	CV (%)		12.47	6.07	9.03	11.56	8.35	8.44

ns, Not-significant; *, Significant at 5%; **, Significant at 1% error probability. Means followed by the same letters in each column are not significantly different by Duncan's multiple range test at 5% probability level.

25% in 2021–22 in the December 20 treatment (Table 5), confirming reduced efficiency in converting intercepted light into biomass. These results align with Richards *et al.* (2020), who reported that delayed planting decreases the duration of photosynthetically active leaf area and limits radiation capture.

Photosynthetic rate varied by both planting date and cultivar. Winter cultivars exhibited the highest rates under the October 20 planting, while no significant differences were observed among cultivars in the November 20 sowing (Table 5). Interestingly, in the December 20 treatment, spring cultivars (*'Sirvan'* and *'Pishtaz'*) showed superior photosynthetic performance, suggesting better adaptation to shortened growth periods and late-season stress (Mubvuma *et al.* 2021). The superior performance of spring cultivars under late sowing conditions can be attributed to their phenological escape mechanism. Spring-type wheats have a shorter vegetative phase and accelerated reproductive development, allowing them to complete grain filling before the onset of terminal heat stress (Mubvuma *et al.* 2021). Furthermore, the source-sink dynamics in spring cultivars enable more efficient re-mobilisation of pre-anthesis assimilates to the developing grains under stress conditions, partially compensating for the reduced photosynthesis duration (Richards *et al.* 2020).

Growth parameters and yield components: Leaf area index (LAI) declined significantly with delayed sowing, especially in winter cultivars (Table 4). Early planting resulted in maximum LAI across all cultivars, promoting greater light interception and canopy photosynthetic capacity. The reduced LAI under late sowing likely contributed to lower biomass accumulation and diminished yield potential, which is supported by Bhattacharya (2018). The observed 25–27% reduction in RUE under late sowing conditions could be partially mitigated through agronomic interventions. Increasing seeding density from 400 to 500 seeds/m² in late-planted wheat can compensate for reduced tillering and LAI (Shah *et al.* 2020). Similarly, split application of nitrogen fertiliser, with a higher proportion applied at stem elongation, can improve nitrogen uptake efficiency and delay leaf senescence, thereby maintaining photosynthetic activity during grain filling (Ullah *et al.* 2019). These complementary strategies could offset the yield penalties associated with delayed sowing.

Biological yield followed a similar trend, with the highest values recorded under early sowing and the lowest in the December 20 treatment. Winter cultivars were more adversely affected by late sowing than spring cultivars, accumulating less biomass due to their longer vegetative requirements. Grain yield was also significantly reduced with delayed planting. Winter and intermediate cultivars achieved the highest yields when sown on October 20 or November 20, while spring cultivars performed better under late planting, achieving relatively stable yields despite the shortened growing period (Table 6). The slight variation in grain yield between the two growing seasons can be partly attributed to differences in meteorological conditions during the critical growth stages. For instance, the higher precipitation in April (26.8 mm) and May (8.4 mm) of the 2020–21 season compared to the 2021–22 season may have

Table 6 Analysis of variance for the effects of planting date and cultivar on the physiological and yield indices of wheat

Planting date	Cultivar	Seed yield (kg/ha)		Biological yield (kg/ha)	
		2021–22	2020–21	2021–22	2020–21
October 20	*Zare*	6,320^{a}	6,535^{a}	12,520^{b}	14,020^{a}
	Heidari	6,335^{a}	5,830^{b}	12,650^{b}	11,630^{cd}
	Pishgam	6,022^{a}	5,620^{bc}	12,720^{ab}	12,840^{b}
	Alvand	5,415^{b}	6,050^{ab}	11,430^{d}	13,040^{b}
	Sirvan	5,120^{c}	4,915^{c}	11,832^{cd}	12,220^{c}
	Pishtaz	5,820^{ab}	5,040^{c}	13,330^{a}	12,925^{b}
November 20	*Zare*	5,220^{c}	5,930^{b}	10,340^{ef}	12,930^{b}
	Heidari	5,425^{bc}	6,025^{ab}	10,725^{e}	13,300^{ab}
	Pishgam	6,108^{a}	5,520^{bc}	13,035^{a}	13,730^{a}
	Alvand	6,320^{a}	6,108^{b}	12,210^{bc}	13,140^{b}
	Sirvan	6,110^{a}	5,130^{c}	12,908^{ab}	11,320^{d}
	Pishtaz	5,720^{bc}	4,640^{c}	11,910^{c}	12,125^{c}
December 20	*Zare*	3,512^{d}	4,710^{d}	10,800^{e}	10,808^{e}
	Heidari	4,320^{cd}	5,110^{cd}	12,300^{b}	12,308^{b}
	Pishgam	5,410^{bc}	5,024^{c}	11,110^{de}	11,625^{cd}
	Alvand	5,400^{bc}	5,320^{c}	11,300^{d}	11,310^{d}
	Sirvan	4,320^{cd}	5,116^{cd}	11,200^{d}	11,235^{d}
	Pishtaz	5,115^{cd}	5,720^{ab}	12,200^{bc}	12,205^{bc}

Means followed by the same letters in each column are not significantly different by Duncan test at 5% probability level.

contributed to improved grain filling and higher yields in the first year (Table 1). These results are in line with previous studies showing that late sowing exposes wheat to terminal heat stress and reduces grain filling duration (Hu and Wiatrak 2012, Dai *et al.* 2017).

Practical implications for wheat cultivation: Overall, these findings reinforce the importance of optimising planting dates to enhance wheat physiological performance and yield. Early sowing promotes better nutrient uptake, water retention, photosynthetic efficiency and biomass accumulation, ultimately leading to higher grain production. However, when late sowing is unavoidable due to climatic or logistical constraints, selecting cultivars with flexible growth habits, particularly spring or intermediate types, can help mitigate yield losses. Furthermore, improved agronomic management practices, including precise fertilisation and irrigation scheduling, may further enhance performance across different sowing windows (Ullah *et al.* 2019).

This study demonstrated that planting date plays a critical role in determining the physiological performance and yield potential of wheat cultivars with different growth habits. Delayed planting resulted in reduced nutrient uptake, lower relative water content, increased ion leakage and a decline in radiation use efficiency, all of which contributed to a significant reduction in grain yield. The negative effects of late sowing were more pronounced in winter cultivars due to their longer growth cycle, whereas spring cultivars exhibited better adaptation to delayed planting.

The findings emphasised the importance of early planting in maximising yield potential, particularly for winter wheat varieties. However, in conditions where late sowing is necessary, the use of intermediate or spring cultivars can help mitigate yield losses. The integration of effective agronomic management practices, including optimised fertilisation, irrigation scheduling and appropriate cultivar selection, is essential for enhancing wheat productivity under different planting scenarios. Future research should focus on the development of wheat cultivars with enhanced adaptability to fluctuating planting dates, particularly under changing climate conditions. Additionally, further investigations on the physiological mechanisms underlying wheat responses to late planting can provide valuable insights for breeding programmes and sustainable wheat production strategies.

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