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Optimizing wheat yield and quality through the selection of climate-resilient varieties and appropriate planting dates

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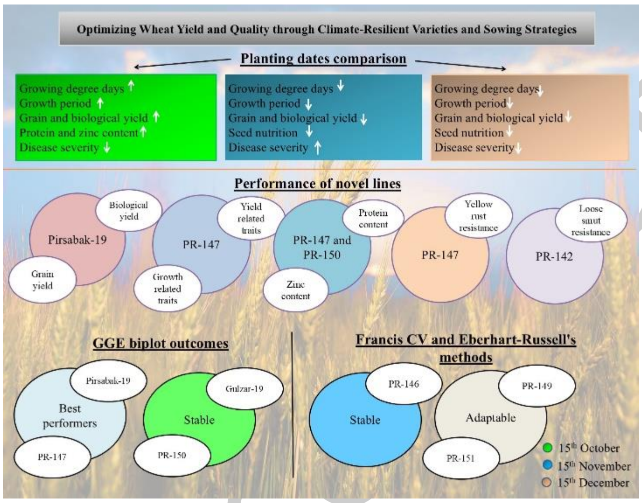
Graphical abstract



Abstract

Suboptimal planting dates and disease susceptibility threaten wheat yield and quality, impacting food security, particularly in the context of climate change. Field experiments were conducted at the Cereal Crop Research Institute (CCRI) Pirsabak, Pakistan, during the winters of 2021-22 and 2022-23 to evaluate the performance of 11 wheat lines/varieties (PR142, PR-146, PR-147, PR-148, PR-149, PR-150, PR151, PR-152, Khaista-17, Gulzar-19, and PS-19) across different planting dates (15th October, 15th November, and 15th December) using a Randomized Complete Block Design (RCBD) with a split-plot arrangement and three replications. Delayed planting reduced the number of growing degree days (GDD), negatively affecting phenology, yield, and quality. October 15th planting led to a 113.5% increase in grain yield and 80.4% increase in biological yield compared to December planting. PR-147 and Pirsabak-19 yielded the highest (3875 kg ha^{-1} and 10791 kg ha^{-1}, respectively), whereas PR-150 had the highest zinc content. Early planting improved protein (12.18%) and zinc (31.27 mg kg^{-1}) contents. GGE biplot analysis identified PR-147 and Pirsabak-19 as top performers. Yellow rust and loose smut incidences were lower with December planting than with November planting. Early planting and resilient varieties are key to enhancing wheat productivity and quality under climate change.

Keywords: Grain yield; GGE biplot; growing degree days; novel lines; physiology, sustainability, Environmental adaptation

1. Introduction

As the global population continues to grow rapidly, the available land for cereal grain cultivation is decreasing, necessitating the optimization of crop production per unit of land area. Wheat (*Triticum aestivum* L.), a major cereal crop in the Poaceae family, is cultivated worldwide and serves as a staple food for millions of people (Jamal *et al.* 2023). Its dominance extends beyond that of other grain varieties, as evidenced by its widespread acreage, productivity, and utilization (Hopkins and Hansen 2019). Major wheat-producing countries, such as China, India, the United States, Russia, France, Australia, Canada, Argentina, Turkey, Pakistan, the United Kingdom, Italy, and Iran, collectively account for more than 71% of the world's wheat production. Wheat is the most important crop in Pakistan, accounting for approximately 37% of the country's food supply and playing a vital role in ensuring food security. It contributes 2.6% to Pakistan's GDP and accounts for 12.5% of the value added to agriculture (Khan *et al.* 2022). However, a persistent gap between wheat production and consumption remains, which is widening due to the impacts of climate change and a growing population (Mottaleb *et al.* 2023). Consequently, food insecurity remains a challenge in several regions.

Climate change threatens agriculture with increased temperatures, erratic weather, and emerging pests and diseases, contributing to decreased yields and diminishing crop quality (Habib-ur-Rahman *et al.* 2022). Adaptation is required to maintain production. Optimizing the planting schedule is an efficient method for increasing wheat productivity by providing improved conditions for growth and yield (Yusuf *et al.* 2019). Late planting exposes wheat crops to unfavorably low temperatures at germination and excessive temperatures during the reproductive phase, resulting in poor yields (Smita Gupta *et al.* 2017). Early planting results in stunted growth and poor root development, which impact development, yield, and quality (Nahar *et al.* 2010). Thus, adjusting planting dates has a substantial impact on the timing and length of vegetative and reproductive growth stages, which are critical for optimizing the yields of small-grain cereals such as wheat (El-Sarag and Ismaeil 2013). Optimal planting time is highly significant for improving wheat grain yield and baking quality because it establishes appropriate phenological, environmental, and physiological conditions for adaptation (Qiao *et al.* 2023). Additionally, choosing the right planting date controls the crop's access to vital resources, such as water, heat, and sunlight (Silva *et al.* 2014). Thus, strategic plantation date management and cultivation of corresponding varieties can boost wheat grain yield by 8% to 27% (Wang *et al.* 2020).

From an agricultural economics perspective, planting dates and varietal selection play critical roles in influencing farm profitability and risk mitigation (Sánchez *et al.* 2022). Decisions regarding input timing and crop choice affect not only yields, but also cost efficiency, resource allocation, and resilience to market fluctuations (Mihrete and Mihretu 2025). In particular, timely sowing can reduce the need for late-stage interventions, thereby optimizing labor and fertilizer use (Tlatlaa *et al.* 2024). Furthermore, climate-resilient varieties improve productivity stability, which is an essential factor in ensuring income security for smallholder farmers under volatile weather conditions (Acevedo *et al.* 2020). Integrating agronomic strategies with economic considerations provides a comprehensive approach to address food security and sustainability (Mihrete and Mihretu 2025).

Increasing climate-resilient wheat varieties has the potential to increase yields, as variety performance is influenced by genetic potential and environmental flexibility, whereas poor selection can have adverse effects on yield (Zohaib *et al.* 2019). Wheat genotypes utilize mechanisms such as leaf rolling, thickening, shedding, smaller leaf size, shorter developmental stages, and transpirational cooling to respond to heat stress (Farhad *et al.* 2023). Additionally, cultivars show significant variations in spike length, tillers, grains per spike, seed yield, herbage yield, and other key traits (Jat *et al.* 2018). The enhancement of wheat yield mostly depends on the production of new varieties with good yield potential and tolerance to varying environmental conditions, such as drought. Therefore, the focus should be on selecting appropriate wheat varieties that can adjust their temperature requirements to minimize the effects of temperature variation resulting from changes in planting dates. Numerous studies have been conducted to identify the optimal planting time for various wheat varieties developed so far. However, there is still a need to evaluate several recently developed wheat lines to improve farmers' economic situation by optimizing production. Therefore, this study hypothesized that optimizing planting dates and selecting suitable wheat varieties could significantly impact wheat yield and quality, thereby addressing the challenges posed by climate change and contributing to improved food security and economic sustainability of wheat farming.

2. Materials and Methods

2.1. Study site and experimental design

Two consecutive field trials were conducted at the Cereal Crop Research Institute (CCRI) Pirsabak Nowshera, Pakistan (34°N latitude, 72°E longitude, and 288 m altitude) during the periods of 2021-22 and 2022-2023. The meteorological data for the study site are presented in **Figure 1**. The trials were organized using a Randomized Complete Block Design (RCBD) with a split-plot arrangement, consisting of three replications. The main plots were assigned different planting dates (PD1:15th October, PD2: 15th November, and PD3: 15th December). The subplot factor comprised nine new wheat lines along with three check varieties (PR142, PR-146, PR-147, PR-148, PR-149, PR-150, PR-151, PR-152, Khaista-17, Gulzar-19, and Pirsabak-19) obtained from the wheat breeding section of CCRI. The parentages of these varieties/lines are presented in **Table 1**.

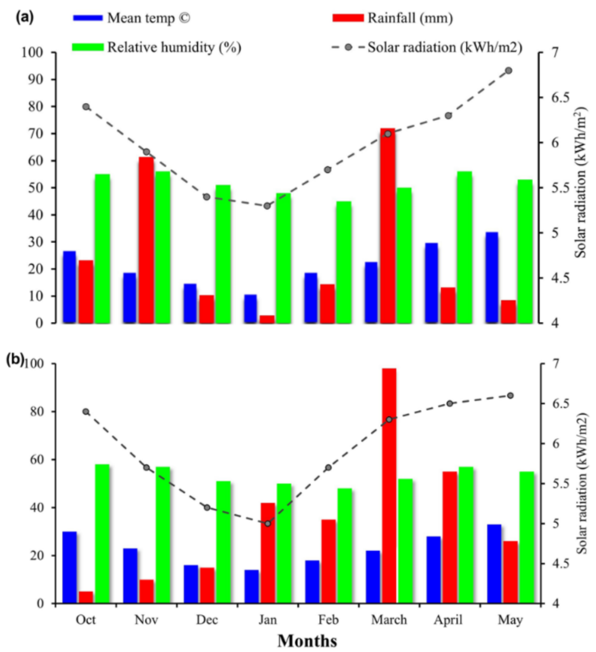


Figure 1. Meteorological data recorded during the 2021-22 (a) and 2022-23 (b) growing season.

Table 1. Parentages of Varieties/Lines evaluated in experiments.

Variety/ Lines	Pedigree	Origin
PR-142	KAUZ/ALTAR84/AOS/3/MILAN/KAUZ/4/…. / PR-105	Fix line V-8327 (2017-18)
PR-146	SOKOLL/3/PASTOR//HXL7573/2*BAU*2/6/OASIS/5*BORL95/5/CNDO/R143//ENTE/MEXI75/3/AE.SQ/4/2*OCI	SAWYT V-4 (2018-19)
PR-147	MUNAL*2/WESTONIA/4/KACHU/3/WHEAR//2*PRL/2*PASTOR	ESWYT V-30 (2020-21)
PR-148	Pirsabak-13/ Khaista-17	FIX Line 8065 (2018-19)
PR-149	BORL14*2/8/REH/HARE//2*BCN/3/CROC_1/AE.SQUARROSA(213)//PGO/4/HUITES/5/ T.DICOCCON PI94624/AE.SQUARROSA (409)//BCN/6/REH/HARE// 2*BCN /3/ CROC_1/AE.SQUARROSA (213)//PGO/4/ HUITES/7/ MUTUS	SABWGPYT-5 V-35 (2019-20)
PR-150	WHEAR/VIVITSI//WHEAR/3/FRNCLN/5/SHORTENED SR26 TRANSLOCATION/4/3*CHIBIA//PRLII/CM65531/3/MISR 2/6/BORL14	SBWGPYT-9 V-19 (2019-20)
PR-151	KACHU//KIRITATI/2*TRCH/3/KFA/2*KACHU	HTWT V-41 (2019-20)
PR-152	MERCATO/BECARD//BOKOTA	IBWSN V-127 (2018-19)
Khista-17	KAUZ//ALTAR 84/AOS/3/MILAN/KAUZ/4/HUITES/7/ CAL/NH//H567.71/3/SERI/4/CAL/ NH//H567.71 /5/2*KAUZ/6/PASTOR	SRNV-113 (2011-12)
Gulzar-19	VORB/3/T.DICOCCONPI94625/AE.SQUARROSA (372)//3*PASTOR	SAWYT V-15 (2012-13)
Pirsabak-19	NAC/TH.AC//3*PVN/3/MIRLO/BUC/4/2*PASTOR/5/ KACHU/6/KACHU	ESWYTV-17 (2011-12)

2.2. Agronomic management

The field was initially organized by plowing with a cultivator, followed by the use of a rotavator to create a consistent seedbed. The plot size was 3.2 m^2. Each plot was comprised four rows, each 3 m in length and spaced 30 cm apart. The same layout as in the first experiment was maintained for the following year. Seeds of all the lines and varieties were planted in lines with the help of a hand hoe at a rate of 125 kg ha^{-1} in both years. Nitrogen (N) at a rate of 120 kg ha^{-1} was calculated based on the percentage of nitrogen present in urea and was applied to plots in divided doses at the necessary growth stages. Half of the calculated amount was applied at sowing, and the remaining half was applied at the tillering stage. The field received basal doses of phosphorus (P) and potassium (K) at rates of 90 and 60 kg ha^{-1}, respectively, using single super phosphate and potassium sulfate. Manual weeding was conducted at the boot stage in all plots. Furthermore, irrigation was applied four times during the first year and five times during the second year using flood irrigation across all the plots to ensure an adequate water supply.

2.3. Soil physiochemical analysis

Soil samples were collected from a depth of 5-15 cm using a soil auger for pre- plantation analysis of soil physiochemical properties. The soil samples were then oven- dried and finely ground for analysis of soil texture, pH, moisture, bulk density, electric conductivity, organic matter, organic carbon, and available N, P, and K. The texture of the soil was determined using the method described by Foth (1991), while pH and electric conductivity were determined by following the procedures described by Herrera (2000). The method described by Alexander (1978) was used to analyze the percentages of sand, silt, and clay by employing different sieves and measuring their settling rates in a water solution using a hydrometer. soil organic matter and carbon were determined using the wet oxidation method outlined by Walkley and Black (1934). Finally, the available N, P, and K contents (mg kg^{-1}) were recorded using the Olsen extractant $NaHCO_3$ procedure (Olsen 1954). The soil type, classified as Calcaric Luvisols according to the World Reference Base (WRB) system of soil taxonomy, exhibited a sandy clay loam texture (39.4% sand, 29.4% silt, and 29.8% clay), an alkaline pH (7.68), and non-saline conditions (electrical conductivity of 0.84 dS m^{-1}). It showed a low organic matter content (1.52 g kg^{-1}) and organic carbon content (11.14 g kg^{-1}). The moisture content was 8.47%, and the soil bulk density was 1.68 gcm^{-1}. Nutrient analysis revealed an available nitrogen content of 3.08 mg kg^{-1}, AB-DTPA assimilable phosphorus content of 4.54 mg kg^{-1}, and potassium content of 79 mg kg^{-1}.

2.4. 2.4 Wheat physiology

To calculate Growing Degree Days (GDD) for various phenophases of wheat lines, the following equation was adopted from McMaster and Wilhelm (1997).

$$GDD = \left(Tmax + Tmin\right) - Tbase \div 2$$

Here, Tmax is the daily maximum temperature.

Tmin is the daily minimum temperature.

Tbase is the base temperature specific to the crop.

Days to emergence were recorded as the number of days from sowing until 90% of seedlings had emerged in the experimental plots. Days to anthesis were calculated as the duration from sowing to the onset of anthesis, defined as the point when 80% of the plants within each subplot exhibited visible anther production. Similarly, days to physiological maturity were documented from the sowing date to the stage when 80% of the plants in each subplot had reached maturity.

2.5. Growth and yield and its attributes

The height of the three plants at maturity was measured using a meter stick. Grain $spike^{-1}$ data were determined by counting the grains in randomly selected spikes from each plot. Similarly, the number of spikes m^{-2} was calculated by counting the spikes within randomly chosen 1m^2 areas in each plot. Thousand-grain weight was measured for each subplot by weighing 1000 seeds per subplot. To calculate the grain yield (kg ha^{-1}), the grains from the central two rows were harvested in each plot, weighed using an electronic scale, and then converted using equation 1 (Saeed *et al.* 2021). Biological yield was determined by harvesting four rows from each subplot, drying the material in the sun for five days, and subsequently weighing and converting the data to kg ha^{-1} using equation 2 (Saeed *et al.* 2021).

$$\text{Grain Yield}\left(\text{Kg ha}^{-1}\right) = \frac{\text{Biological yield in 4 central rows}}{\text{R}-\text{R distance (m)} \times \text{Row length (m)} \times \text{No. of rows}} \times 10000\ \text{m} \quad (1)$$

$$\text{Biological yield}\left(\text{Kg ha}^{-1}\right) = \frac{\text{Total plant weight } in \text{ 4 central rows}}{\text{R}-\text{R distance (m)} \times \text{Row length (m)} \times \text{No. of rows}} \times 10000\ \text{m}^2 \quad (2)$$

2.6. Grain quality

For grain protein content (%), a Micro-kjeldahl (C, 1883) setup was used to convert digestion and distillation samples into a saturated boric acid solution, from which the total nitrogen content was determined. The percentage of protein was calculated by applying a constant factor of 6.25 to the grain nitrogen content. For the zinc content analysis, grains were randomly selected from all plots, oven-dried, finely ground, and digested in HNO_3. The zinc content in the digest samples was subsequently analyzed using an atomic absorption spectrophotometer and expressed in mg kg^{-1}.

2.7. Disease incidence

Yellow rust (during anthesis) and loose smut severity (during grain filling) assessments were conducted for all evaluated wheat lines/varieties across various treatments using the Modified Cobb Scale (Peterson *et al.* 1948). This visual observation method employs a percentage-based scoring system to assess disease incidence. Specifically, disease severity was categorized as follows: 0-5% indicating a high level of resistance, 6-10 % representing resistance, 11-20 % denoting moderate resistance, 21-30 % reflecting moderate susceptibility, 31-50 % indicating susceptibility, and 51-100% signifying a high level of susceptibility to the diseases.

2.8. Statistical analysis

The collected data were statistically analyzed using analysis of variance (ANOVA) as appropriate for split-plot RCBD using the statistical package Statistix8.1 (Statistix8.1, Tallahassee, FL, USA) (Steel and Torrie 1960). If the F values were significant, the means were compared using the Least Significant Difference (LSD) test at p = 0.05 probability levels.

3. Results

3.1. Wheat physiology

The growing degree days (GDD) required for different physiological stages of wheat varied significantly based on planting date (PD). Earlier planting (15th October) demanded significantly higher GDD for tiller initiation, anthesis, and maturity stages than later plantings (15th November and 15th December) in both years (**Figure 2**). For PD1, representing October 15th, the crop required 455 and 432 GDD for tiller initiation, 896 and 898 GDD for the anthesis stage, and 1870 and 1890 GDD for maturity. PD2, corresponding to planting on November 15th, required 342 and 315 GDD for tiller initiation, 832 and 843 GDD for anthesis, and 1609 and 1619 GDD for reaching maturity. Lastly, wheat planted late in both seasons (15th December) progressed through these stages more swiftly, likely due to warmer conditions, that recorded 271 and 279 GDD for tiller initiation, 813 and 823 GDD for anthesis, and 1549 and 1510 GDD for maturity in 2021-22 and 2022-23, respectively (**Figure 2**).

The physiological development of wheat, as elucidated by the provided data, exhibited complexity between planting dates (PD) and wheat lines (L). Days to emergence was non-significant for all the lines and check varieties but was significantly influenced by planting dates in both years (**Table 2**), with delayed planting resulting in late emergence (13$\pm$0 days) as compared to early planting (6$\pm$1 days). The number of days plants took to produce anthers was significantly reduced as planting was delayed (ranging from 116$\pm$3 to 136$\pm$3 days). Among the tested lines and checks, late anthesis was recorded for Gulzar-19 and Pirsabak-19 (129$\pm$8 days), and early anthesis was noted for PR-151 and PR-152 (126$\pm$9 and 126$\pm$10 days). Early Planting extended the maturity period (170$\pm$3 days) in October compared to December (146$\pm$2 days) (**Table 2**). Moreover, a prolonged growth period leading to maturity was observed in Khaista-17 and PR-152 (164$\pm$12 days). The PD×L interaction for days to anthesis and maturity was also significant, indicating that the anthesis and maturity periods were extended in early planting compared to late planting (**Figure 3a and 3b**). Gulzar-19 took the longest period to reach the anthesis stage whereas the time taken by PR-152 and Khaista-17 took the longest period to reach the maturity stage when the plantation commenced on 15th October compared to other planting dates.

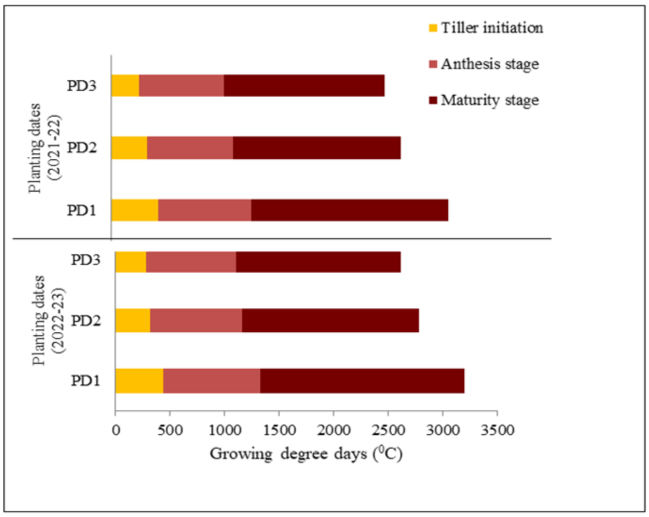


Figure 2. Variation in GDD among different planting dates for Physiological stages of wheat lines during 2021-22 and 2022-23.

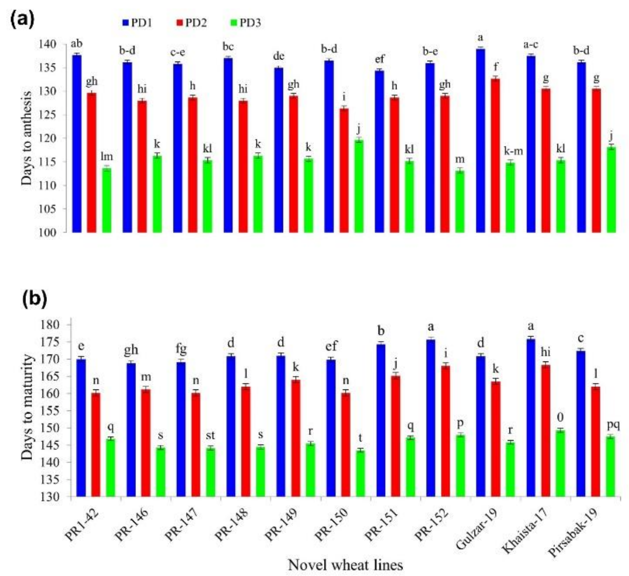


Figure 3. Interactive effect of planting dates and wheat lines on days to anthesis (a) and days to maturity (b) of wheat in 2021-22 and 2022-23. The data are reported as a means of 3 replicates. Means followed by the same letter do not significantly differ at p ≤ 0.05 according to Tukey's test. The bars represent the standard error.

3.2. Growth, yield, and its attributes

Growth and yield related attributes of wheat lines exhibited variations attributable to PD and L. The interactive effect (PD×L) was significant for all parameters except spike m^{-2} (Table 3). Among the planting dates, October 15th planting led to the tallest plants (106+9 cm), while December 15th planting resulted in the shortest (90+8 cm) in successive years. Among the wheat lines, PR-149 displayed the tallest plants (110+7 cm), whereas PR-142 had the shortest (81+5 cm) (Table 3). The interaction between (PD × L) indicated a decrease in plant height for all wheat lines when planting was delayed beyond October 15th (**Figure 4a**). Specifically, PR-149 plants were tallest when the crop was planted on October 15th.

In terms of planting dates, October 15th yielded the highest grains $spike^{-1}$ (45+7), while the lowest was observed on December 15th (30+4). Among the wheat lines, PR-147 and Pirsabak-19 demonstrated the highest grains $spike^{-1}$ (46+10), whereas a lower grains $spike^{-1}$ (33+5) was recorded for PR-142 in both years. These results were also reflected in the interactive effect of PD×L (**Figure 4b**).

Table 2. Physiology of wheat lines as influenced by planting dates.

Planting dates	Days to emergence			Days to anthesis			Days to maturity		
	2021-22	2022-23	Means	2021-22	2022-23	Means	2021-22	2022-23	Means
15th Oct	6+1 c	6+1c	6+1 c	134+2 a	139+2 a	136+3 a	170+2 a	173+3 a	170+3 a
15th Nov	9+0 b	9+1b	9+0 b	126+3 b	132+2 b	129+4 b	163+3 b	164+3 b	163+3 b
15th Dec	12+0 a	13+1a	13+0 a	114+3 c	117+1 c	116+3 c	147+2 c	145+2 c	146+2 c
LSD(0.05)	0.47	0.16	ns	0.68	2.26				
	1.0	1.0	0.71	0.46					
				Wheat lines					
PR-142	9+3	9+3	9+2	125+11 c	129+10 bc	127+11 c	159+9 e	159+11 g	159+10 e
PR-146	9+2	9+3	9+3	125+7 c	129+10 bc	127+9 c	158+9 f	158+13 f	158+11 f
PR-147	9+2	9+3	9+2	125+9 c	129+10 bc	127+9 c	158+10 f	158+12 f	158+11 f
PR-148	9+2	10+3	9+3	125+9 c	129+9 bc	127+9 c	159+11 e	159+13 e	159+11 e
PR-149	9+3	9+3	9+3	124+8 d	129+10 bc	127+9 c	160+11 d	161+12 c	161+11 c
PR-150	9+3	9+3	9+2	126+7 b	129+8 bc	128+7 b	158+10 f	157+13 h	158+11 f
PR-151	9+2	9+3	9+3	124+8 d	128+9 c	126+9 d	161+11 c	163+13 b	162+12 b
PR-152	9+2	9+3	9+3	124+10 d	128+11 c	126+10 d	163+11 b	165+14 a	164+12 a
Khaista-17	9+2	9+3	9+3	125+9 c	131+11 a	128+10 b	164+11 a	165+13 a	164+12 a
Gulzar-19	9+2	10+3	9+3	127+12 a	131+10 a	129+11 a	160+10 d	160+12 d	160+11 d
Pirsabak-19	9+2	9+3	9+2	127+7 a	130+9 b	129+8 a	160+10 d	161+12 c	161+11 c
LSD (0.05)	ns	ns	ns	0.18	1.43	1.0	0.5	0.76	0.44
Year	NS	**	***						
PD×L	NS								
ns	1.6	0.8							

****= very highly significant at P ≤ 0.05, **= highly significant at P ≤ 0.05 and *= significant at P ≤ 0.05; NS= non-significant. The data are reported as means of 3 replicates ± standard deviation. Means followed by the same letter do not significantly differ at p ≤ 0.05 according to Tukey's test.*

Among the planting dates, October 15th produced the highest number of spikes m^{-2} (350+15) compared to December 15th (278+14). Similarly, spikes m^{-2} was observed the highest for Pirsabak-19 (328+33) and statistically at par with PR-147 (324±32). In contrast, spike m^{-2} was the lowest for PR-142 (304±38) as shown in **Table 3**. Thousand grain weight displayed notable differences with 15th October producing better results (41.7±3.6 g) than the rest of the planting dates. Among the wheat lines, the heaviest grains were recorded for Pirsabak-19 (40.6±5.3 g) and PR-147 (41.1±5.3 g), while lighter grains were produced by PR-142 (33.1±3.2 g) (**Table 4**). The interactive effects (PD × L) showed that the thousand-grain weights of PR-147 and Pirsabak-19 were higher on 15th October compared on other dates (**Figure 4c**).

Table 3. Growth and yield attributes of wheat lines as influenced by planting dates.

Planting dates	Plant height (cm)			Grains spike^{-1}			Spikes m^{-2}		
	2021-22	2022-23	Means	2021-22	2022-23	Means	2021-22	2022-23	Means
15th Oct	106±9 a	107±9 a	106±9 a	43±4 a	47±9a	45±7 a	350±9 a	351±19 a	350±15 a
15th Nov	99±9 a	101±9 b	100±9 b	38±6 b	41±10 b	40±8 b	321±7 b	325±6 b	322±7 b
15th Dec	90±7 b	90±8 c	90±8 c	30±4 c	31±5 c	30±4 c	316±15 c	279±14 c	278±14 c
LSD (0.05)	8.2	0.98							
	3.0	1.0	1.2	0.6	21	21	12		
Wheat lines									
PR-142	82±4 f	80±7 h	81±5 g	33±5 i	33±5 f	33±5 h	301±39 e	307±40 e	304±38 e
PR-146	102±6 bc	104±5 c	103±6 c	40±4 c	44±6 c	42±5c	312±34 d	313±35 de	313±33 cd
PR-147	96±6 d	95±4 f	96±5 e	44±4 a	49±8 a	46±7 a	323±33 ab	325±33 ab	324±32 ab
PR-148	105±8 b	107±6 b	106±7 b	36±7 e	39±12 d	37±10 e	314±33 cd	318±34 cd	316±32 cd
PR-149	109±7 a	112±8 a	110±7 a	39±7 d	37±7 e	38±7 d	317±34 bc	321±34 abc	319±33 bc
PR-150	101±10 c	100±8 e	101±9 d	39±7 d	46±9 b	43±8 b	317±29 bc	322±29 ab	320±28 bc
PR-151	92±8e	92±7 g	92±7 f	34±6 fg	35±6 ef	35±6 f	315±31 cd	319±32 bc	317±30 cd
PR-152	101±9 c	100±8 e	100±9 d	35±9 ef	35±14 ef	35±12 f	314±34 cd	318±34 cd	316±33 cd
Khaista-17	100±13 c	102±10 d	101±11 d	33±7 hi	34±7 f	34±7 g	315±33 cd	318±33 cd	317±32 cd
Gulzar-19	99±11 c	102±10 d	101±10 d	34±7 fg	35±11 ef	35±9 f	317±32 bc	310±36 de	313±33 cd
Pirsabak-19	96±12 d	99±10 e	97±11 e	42±6 b	49±12 a	46±10 a	327±34 a	330±34 a	328±33 a
LSD (0.05)	2.8	1.85	1.68	1.0	2.0	1.0	5.7	10	6
Year	Ns	*	ns						
PD×L	4	2	ns						

****= very highly significant at P ≤ 0.05, **= highly significant at P ≤ 0.05 and *= significant at P ≤ 0.05; NS= non-significant. The data are reported as means of 3 replicates ± standard deviation. Means ± standard error followed by the same letter are not significantly different for p ≤ 0.05 according to Tukey's test.*

Table 4. Thousand grain weight (g), grain and biological yield (kg ha^{-1}) of wheat lines as influenced by planting dates.

Planting dates	Thousand grain weight (g)			Grain yield (kg ha^{-1})			Biological yield (kg ha^{-1})		
	2021-22	2022-23	Means	2021-22	2022-23	Means	2021-22	2022-23	Means
15th Oct	40.8±3.2 a	42.6±3.8 a	41.7±3.6 a	4121±538 a	4420±637 a	4270±604 a	11584±1276 a	12119±1813 a	11851±1579 a
15th Nov	36.9±4.4 b	37.3±5.3 b	37.1±4.9 b	3126±533 b	3250±635 b	3188±585 b	7571±1024 b	7509±1228 b	7540±1122 b
15th Dec	31.3±2.2 c	32.1±2.4 c	31.7±2.3 c	1920±444 c	2082±478 c	2001±465 c	6637±1126 c	6505±1089 c	6571±1101 c
LSD (0.05)	1.5	2.1	1.1	526	527	309	162	287	136
Wheat lines									
PR-142	32.3±2.9 e	33.8±3.4 e	33.1±3.2 f	2851±563 e-g	3202±953 d	3027±781 de	7725±1352 g	7692±1358g	7708±1315 h
PR-146	33.6±3.6 d	35.2±3.3 e	34.4±3.5 e	3140±715 cd	3230±920 cd	3235±806 c	8020±1460 ef	8114±1487 f	8067±1430 g
PR-147	40.7±4.8 a	41.6±6.0 ab	41.1±5.3 a	3533±776 b	3716±892 ab	3625±817 b	9776±2089 b	9917±2135 b	9847±2051 b
PR-148	34.3±5.7 c	35.3±6.4 de	34.8±5.9 de	2575±1100 h	2572±1151 f	2573±1092 f	7859±2728 fg	7381±2495 h	7620±2548 h
PR-149	39.2±5.4 b	39.5±6.8 bc	39.4±6.0 b	3318±1195 c	3619±1274 bc	3468±1208 b	8952±1976 c	9625±2818 c	9288±2386 c
PR-150	38.9±4.5 b	39.1±5.9 c	39.0±5.1 bc	3043±1082 de	3220±1019 cd	3182±1030 c-e	8062±1868 ef	8132±1939 f	8097±1847 g
PR-151	38.8±3.5 b	37.3±6.6 cd	38.0±5.2 c	2879±1124 ef	3139±1366 de	3009±1221 e	8198±3554 de	8142±3749 ef	8170±3544 fg
PR-152	34.0±4.9	35.1±4.9	34.5±4.8	2655±1088	2841±1116	2748±1074	8189±3054	8333±3683	8261±3283 f

	cd	de	e	f-h	ef	f	de	e	
Khaista-17	34.2±3.3 c	34.2±4.3 e	34.5±3.8 e	2709±1216 gh	2749±1159 f	2729±1152 f	8306±3328 d	8698±4418 d	8502±3800 e
Gulzar-19	34.4±5.1 c	37.3±5.8 cd	35.8±5.5 d	3126±1035 cd	3301±988 cd	3214±985 cd	8810±1678 c	8879±1626 d	8845±1603 d
Pirsabak-19	39.2±5.1 b	42.1±5.5 a	40.6±5.3 a	3785±1125 a	3966±1212 a	3875±1138 a	10675±2124 a	10906±3007 a	10791±2528 a
LSD (0.05)	0.6	2.4							
	1.2	204	336	140	228	197	149		
Year	Ns	*	**						
PD×L	2.3	390	267						

****= very highly significant at P ≤ 0.05, **= highly significant at P ≤ 0.05 and *= significant at P ≤ 0.05; NS= non-significant. The data are reported as a means of 3 replicates ± standard deviations. Means ± standard error followed by the same letter are not significantly different for p ≤ 0.05 according to Tukey's test.*

The grain yield of wheat lines was influenced by both PD and L. For planting dates, October 15th resulted in the highest grain yield (4270±604 kg ha^{-1}), and December 15th had the lowest yield (2001±465 kg ha^{-1}). The highest grain yield was noted for Pirsabak-19 (3875±1138 kg ha^{-1}) and the lowest for Khaista-17 (2729±1152 kg ha^{-1}), PR-148 (2573±1092 kg ha^{-1}), and PR-152 (2748±1074 kg ha^{-1}), as presented in **Table 4**. Among the PD, October 15th yielded the highest biological yield (11851±1579 kg ha^{-1}) and the lowest was recorded on December 15th (6571±1101 kg ha^{-1}). The highest biological yield was observed for Pirsabak-19 (10791±2528 kg ha^{-1}) and the lowest for PR-148 (7620±2548 kg ha^{-1}). The interaction between (PD×L) indicated that as planting was delayed, both grain and biological yields decreased for all wheat lines (**Figure 5a and 5b**). Specifically, Pirsabak-19 and PR-149 recorded maximum grain yield, with only Pirsabak-19 attaining the highest biological yield on 15th October compared to other planting dates.

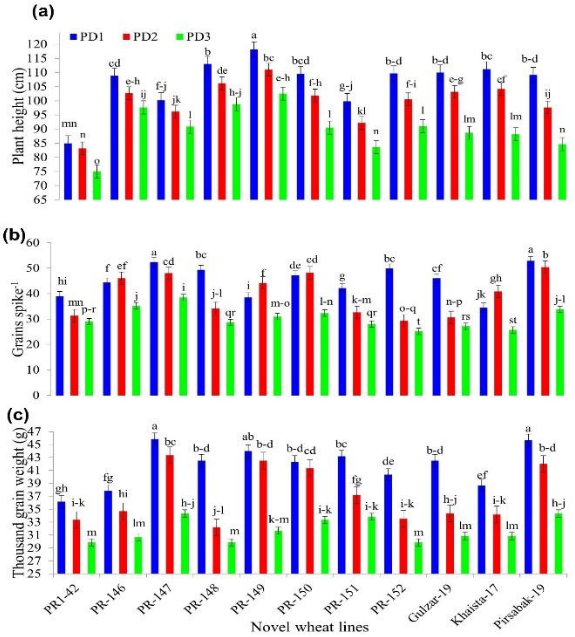


Figure 4: Interactive effect of planting dates and wheat lines on plant height (a), grains spike^{-1} (b) and thousand grain weight (c) of wheat in 2021-22 and 2022-23. The data are reported as means of 3 replicates. Means followed by the same letter do not significantly differ at p ≤ 0.05 according to Tukey's test. The bars represent the standard error.

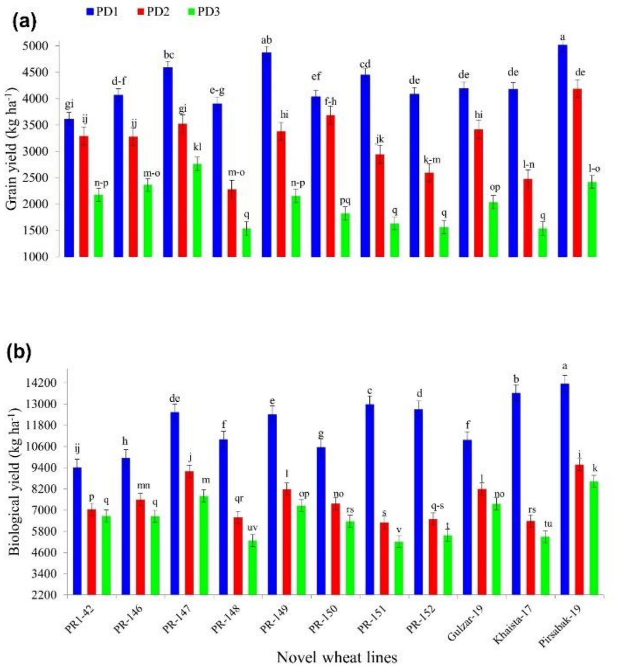


Figure 5. Interactive effect of planting dates and wheat lines on grain yield (a) and biological yield (b) of wheat in 2021-22 and 2022-23. The data are reported as a means of 3 replicates. Means followed by the same letter do not significantly differ at p ≤ 0.05 according to Tukey's test. The bars represent the standard error.

3.3. Grain quality attributes

Planting dates (PD) and wheat lines (L) had a significant effect on grain protein and zinc content (**Table 5**). Among the planting dates, the highest protein content (12.18±1.24 %) was observed in crops sown on October 15th, followed by those planted on November 15th (11.09±0.95 %). The lowest grain protein content was recorded in crops sown on December 15th (8.67±1.45 %). Regarding wheat lines, PR-147 (11.57±1.69 %) and PR-150 (11.94±1.46 %) exhibited the highest grain protein content (**Table 5**).

In terms of zinc content , crops sown on October 15th showed the highest (31.27±1.65 mg kg^{-1}) concentration, which was statistically similar to those sown on November 15th (31.17±1.87 mg kg^{-1}). The lowest zinc (28.58±0.84 mg kg^{-1}) content was observed in crops sown on December 15th (**Table 5**). Among the wheat lines, PR-150 had the highest (33.92+3.42 mg kg^{-1}) zinc content, while, PR-152 (29.26+1.43 mg kg^{-1}), Pirsabak-19 (29.36+1.27 mg kg^{-1}) and PR-146 (29.39+1.42 mg kg^{-1}) recorded comparatively lower values.

The interaction between planting dates and wheat lines (PD×L) was also significant. PR-148 produced the highest protein content when sown on October 15th (**Figure 6a**), whereas PR-150 recorded the highest zinc content when sown on both October 15th and November 15th (**Figure 6b**).

Table 5. Grain quality of wheat lines as influenced by planting dates.

Planting dates	Protein content (%)			Zinc content (mg kg^{-1})		
	2021-22	2022-23	Means	2021-22	2022-23	Means
15th Oct	12.27+1.24 a	12.17+1.24 a	12.18+1.21a	31.21+1.66 a	31.34+1.67 a	31.27+1.65 a
15th Nov	11.11+1.07 b	11.08+1.07 b	11.09+0.95b	31.11+1.75 a	31.24+1.99 a	31.17+1.87 a
15th Dec	8.71+1.73 c	8.63+1.73 c	8.67+1.45c	28.49+0.84 b	28.67+0.85 b	28.58+0.84 c
LSD (0.05)	0.76	0.73	0.45	0.32	0.35	0.20
			Wheat lines			
PR-142	10.01+2.30 de	9.34+2.30 fg	9.67+2.11de	30.84+1.41 b	30.71+1.55 b	30.78+1.44 b
PR-146	10.70+1.79 b-d	10.86+1.79 c-d	10.78+1.73c	29.35+1.54 f	29.43+1.39 f	29.39+1.42 f
PR-147	11.43+1.72 a	11.71+1.72 ab	11.57+1.69ab	30.28+0.85 cd	30.08+0.77 c-e	30.17+0.79 de
PR-148	10.98+2.27 ab	10.47+2.27 de	10.73+2.25c	30.44+0.69 c	30.61+0.89 bc	30.52+0.77 bc
PR-149	9.50+1.96 e	9.25+1.96 g	9.37+1.94e	29.89+1.72 e	30.27+1.52 b-d	30.08+1.58 de
PR-150	11.43+1.19 a	12.44+1.19 a	11.94+1.46a	33.74+3.38 a	34.10+3.65 a	33.92+3.42 a
PR-151	10.16+1.28 de	10.16+1.28 ef	10.16+1.20d	30.35+1.30 cd	30.31+1.60 b-d	30.33+1.41 cd
PR-152	11.18+1.84 ab	11.14+1.84 b-d	11.16+1.79bc	29.14+1.48 f	29.39+1.46 f	29.26+1.43 f
Khaista-17	10.26+2.64 cd	9.63+2.64 fg	9.95+2.42d	30.05+0.70 de	30.10+0.63 c-e	30.07+0.65 de
Gulzar-19	11.06+1.23 ab	11.34+1.23 bc	11.20+1.04bc	29.76+1.25 e	29.97+1.30 d-f	29.86+1.24 e
Pirsabak-19	10.95+1.74 a-c	10.52	10.73+1.69c	29.14+1.29 f	29.58+1.29 ef	29.36+1.27 f
LSD (0.05)	0.70	0.69				
	0.54	0.36	0.59	0.34		
Year	ns		*			
PD×L	0.95	0.59				

****= very highly significant at P < 0.05, **= highly significant at P < 0.05 and *= significant at P < 0.05. The data are reported as a means of 3 replicates ± standard deviations. Means ± standard error followed by the same letter are not significantly different for p ≤ 0.05 according to Tukey's test.*

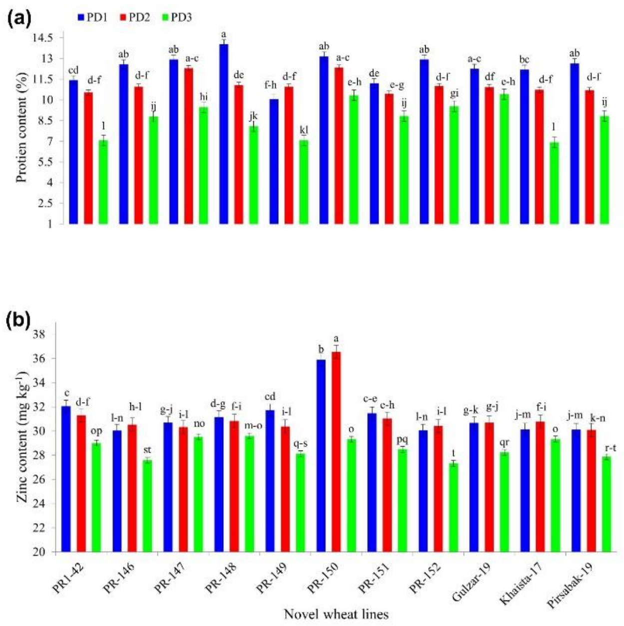


Figure 6. Interactive effect of planting dates and wheat lines on grain protein (a), and grain zinc (b) content of wheat in 2021-22 and 2022-23. The data are reported as a means of 3 replicates. Means followed by the same letter do not significantly differ at p ≤ 0.05 according to Tukey's test. The bars represent the standard error.

3.4. Disease incidence

The incidence of yellow rust varied significantly across planting dates, with the lowest severity observed in crops sown on December 15th (15.6+3.6 %), followed by those planted on October 15th (20.9+4.3 %) and November 15th (23.3+4.1 %). Among the wheat lines, PR-147 was classified as resistant to yellow rust (15.5+3.0 %), while PR-150 exhibited the highest susceptibility (23.3+5.9 %) (**Table 6**).

Similarly, the incidence of loose smut showed significant variations based on both planting dates and wheat lines. The highest severity was recorded in crops sown on October 15th and November 15th, whereas the lowest severity (14.1+4.1 %) was observed in crops planted on December 15th. Among the wheat lines, PR-142 and PR-152 showed the highest resistance to loose smut (15.7+3.2 and 15.7+2.9 %, respectively), while PR-149 was the most susceptible (27.1+1.8%) (**Table 6**).

The interaction between planting dates and wheat lines (PD×L) revealed that the severity of both yellow rust and loose smut was higher in early (October 15th) and mid-early (November 15th) sowings, whereas late planting (December 15th) consistently resulted in the lowest disease severity across all wheat lines and check varieties (**Figure 7a and 7b**).

Table 6. Disease severity of wheat lines as influenced by planting dates.

Planting dates	Yellow rust (%)			Loose smut (%)		
	2021-22	2022-23	Means	2021-22	2022-23	Means
15th Oct	20.8±4.4 b	21.0±4.3 b	20.9±4.3 b	22.0±3.2 a	21.0±3.2 a	21.5±3.3 a
15th Nov	23.3±4.2 a	23.2±4.1 a	23.3±4.1 a	20. 5±2.9 a	19.1±2.9 a	19.6±2.9 b
15th Dec	15.7±3.6 c	15.4±3.5 c	15.6±3.6 c	14.8±3.7 b	13.4±4.4 c	14.1±4.1 c
LSD (0.05)	0.9	1.2	0.6	1.6	0.9	0.3
			Wheat lines			
PR-142	22.0±4.4 bc	22.0±4.6 a	22.0±4.4 b	16.1±3.3 i	15.4±3.3 e	15.7±3.2 g
PR-146	22.2±6.9 b	22.1±6.9 a	22.1±6.7 b	18.3±3.3 e	17.2±3.2 cd	17.7±3.2 d
PR-147	15.3±2.8 h	15.6±3.3 e	15.5±3.0 g	17.0±2.3 h	16.1±2.1 de	16.5±2.2 f
PR-148	18.8±4.3 g	18.2±4.1 d	18.5±4.1 f	17.3±3.3 g	16.3±3.3 c-e	16.8±3.2 ef
PR-149	18.3±6.4 g	18.6±6.7 d	18.5±6.4 f	27.6±1.8 a	26.7±1.8 a	27.1±1.8 a
PR-150	23.6±6.1 a	23.2±6.0 a	23.3±5.9 a	20.0±5.4 c	19.0±5.1 b	19.5±5.3 b
PR-151	20.2±4.2 de	20.1±4.0 bc	20.1±3.9 cd	20.3±4.8 b	19.3±4.6 b	19.8±4.7 b
PR-152	19.3±4.5 e-g	19.4±4.0 b-d	19.3±4.1 de	16.1±3.0 i	15.3±2.8 e	15.7±2.9 g
Khaista-17	18.9±5.2 fg	19.1±4.9 cd	19.0±4.9 ef	17.8±1.9 f	16.9±1.5 cd	17.4±1.6 de
Gulzar-19	20.9±4.3 cd	20.0±5.0 b	20.6±4.6 c	19.6±3.6 d	17.6±5.5 c	18.6±4.5 c
Pirsabak-19	20.1±3.8 d-f	20.1±4.2 bc	20.0±3.9 cd	18.3±3.5 e	16.3±5.6 c-e	17.3±4.6 de
LSD (0.05)	1.2	1.3	0.8	0.2	1.2	0.6
Year	NS		**			
PD×L	1.6	1.1				

****= very highly significant at P ≤ 0.05, **= highly significant at P ≤ 0.05 and *= significant at P ≤ 0.05; NS= non-significant. The data are reported as means of 3 replicates ± standard deviations. Means ± standard error followed by the same letter are not significantly different for p ≤ 0.05 according to Tukey's test.*

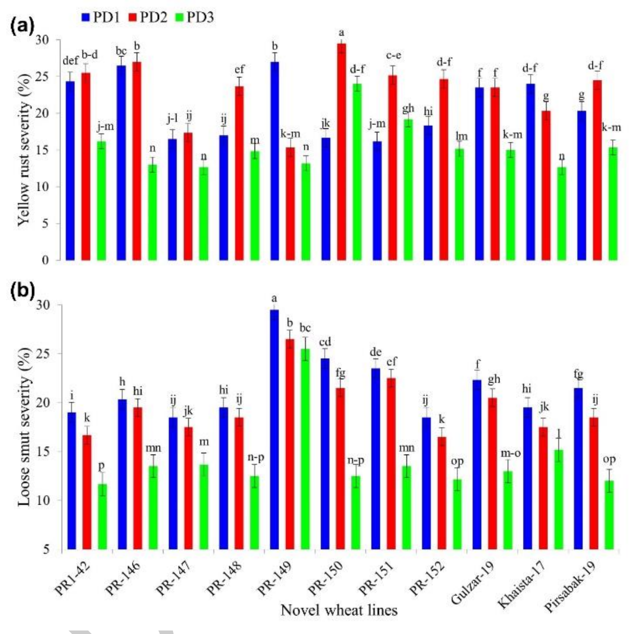


Figure 7. Interactive effect of planting dates and wheat lines on disease incidence, yellow rust (a) and loose smut (b) of wheat in 2021-22 and 2022-23. The data are reported as means of 3 replicates. Means followed by the same letter do not significantly differ at p ≤ 0.05 according to Tukey's test. The bars represent the standard error.

3.5. Polygon view of GGE biplot for grain yield across various planting dates

GGE biplot analysis was used to determine the optimal line for each planting date and evaluate their stability. The relationship between planting dates was modeled using environment-centered (centering, 2) and dual-metric-preserving (SVP, 2) methods in GEA-R software, with no scaling applied. The resulting biplots accounted for 92% of the total variation, with the first principal component (PC1) explaining 73.26% and the second principal component (PC2) explaining 18.93%.

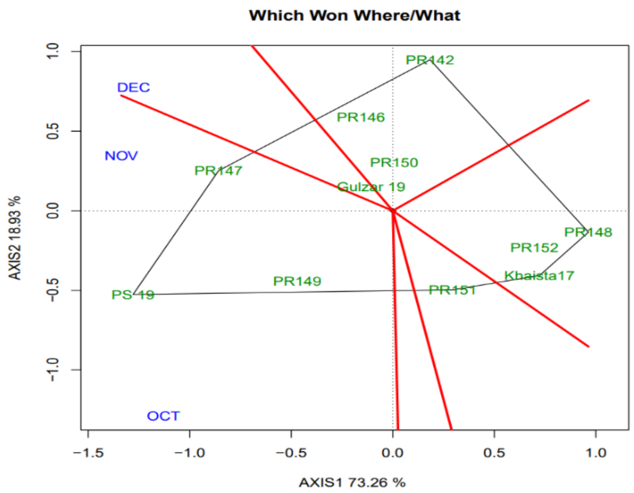


Figure 8. Polygon view of GGE biplot for wheat lines across three planting dates in terms of grain yield.

The 'which-won-where' analysis divided the GGE biplot into six sectors (**Figure 8**). Pirsabak-19 and PR-147 emerged as vertex genotypes, indicating their superior performance across planting dates. Line PR-149 also fell within the same sector, suggesting its favorable yield potential. In contrast, Gulzar-19 and PR-150 were located near the origin of the biplot, indicating their stability across the different planting dates . On the other hand , lines PR-142, PR-148, PR-151 and Khaista-17 appeared as vertex genotypes in sectors not associated with any of the studied environments (planting dates), suggesting poor adaptability and low grain yield performance under the tested planting dates.

3.6. Stability analysis

The stability of wheat lines was assessed using the Francis coefficient of variation (CV) and the Eberhart and Russell method. The CV% versus mean yield plot revealed that 5 out of the 11 lines/varieties PR-150, PR-146, PR-147, Pirsabak-19 and Gulzar-19 were highly productive and stable across the different planting dates, as they were positioned in the 4^{th} quadrant of the plot (**Figure 9a**).

Eberhart and Russell's analysis, based on the regression coefficient (bi) and deviation from regression (S^2di), categorized the studied lines into three groups (adapted, stable and both stable and adapted). A genotype with a bi value close to 1 is considered adaptable, While an S^2di value near zero indicates stability. Genotypes exhibiting both a high bi and low S^2di are regarded as both adaptable and stable. Based on these criteria, PR-151 and PR-149 were identified as adoptable, whereas PR-146 was classified as stable across environments (**Figure 9b**). However, none of the lines in our study simultaneously exhibited both high adoptability and stability.

4. Discussion

Our research findings highlighted the significant influence of planting dates (PD) and wheat lines (L) on various agronomic traits. Growing degree days (GDD) played a crucial role in estimating developmental stages. Early planting (PD1: 15^{th} October) accumulated higher GDD compared to later planting dates (PD2 and PD3). Physiological stages such as tillering, anthesis, and maturity were delayed under PD1 due to lower ambient temperatures. In contrast, later plantings accumulated fewer GDD, which negatively impacted heat use efficiency, photosynthetically active radiation (PAR), and source-sink balance (Aslam *et al.* 2017, Sattar *et al.* 2023, Nandini and Sridhara 2019, Tahir *et al.* 2019). Germination was more rapid in October plantings due to warmer temperatures, whereas delayed planting (for example, December 15^{th}) resulted in prolonged emergence caused by cooler conditions (Mashiqa *et al.* 2022, Muhsin *et al.* 2021).

The test varieties Gulzar-19 and Khaista-17 showed an extended anthesis duration , with anthesis delayed by approximately three days compared to PR-151 and PR-152, likely due to possible genetic variations (Munsif et al. 2013). Early planting on October 15^{th} resulted in a longer anthesis period, while later planting on December 15^{th} accelerated anthesis by upto 22 days, attributed to warmer temperatures that hastened crop development (Hussain *et al.* 2023). Variations in maturity duration were also observed; for instance, Khaista-17 and PR-152 required approximately eight additional days to reach maturity compared to PR-150, reflecting both genetic differences and environmental influences (Acevedo *et al.* 2002). Late planting significantly accelerated maturity, shortening the growth cycle by up to 28 days, highlighting the effect of high temperatures in expediting developmental phases (Dev *et al.* 2019).

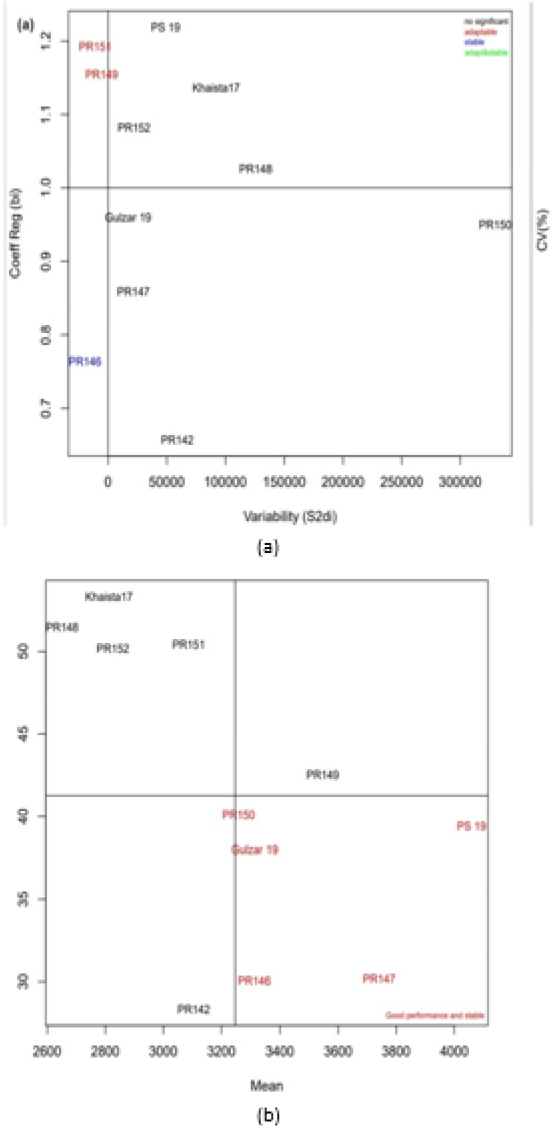


Figure 9. Stability analysis for wheat lines across three planting dates regarding grain yield.

Among the wheat lines, PR-149 achieved the highest plant height, whereas PR-142 was the shortest, possibly due to genotypic differences and environmental interactions (Tian *et al.* 2022). Early planting (October 15^{th}) resulted in taller plants, attributed to favorable environmental conditions (Desta *et al.* 2020). The highest number of grains per spike was recorded in Pirsabak-19 and PR-147, producing up to 26 more grains than PR-142, reflecting both genetic potential and environmental adaptability (Upadhyaya and Bhandari 2022). Similarly, the October 15^{th} planting produced the highest number of grains per spike, while delayed plantation reduced emergence and impaired grain development (Shah *et al.* 2020).

In terms of spike density, Pirsabak-19, PR-147, PR-149, and PR-150 recorded the highest number spikes m^{-2}, while PR-142 had the lowest, consistent with the findings of Ahmed et al. (2023). Spikes m^{-2} was also highest in the October plantation, with a decline of approximately 20% observed under late planting conditions. This reduction is likely due to wheat's sensitivity to elevated temperatures during critical developmental stages (Kamrozzaman *et al.* 2016, Kalwar *et al.* 2018).

Pirsabak-19 recorded the highest grain yield, which was 34% higher than that of Khaista-17. This superior performance was attributed to a higher number of spikes m^{-2}, more grains per spike, and greater thousand-grain weight. Grain yield declined by approximately 55% when planting was delayed until December 15th, as previously reported by Swami et al. (2019). The shortened grain filling period under late planting conditions reflects the adverse effects of high temperatures on grain development and yield (Abdelkhalik and Hagras 2021). Similarly, the highest biological yield was observed in Pirsabak-19, while delayed planting on December 15th led to a 45% reduction, primarily due to poor seedling emergence and reduced tillering (Shazma Anwar *et al.* 2015).

PR-147 and Pirsabak-19 exhibited the thousand-grain weight, which could be attributed to genetic variation (Cao *et al.* 2020, Choudhary *et al.* 2020). Early planting contributed to heavier grains by extending the duration of favorable growth conditions, thereby enhancing assimilate translocation to the developing grains (Hussain *et al.* 2018). In terms of grain protein content, PR-147, PR-150, PR-152, Gulzar-19, and Pirsabak-19 showed superior performance, which can be attributed to inherent genetic differences (Mosleth *et al.* 2020). Additionally, early sowing increased protein concentration by prolonging the grain-filling stage (Shaykhutdinov F 2022). PR-150 recorded the highest grain zinc content, which is explained by genotype-environment interactions (Khokhar *et al.* 2018). In contrast, zinc levels declined significantly under December sowing conditions(Hussain *et al.* 2023).

The incidence of yellow rust varied, and the lowest incidence was observed for the December 15th planting. Early planting resulted in more rust, with cooler temperatures being more conducive to pathogen development (Afzal *et al.* 2022). Conversely, Megahed et al. (2022) reported increased rust in late planting, contradicting our findings. PR-147 was resistant, and PR-150 was more susceptible, which was attributed to certain resistance genes (Zhang *et al.* 2023). Loose smut severity was lowest in December 15th planting and greatest on November 15th, since delayed planting minimized exposure to favorable conditions (Singh *et al.* 2009). PR-142 was the most resistant, whereas PR-149 was greatly affected, consistent with the observations of Kharina and Amunova (2020).

GGE biplot analysis (Yan and Tinker 2006) revealed that Pirsabak-19, PR-147, and PR-149 were the most stable and highest yielding genotypes across different planting dates. The genotype-environment interaction (GEI) had a significant effect on yield, with the environment contributing the largest portion of t variation (Ghazy *et al.* 2023). PR-146 demonstrated stability across planting dates, consistent with the Eberhart and Russell (E-R) model, where regression values greater than 1 indicate genotypic stability across environments (Ibrahim HA 2021).

In addition to agronomic outcomes, planting dates and varietal choices have important economic implications for farmers. Yield variability, which increases with delayed planting, poses a significant income risk. This is compounded by market price volatility, which can further destabilize farmers' revenues (Anderson and Dillon 1992). The adoption of resilient varieties, such as PR-147 and Pirsabak-19, may reduce the likelihood of crop failure, thereby lowering the downside risk. Although this study did not employ a quantitative risk model, the multiyear yield consistency of these varieties suggests their potential for mitigating yield risk, a critical factor influencing farmers' sowing decisions (Just and Pope 1979). Future studies should integrate stochastic models or Monte Carlo simulations to quantify such risks more explicitly.

5. Conclusions

The current research highlights the importance of early planting (15th October) to improve agronomic performance. Pirsabak-19 outperformed the other varieties in terms of grain yield, whereas PR-147 had higher yield components. PR-150 and PR-152 had greater protein and zinc contents, respectively, whereas PR-147 was resistant to yellow rust and PR-142 to loose smut. This study highlights the importance of selecting varieties based on prevailing environmental conditions. Pirsabak-19 is recommended for mid-October planting in sub-tropical Pakistan to achieve higher yields. Further evaluation of other wheat lines is warranted to consider them for certified variety status. These insights can aid agronomic decision-making, breeding strategies, and food security in wheat cultivation.

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Author Contributions

The authors confirm their contribution to the paper as follows: study conception and design: Uzair Ahmed, Muhammad Arif, and Waseem Abbas; data collection: Uzair Ahmed, and Waseem Abbas; analysis and interpretation of results: Muhammad Farhan Saeed, Aftab Jamal, Katarzyna Pentoś and Emanuele Radicetti: draft manuscript preparation: Aftab Jamal, Katarzyna Pentoś, Muhammad Arif, and Muhammad Farhan Saeed. All authors reviewed the results and approved the final version of the manuscript.

Institutional Review Board Statement

Not applicable

Data Availability Statement

The data presented in this study are available on request from the corresponding author due to institutional data protection.

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Conflicts of Interest

The authors declare no conflicts of interest.

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