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Research Article

EVALUATION OF COMMERCIAL WHEAT VARIETIES FOR YIELD AND RESISTANCE TO LEAF RUST UNDER VARYING SOWING DATES

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ABSTRACT

To determine the effects of different planting dates and heat stress on yield and associated traits of 10 wheat varieties from Sindh, as well as their resistance to leaf rust disease, a study was conducted at the Experimental Farm of the Nuclear Institute of Agriculture, Tandojam, Pakistan, during the 2023-24 wheat season. The experiment was carried out under three different planting dates: early (8th November), normal (25th November), and late (10th December). The results indicated that the mean squares for genotypes, sowing dates, and genotype × sowing date interaction were highly significant ($P \leq 0.001$) for various traits. A linear decline in all traits was observed with delayed planting, including days to booting, days to heading, days to maturity, grain filling period, plant height, spike length, spikelets per spike, number of grains per spike and main spike yield. The late-planted trial suffered severe leaf rust infestation. The highest disease severity was recorded in the varieties TD-1, SKD-1, and TJ-83. Early planting led to better performance, with varieties producing the longest spike (14.1 cm), the highest number of spikelets per spike (20.1), the greatest number of grains per spike (60.6) and the maximum main spike yield (2.59 g) compared to normal and late planting. The varieties Sassui and Bakhtawar showed resistance to leaf rust while most other varieties were moderately susceptible to susceptible. The study concludes that early planting of wheat is recommended to achieve higher grain yield and to escape leaf rust disease.

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INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the major staple food crops globally, with nearly 40% of the world's population depending on its production (Gupta et al., 2008). The wheat crop is highly sensitive to elevated temperatures (Satorre and Slafer, 2024) and various researchers have reported increasing temperature trends in major wheat-producing regions (Alexander et al., 2006; Hennessy et al., 2008). Wheat is affected by heat stress at various phenological stages, with the reproductive phase being the most vulnerable, leading to a direct reduction in dry matter accumulation and grain formation (Wheeler et al., 1996). Terminal heat stress is expected to intensify in wheat-growing areas in the coming years (Mitra and Bhatia, 2008; Semenov, 2009).

By the end of the current century, global climate models predict a rise in mean ambient temperatures ranging from 1.8°C to 5.8°C (IPCC, 2007). Increased temperature variability, along with a higher frequency of hot days, is expected to significantly affect future climatic conditions (Pittock et al., 2003). Therefore, it is essential to understand how plants respond to elevated temperatures and how heat tolerance can be enhanced (Halford, 2009). Plants perceive increased temperatures through changes in protein structure, metabolic disturbances, cytoskeletal organization, and membrane fluidity (Ruelland and Zachowski, 2010). These changes trigger adaptive responses, including the production of heat shock proteins. Temperatures exceeding the optimal range for plant growth can be detrimental, leading to irreversible damage referred to as heat stress (Wahid et al., 2007).

Sowing date is one of the major factors responsible for yield reduction, followed by the selection of undesirable genotypes, non-significant seeding rates, unsuitable crop geometry and inappropriate soil texture. Alam et al. (2013) reported higher grain yield potential in wheat when sown on November 25 compared to later sowing dates, as earlier planting allowed more time for physiological maturity. Valizadeh et al. (2014) recorded a final yield reduction in wheat ranging between 1% and 37%. Sohail et al. (2014) observed about a 29% decrease in crop production due to late planting. Mumtaz et al. (2015) reported the highest 1000-grain weight, number of grains per spike, and overall grain yield when the crop was planted early compared to late sowing.

Wheat crop produced the highest yield when sown on November 1, as noted by Shahzad et al. (2002) and Yadav et al. (2018). Similarly, Ejaz et al. (2003) and Tanveer et al. (2009) observed that wheat cultivars sown in the last week of October or the first week of November performed better and produced maximum yields. They also reported that each day of delay in planting after mid-November resulted in an approximate 1% reduction in crop yield. Subhan (2003) and Qasim et al. (2008) concluded that, compared to early or late sowing, optimal grain yield was achieved with normal sowing around November 15.

Late-sown wheat is prone to yield reduction (Farooq et al., 2008) due to a shortened tillering period and an increased risk of high temperatures during the sensitive grain formation stage (Hays et al., 2007). Late planting adversely affects grain yield and can cause significant losses in 1000-grain weight (Mumtaz et al., 2015). A reduction in test weight is also recorded due to delayed planting (Eslami et al., 2014). Wheat sown late is often forced to mature early by desiccating winds and the high temperatures of April, which is a major cause of reduced test weight (Tomar et al., 2014; Kaur, 2017). During the post-anthesis stage of late-planted wheat, elevated temperatures shorten the grain filling period, leading to increased protein content, reduced grain weight and smaller endosperm size (Ahmad et al., 2015). Regulating the planting time to an optimal date can help mitigate the adverse effects of heat stress. Numerous studies have confirmed the detrimental effects of delayed planting on wheat crop performance (Wajid et al., 2002; Kumar and Sharma, 2003; Subhan, 2003; Qamar, 2004; Qasim et al., 2008; Mumtaz et al., 2015; Kamboj et al., 2022).

Several wheat pathogens cause significant yield losses (Mehboob et al., 2014; Mukhtar et al., 2018; Ahmad et al., 2024; Mukhtar and Saeed, 2024) with rust diseases being among the major constraints in wheat production worldwide. Leaf rust, in particular, is considered the most frequently occurring and potentially the most damaging, leading to substantial grain yield losses (Herrera-Foessel et al., 2006). The disease reduces the number of grains per spike and decreases kernel weight. Kolmer et al. (2005) and Huerta-Espino et al. (2011) reported average yield losses for slow-rusting, race-specific, and susceptible genotypes under both normal and late planting conditions. Yield losses due to early infection can range from 30-50%, depending on the cultivar (McIntosh et al., 1995). The most effective and economical strategy for managing leaf rust is the use of resistant cultivars.

The present study was conducted to evaluate the performance of ten different wheat cultivars for resistance against various diseases and tolerance to heat stress. The screening aimed to identify genotypes suitable for early, normal, and late sowing conditions to ensure high productivity. The response of wheat to elevated temperatures during grain filling and reproductive stages was also assessed to explore potential for improving heat tolerance. High-yielding and disease-resistant cultivars under early, normal, and late sowing conditions will be selected for further breeding and improvement to achieve the desired goals.

MATERIALS AND METHODS

Experimental materials

Ten commercial bread wheat (*Triticum aestivum* L.) varieties, namely Sarsabz, Kiran, Khirman, SKD-1, NIA-Saarang, TD-1, TJ-83, Sassui, NIA-Amber and Bakhtawar, were sown at three different planting dates: November 8, 2023 (early), November 25, 2023 (normal) and December 10, 2023 (late), at the research fields of the Nuclear Institute of Agriculture (NIA), Tandojam, Sindh, during the 2023-24 cropping season.

Experimental design

The experiment was conducted in a randomized complete block design (RCBD) with four replications. Each plot consisted of two rows, each 2 m long, with an inter-row spacing of 30 cm. A seeding rate of 50 kg/ha was used for each planting date. Meteorological data were recorded throughout the cropping season. Two rows of a susceptible check variety (Morocco) were sown to ensure uniform disease infection.

Disease assessment

All experimental fields experienced natural infection due to high inoculum pressure in the area, which is common due to the continuous cultivation of wheat and favorable environmental conditions. Observations were initiated at the first appearance of pathogen infection on the susceptible check variety, Morocco. Leaf rust severity was assessed using the modified Cobb's scale (Peterson et al., 1948) and infection responses were recorded following the method described by Roelfs (1992). Reaction types (Table 1) were noted from the flowering to soft dough stages, as per Jin et al. (2007).

Data collection

To evaluate the influence of different planting dates on wheat growth and yield, data were recorded from the first week of November to the last week of March. Agronomic and yield-contributing traits recorded at each sowing date included days to booting, days to heading, days to maturity, grain filling period, plant height, spike length, number of spikelets per spike, number of grains per spike, and main spike yield.

Statistical analysis

The collected data were subjected to analysis of variance (ANOVA) using Statistix 8.1 software. Mean comparisons were conducted using Duncan's Multiple Range Test (DMRT) at a 5% level of significance (Duncan, 1955). ANOVA was performed for the eight agronomic and yield-related traits recorded for the ten wheat cultivars.

Table 1. Modified Cobb's scale (Peterson et al., 1948) used for the leaf rust disease data recording during present study.

Reaction	Infection type	Field response
No disease	0	No visible infection
Resistant	R	Necrotic areas with or without minute uredia
Moderately Resistant	MR	Small uredia present surrounded by necrotic area
Moderately resistant, moderately Susceptible	MRMS	Small uredia present surrounded by necrotic areas as well as medium uredia with no necrosis but possible some distinct chlorosis
Moderately susceptible	MS	Medium uredia with no necrosis but possible some distinct chlorosis
Moderately susceptible-susceptible	MSS	Medium uredia with no necrosis but possible some distinct chlorosis as well as large uredia with little or chlorosis present
Susceptible	S	Large uredia and little or no chlorosis present

RESULTS

The pooled analysis of variance for eight recorded traits is presented in Tables 2a and 2b. The results indicated that genotypes, sowing dates, and their interaction (genotype × sowing date) differed significantly ($P \leq 0.05$) for most of the traits assessed. The mean squares from the pooled ANOVA revealed highly significant differences among genotypes for days to booting, days to heading, days to maturity, plant height and number of grains per spike. Similarly, sowing dates exhibited significant variation for all traits. The genotype × sowing date interaction showed significant variability for days to booting, days to heading and plant height.

Table 2a. Pooled analysis of variance for various traits of wheat genotypes evaluated under different sowing dates.

Source of variation	D.F.	Mean square (MS)			
		Days to booting	Days to heading	Days to maturity	Grain filling period
Replications (R)	2	2.144	1.73	214.71	224.34
Genotypes (G)	9	124.03***	104.18***	71.27***	13.25
R × G	18	1.614	4.25	4.93	6.65
Sowing dates (SD)	2	939.07***	1159.6***	8503.14***	1528.41***
G × SD	18	27.69***	28.16***	14.92	30.53
R × G × SD	40	1.51	4.0	18.59	22.69
Total	89	--	--	--	--

* = Significant at P≥0.05. ** = Significant at P≥ 0.01. *** = Significant at P≥ 0.001.

Table 2b. Pooled analysis of variance for various traits of wheat genotypes evaluated under different sowing dates.

Source of variation	D.F.	Mean square (MS)				
		Plant height	Spike length	Spikelet per spike	Grains per spike	Main spike yield
R	2	15.48	30.21	1.87	17.73	0.896
G	9	684.52***	3.15*	3.12	87.52***	0.209*
R × G	18	24.28	1.206	3.65	11.24	0.089
SD	2	1380.74***	127.84***	162.71***	5500.3***	1.838***
G × SD	18	88.36***	2.31	6.48*	36.81*	0.203***
R × G × SD	40	24.02	2.14	3.07	15.99	0.05
Total	89	--	--	--	--	--

*= Significant at P≤0.05. ** = Significant at P≤ 0.01. *** = Significant at P≤ 0.001.

Days to booting

Analysis of variance for days to 50% booting among 10 different wheat cultivars at three sowing dates (Table 3) revealed significant variation (P ≤ 0.05). A comparison of average days to booting showed that early sowing resulted in a significantly longer duration to reach 50% booting (mean ± SE = 72.2 ± days) compared to normal (68.1 ± days) and late (61.2 ± days) sowing. Under early sowing, days to 50% booting ranged from 66 days in SKD-1 to 82 days in Bakhtawar. Under normal sowing, the range was 59.6 days in TD-1 to 72 days in Bakhtawar, while under late sowing; it ranged from 56.0 days in Sarsabz to 64.6 days in Bakhtawar.

Days to heading

Analysis of variance for days to 50% heading at three different planting times also showed significant variability (P ≤ 0.05) among the 10 wheat varieties (Table 3). Mean comparison indicated that early sowing significantly prolonged the time to 50% heading (mean ± SE = 80.31 ± days) compared to normal (74.93 ± days) and late (67.9 ± days) sowing. Under early planting, days to heading ranged from 75 days in Sarsabz to 91 days in Bakhtawar. For normal planting, the range was 66 days in TD-1 to 78 days in NIA-Amber and Bakhtawar. Under late planting, heading occurred between 63 days in Sarsabz and 72 days in Bakhtawar.

Days to maturity

Analysis of variance revealed significant differences (P ≤ 0.05) in days to maturity among 10 wheat genotypes across the three sowing dates (Table 3). Mean comparison showed that early sowing resulted in a significantly longer duration to maturity (mean ± SE = 129.9 ± days) compared to normal (111.7 ± days) and late (96.2 ± days) sowing. Under early sowing, days to maturity ranged from 125 days in SKD-1 to 138.6 days in Bakhtawar. For normal planting, maturity ranged from 108 days in Kiran to 116 days in Sassui, while under late sowing, it ranged from 93.3 days in Sarsabz to 99 days in Bakhtawar.

Grain filling period

Significant (P ≤ 0.05) variation was observed among the three sowing dates for the grain filling period (Table 4). Comparative mean values indicated that early sowing resulted in a significantly longer grain filling period for genotypes (mean ± SE = 49.6 ± days) compared to normal (48.3 ± days) and late sowing (36.6 ± days). Under early sowing, the grain filling period ranged from 46.3 days in 'Sassui' to 53 days in 'NIA Amber'. For normal sowing, it ranged from 30 days in 'Kiran' to 43 days in 'TD-1' while under late sowing it ranged from 45.6 days in 'TJ-83' to 53 days in 'Kiran'.

Plant height (cm)

Analysis of variance revealed significant ($P \leq 0.05$) differences in plant height among 10 wheat cultivars at three different sowing dates (Table 4). The results showed that early sowing resulted in significantly greater plant height for genotypes (mean ± SE = 91.6 ±) compared to normal (90.0 ± cm) and late sowing (79.5 ± cm). Under early sowing, plant height ranged from 64.6 cm in 'TD-1' to 101.6 cm in 'Sarsabz'. Under normal sowing, it ranged from 63 cm in 'TD-1' to 98.3 cm in 'Khirman' and 'NIA Saarang', while under late sowing it ranged from 71 cm in 'TD-1' to 86.3 cm in 'Kiran' and 'Khirman'.

Spike length (cm)

The results indicated that all 10 wheat genotypes differed significantly ($P \leq 0.05$) in spike length across the three sowing dates (Table 4). Mean comparisons showed that early sowing resulted in a significantly longer spike length (mean ± SE = 14.1cm ±) compared to normal (13.76 ± cm) and late sowing (10.3 ± cm). Under early sowing, spike length ranged from 12.8 cm in 'Bakhtawar' to 15.3 cm in 'SKD-1'. For normal sowing, it ranged from 12.2 cm in 'Sarsabz' to 15.1 cm in 'Sassui' while under late sowing it ranged from 8.6 cm in 'Sassui' to 12.2 cm in 'Kiran'.

Table 3. Overall comparison of different traits as affected by different planting times.

Genotypes	Days to booting			Days to heading			Days to maturity		
	Early	Normal	Late	Early	Normal	Late	Early	Normal	Late
Sarsabz	67.0 d	69.0 d	56.0 c	75.0 d	76.0 bc	63.0 g	127.0 cd	109.0 cd	93.3 d
Kiran	70.0 c	70.0 c	57.0 c	78.0 d	78.0 a	64.0 f	126.6 cd	108.0 d	97.0 b
Khirman	71.0 c	70.0 c	62.0 ab	78.0 d	75.3 c	70.0 c	129.0 bc	113.6 ab	97.3 b
SKD-1	66.0 d	62.0 f	58.0 c	75.6 d	70.0 d	66.0 e	125.0 d	109.0 cd	95.3 c
NIA-Saarang	70.6 c	69.0 d	61.3 b	79.0 cd	75.0 c	64.3 f	128.0 cd	111.6 bc	97.0 b
TD-1	66.6 d	59.6 g	63.0 ab	76.3 d	66.0 e	69.0 d	127.3 cd	109.0 cd	95.0 c
TJ-83	71.3 c	68.0 e	62.0 ab	79.6 cd	76.0 bc	69.0 d	127.6 cd	112.0 bc	94.6 c
Sassui	77.0 b	71.0 b	64.0 ab	86.0 ab	77.0 ab	71.0 b	132.3 b	116.0 a	97.3 b
NIA-Amber	81.0 a	71.0 b	64.0 ab	84.6 bc	78.0 a	71.0 b	137.6 a	115.6 a	97.0 b
Bakhtawar	82.0 a	72.0 a	64.6 a	91.0 a	78.0 a	72.0 a	138.6 a	113.6 ab	99.0 a
Mean	72.2 a	68.1 b	61.2 c	80.31 a	74.93 b	67.93 c	129.9 a	111.73 b	96.28 c
LSD (0.05)	1.916	0.313	3.13	5.8284	1.565	0.626	3.993	3.464	0.916

Means denoted by the same letters in a column are not significantly different among each other. *S.D = (sowing date) *S.D-1 = Early (8th November); S.D-2 = Normal (25th November); S.D-3 = Late (10th December).

Table 4. Overall comparison of different traits as affected by various planting times.

Genotypes	Grain filling period			Plant Height (cm)			Spike Length (cm)		
	Early	Normal	Late	Early	Normal	Late	Early	Normal	Late
Sarsabz	52.0 ab	50.3 b	33.0 de	101.6 a	90.0 a	79.3 ab	14.3 abc	12.2 c	9.7 cd
Kiran	48.6 ab	53.0 b	30.0 e	91.3 e	93.0 b	86.3 a	14.9 a	13.9 abc	12.2 a
Khirman	51.0 ab	47.3 d	36.3 bcd	101.0 a	98.3 a	86.3 a	14.3 abc	13.4 abc	9.3 cd
SKD-1	49.3 ab	49.3 c	39.3 b	80.0 f	78.6 c	76.0 ab	15.3 a	13.5 abc	10.2 bcd
NIA-Saarang	49.0 ab	52.6 a	36.6 bc	95.3 d	98.3 a	84.0 ab	14.1 abc	14.1 abc	11.8 ab
TD-1	51.0 ab	46.0 f	43.0 a	64.6 g	63.0 d	71.0 b	13.3 bc	13.9 abc	10.7 abc
TJ-83	48.0 ab	45.6 f	36.0 bcd	91.6 e	94.6 b	80.6 ab	13.1 bc	12.4 c	9.8 cd
Sassui	46.3 b	46.3 ef	39.0 bc	95.6 d	97.6 b	73.0 ab	14.1 abc	15.1 a	8.6 d
NIA-Amber	53.0 a	46.0 f	37.6 bc	98.3 b	93.6 b	77.6 ab	14.6 ab	14.4 ab	10.6 abc
Bakhtawar	47.6 ab	47.0 de	35.6 cd	97.0 c	93.0 b	81.3 ab	12.8 c	14.5 a	10.2 bcd
Mean	49.6 a	48.3 b	36.6 c	91.6 a	90.9 b	79.5 c	14.1 a	13.7 b	10.3 c
LSD (0.05)	6.37	3.51	0.80	1.09	2.24	14.2	1.61	2.03	1.76

Means denoted by the same letters in a column are not significantly different among each other *S.D= (sowing date) *S.D-1= Early (8thNovember); S.D-2=Normal (25thNovember); S.D-3=Late (10th December).

Spikelets per spike

Three different sowing dates showed significant differences (P ≤ 0.05) in the number of spikelets per spike (Table 5). The comparison of mean values revealed that early planting resulted in a significantly higher number of spikelets per spike (mean ± SE = 20.1 ±) compared to normal (18.4 ±) and late planting (15.5 ±). Under early planting, the number of spikelets per spike ranged from 17.3 in NIA-Saarang to 22.0 in Bakhtawar. For normal planting, it ranged from 16.6 in SKD-1 to 20.3 in Khirman, while under late planting, it ranged from 13.0 in Sassui to 17.6 in Kiran. The highest average number of spikelets per spike observed under early planting was significantly reduced with delayed sowing.

Number of grains per spike

Analysis of variance revealed significant differences (P ≤ 0.05) in the number of grains per spike among the three planting dates (Table 5). Mean comparisons indicated that early planting resulted in the highest number of grains per spike (mean ± SE = 60.66 ±), followed by normal (40.8 ±), and late planting (34.7 ±). Under early planting, the number of grains per spike ranged from 49.3 in Sassui to 67.0 in Bakhtawar. For normal planting, it ranged from 34.6 in Sassui to 47.3 in NIA-Saarang, while under late planting, it ranged from 31.3 in NIA-Amber to 37.6 in NIA-Saarang.

Main Spike Yield (g)

Mean comparisons for all sowing dates showed significant variations (P ≤ 0.05) in main spike yield (Table 5). Results indicated that early planting produced the highest main spike yield, particularly in the genotype Bakhtawar (mean ± SE = 2.17g ±), followed by NIA-Saarang under normal planting (2.0 ± g), while the lowest yields were recorded for Sarsabz and Khirman under late planting (1.83 ± g). Overall, main spike yield decreased significantly with delayed sowing. Genotypes Bakhtawar and SKD-1 performed better under early planting; NIA-Saarang and Bakhtawar performed well under normal planting; whereas Khirman, Kiran and SKD-1 produced maximum main spike yield under late planting.

Table 5. Overall comparison of different traits as affected by various planting times.

Genotypes	Spikelets per spike			Number of Grains per spike			Main Spike Yield (g)		
	Early	Normal	Late	Early	Normal	Late	Early	Normal	Late
Sarsabz	20.0 a	20.0 a	15.6 ab	57.3 bcd	35.3 ef	37.0 ab	1.83 b	1.97 a	1.51 cd
Kiran	21.0 a	18.6 bc	17.6 a	59.0 abcd	43.0 bc	33.0 d	2.07 ab	1.51 b	2.25 a
Khirman	20.3 a	20.3 a	15.3 abc	61.6 abc	43.3 bc	33.0 d	1.83 b	1.53 b	2.27 a
SKD-1	20.3 a	16.6 d	15.6 ab	55.6 cd	38.6 de	36.3 abc	2.38 ab	1.96 a	2.09 ab
NIA-Saarang	17.3 a	18.6 bc	17.0 a	68.0 a	47.3 a	37.6 a	2.22 ab	2.0 a	1.67 cd
TD-1	19.3 a	17.6 cd	16.6 a	65.0 abc	42.0 bc	35.0 c	2.24 ab	1.97 a	1.50 cd
TJ-83	19.3 a	18.6 bc	14.0 bc	63.0 abc	41.6 c	36.6 abc	2.35 ab	1.66 ab	1.48 cd
Sassui	20.0 a	19.3 ab	13.0 c	49.3 d	34.6 f	35.6 bc	2.27 ab	1.81 ab	1.75b cd
NIA-Amber	21.3 a	17.0 d	16.0 ab	60.6 abc	38.0 de	31.3 d	1.94 b	1.47 b	1.37 d
Bakhtawar	22.0 a	17.3 d	14.0 bc	67.0 ab	44.6 ab	32.0 d	2.59 a	1.98 a	1.78 bc
Mean	20.1 a	18.4 b	15.5 c	60.66 a	40.86 b	34.76 c	2.17	1.78	1.76
LSD (0.05)	4.69	1.61	2.45	10.56	2.954	1.709	0.55	0.34	0.39

Means denoted by the same letters in a column are not significantly different among each other *S.D= (sowing date) *S.D-1= Early (8thNovember); S.D-2=Normal (25thNovember); S.D-3=Late (10th December).

Leaf rust observations

Under natural field conditions, varying patterns of leaf rust occurrence and prevalence were recorded across three different planting dates (Table 6). Early-sown crops experienced less leaf rust infestation compared to late-sown ones. Field observations of commercial wheat varieties revealed that most were moderately susceptible, while the variety TD-1 was consistently susceptible to leaf rust at all three planting dates.

Across most sowing times, TD-1 exhibited a reduction in days to maturity, grain filling period, plant height, spike length, number of grains per spike and main spike yield due to its susceptibility to the disease. Among the ten commercial wheat varieties tested, Sassui and Bakhtawar showed resistance and performed better against leaf rust. Under early sowing conditions, Sassui exhibited a longer grain filling period and greater spike length while Bakhtawar produced a higher number of grains per spike and more spikelets per spike.

Under normal sowing, varieties such as Kiran, Khirman, and NIA-Saarang performed well, while under late sowing, Kiran and Sarsabz showed relatively better performance in various traits. Observations further revealed that SKD-1 and TJ-83 were moderately susceptible to susceptible, which negatively affected their agronomic performance.

Table 6. Leaf rust disease observations during the cropping season.

S. No.	Varieties	Early	Normal	Late
V1	Sarsabz	30 MS	60 MS	70 MS
V2	Kiran	20 MS	50 MS	70 MS
V3	Khirman	30 MS	50 MS	60 MS
V4	SKD-1	30 MS	50 MSS	60 MSS
V5	NIA-	20 MS	40 MS	60 MS
V6	TD-1	50 S	80 S	80 S
V7	TJ-83	40 MS	50 MSS	70 MSS
V8	Sassui	10 R	10 R	20 R
V9	NIA-	10 MS	30 MS	40 MS
V10	Bakhtawa	5 R	10 R	20 R
	Morocco	80 S	100 S	100 S

*Leaf rust data has two parts, first is severity percentage according to modifies Cobb's scale and second is response to infection; R = resistant, MR = moderately resistant, MS = moderately susceptible, MSS= moderately susceptible to susceptible and S = susceptible.

Thermal stress and meteorological data

Daily minimum and maximum temperature data were recorded throughout the cropping season (Figure 1). The mean temperature data indicated that the early-sown trial experienced comparatively favorable minimum temperatures ranging from 18.6°C to 22.6°C while the maximum temperature recorded was around 35°C. During the grain formation phase, the early-sown crop encountered minimum temperatures of around 14.17°C and maximum temperatures up to 35°C. The early trial benefited from a longer period for growth and development, allowing it to escape the adverse effects of high temperatures on most yield-related traits.

In the normally planted trial, mean temperatures ranged from a minimum of 20.25°C to a maximum of 31.5°C during the last week of November. Temperature fluctuations were observed throughout the season. From the third week of December to the first week of March, maximum temperatures gradually decreased and remained below 30°C, conditions considered suitable for wheat growth. However, in the fourth week of March, the temperature rose to 35°C, which adversely affected key phenological stages and yield-contributing traits, ultimately shortening the grain formation period.

The late-sown trial, planted in December, experienced minimum temperatures ranging from 10.17°C to 19.4°C and maximum temperatures from 23.0°C to 31.4°C. The late-planted wheat underwent forced maturity, which significantly reduced the grain filling period, resulting in poorly developed grains and a subsequent decrease in final grain yield. Delayed sowing was also more vulnerable to critical climatic conditions, leading to a reduction in most phenological stages and yield-related traits (Figure 1). Moreover, the delayed planting was affected by leaf rust infestation, which further contributed to a serious decline in yield-associated traits.

DISCUSSION

Among the various causes of low wheat yield, planting dates and genotype selection are of major significance. Seeding time is one of the key factors that can be managed by the grower and has a substantial impact on productivity (Sun et al., 2007; Yamin et al., 2021). Alterations in planting dates can affect yield by influencing spike growth duration, the number of spikes and tillers (Bassu et al., 2010), and kernel weight (Sun et al., 2007). Early planting provides a longer growing period, which promotes better kernel development.

However, planting too early may result in poor crop performance due to temperatures exceeding the optimum range, while delayed planting can significantly reduce yield (Sukhera et al., 2024). In contrast, timely sowing can enhance 1000-grain weight, grains per spike, spikelets per spike, plant height and seed germination (Talpur et al., 2024).

Delayed sowing forces the crop to complete all developmental stages in a shorter time (Khan et al., 2010) and increases the risk of winter injury (Joshi et al., 1992). This can lead to yield losses due to elevated temperatures during grain filling (Subedi et al., 2007; Riaz-ud-Din et al., 2010), a shortened spike growth period, increased spike sterility (Wheeler et al., 1996), delayed maturity (Slafer and Rawson, 1995) and overall yield reductions (Thiry et al., 2002; Chen et al., 2003; Guilioni et al., 2003; Sial et al., 2005), primarily due to accelerated phenological development (Singh and Pal, 2003).

Our findings revealed that all phenological and yield-contributing traits, such as days to booting, heading, maturity, grain formation duration, plant height, spike length, spikelets per spike, grains per spike and main spike yield, were significantly affected by delayed planting. These results are consistent with the findings of Irfaq et al. (2005), Sial et al. (2005), Subedi et al. (2007), Shahzad et al. (2007), Nahar et al. (2010), Hakim et al. (2012) and Munsif et al. (2015). However, some varieties that performed better under late sowing conditions exhibited significant tolerance to thermal stress and may be suitable for delayed planting. Severe yield losses due to delayed sowing were further exacerbated by leaf rust infestation (Farooq et al., 2008; Huerta-Espino et al., 2011).

Under early planting, the varieties SKD-1, Bakhtawar, and Sarsabz performed better, as indicated by their overall mean performance (Tables 2a and 2b). SKD-1 exhibited fewer days to booting and maturity and produced a higher number of spikes. Bakhtawar recorded more spikelets per spike, grains per spike and main spike yield while Sarsabz showed greater plant height and required fewer days to ear emergence.

In contrast, the varieties Kiran, TD-1 and NIA-Saarang were better suited for normal planting dates, based on their overall performance (Tables 2a and 2b). Kiran had a longer grain formation period, matured earlier and attained greater plant height. NIA-Saarang recorded the highest number of grains per spike, main spike yield and plant height. TD-1 showed the shortest time to booting and maturity.

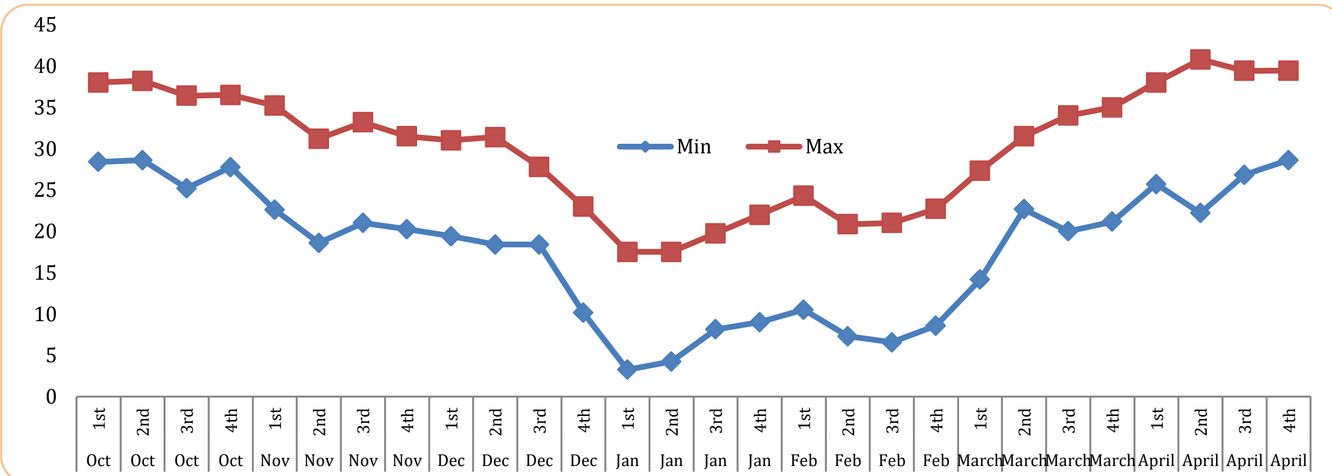

Figure 1. Meteorological data (minimum and maximum temperatures in °C) during the 2023-24 wheat cropping season at the NIA Tandojam experimental site.

Under delayed sowing, the varieties Sarsabz, Kiran and Khirman performed better in terms of various phenological and yield-related traits. Sarsabz exhibited fewer days to booting and ear emergence and ripened earlier. Kiran recorded the tallest plant height, the highest number of spikelets per spike and more spikes. Khirman also showed the highest plant height and produced the maximum main spike yield. The minimal differences observed in Sarsabz, Kiran, and Khirman under delayed sowing suggest that these varieties are less sensitive to thermal stress and are therefore most suitable for late sowing.

Except for Kiran, NIA-Saarang, TJ-83 and Sassui, plant height was reduced in most varieties under normal and late sowing compared to early sowing (Table 3), likely due to increased temperature stress (Munsif et al., 2015). Similarly, a reduction in spike length was observed in most varieties under normal and late sowing, except for TD-1, Sassui and NIA-Amber, as reported by Kasana et al. (2015). Spike length is a crucial trait for enhancing grain number and final yield (Ahmed et al., 2007).

Several researchers have reported that early-sown wheat cultivars produced a higher number of grains per spike compared to those sown late (Sial et al., 2005; Qasim et al., 2008; Sattar et al., 2010). A significant linear decrease in grains per spike under normal and late sowing was also observed by Sial et al. (2005). For main spike yield, Sarsabz performed better under normal planting conditions while Kiran, Khirman and SKD-1 recorded the highest main spike yields under late planting (Table 4). The adverse effects of delayed sowing on main spike yield were similarly reported by Sial et al. (2008) and Nouri et al. (2013).

Weather data showed that wheat varieties sown in December were most affected by leaf rust infestation. This was because, during the last week of January and throughout February, maximum temperatures remained around 20-24°C, accompanied by favorable humidity levels, which created ideal conditions for pathogen infection. The grain formation phase was severely affected by the disease and the combination of high temperatures and infection led to shriveled grains, ultimately reducing the number of grains per spike and the yield of the main spike.

Field observations on commercial varieties revealed that TD-1 was most severely affected by the leaf rust epidemic at most planting dates, followed by SKD-1 and TJ-83 (Table 5). The findings indicated that these varieties experienced the greatest reduction in most phenological and yield-related traits due to disease infestation.

In contrast, the varieties Sassui and Bakhtawar were found to be resistant to the disease at most sowing dates under field conditions. These varieties performed better in terms of phenological and yield-associated traits, such as grains per spike and main spike yield. Only a slight reduction in yield was observed compared to the more susceptible varieties.

It was observed that early and normally planted varieties were less affected by leaf rust, whereas late-planted varieties experienced significant reductions in yield-contributing traits due to disease infestation (Table 6).

Our study suggested that early or normal planting of wheat is preferable for achieving higher yields, as it helps avoid harsh temperature conditions and minimizes leaf rust infestation, which can limit final grain yield. Varieties that performed better under delayed planting conditions demonstrated stability in such traits and could be cultivated as short-duration varieties, as they may possess greater tolerance to thermal stress.

CONCLUSION

Significant variations were recorded among ten commercial wheat cultivars of Sindh for days to booting, days to heading, days to maturity, grain filling duration, plant height, spike length, spikelets per spike, and main spike yield across three different planting dates. Wheat crops sown later experienced higher disease pressure compared to those planted earlier. The results indicate that wheat phenological traits and yield components were significantly affected and notably reduced by delayed planting. The best crop performance was observed with early sowing (8th November), followed by normal sowing (25th November), while the lowest performance occurred with late sowing (10th December). The findings suggest that fluctuating weather conditions greatly impact the performance of wheat cultivars at different sowing times. Therefore, to achieve higher grain yield and reduce the risk of severe rust infection and heat stress, wheat should be planted during early or normal sowing periods. Most of the measured traits showed a significant decline as a result of delayed planting. It is thus recommended that commercial wheat cultivars in Sindh be sown at early or normal planting dates to optimize yield and minimize disease severity.

AUTHORS' CONTRIBUTIONS

HB and MAS designed the study; AWC prepared the materials, collected and analyzed the data; YSA and NK, GHS helped in disease scoring; HB and MAS supervised the studies; AWC, GHJ, and QAM wrote the manuscript; All the authors proofread and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

SUSTAINABLE DEVELOPMENT GOALS TARGETED

SDG 2: Zero Hunger

SDG 12: Responsible Consumption and Production

SDG 13: Climate Action

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