Optimizing Wheat Yield and Quality through the Selection of Climate-Resilient Varieties and Appropriate Planting Dates

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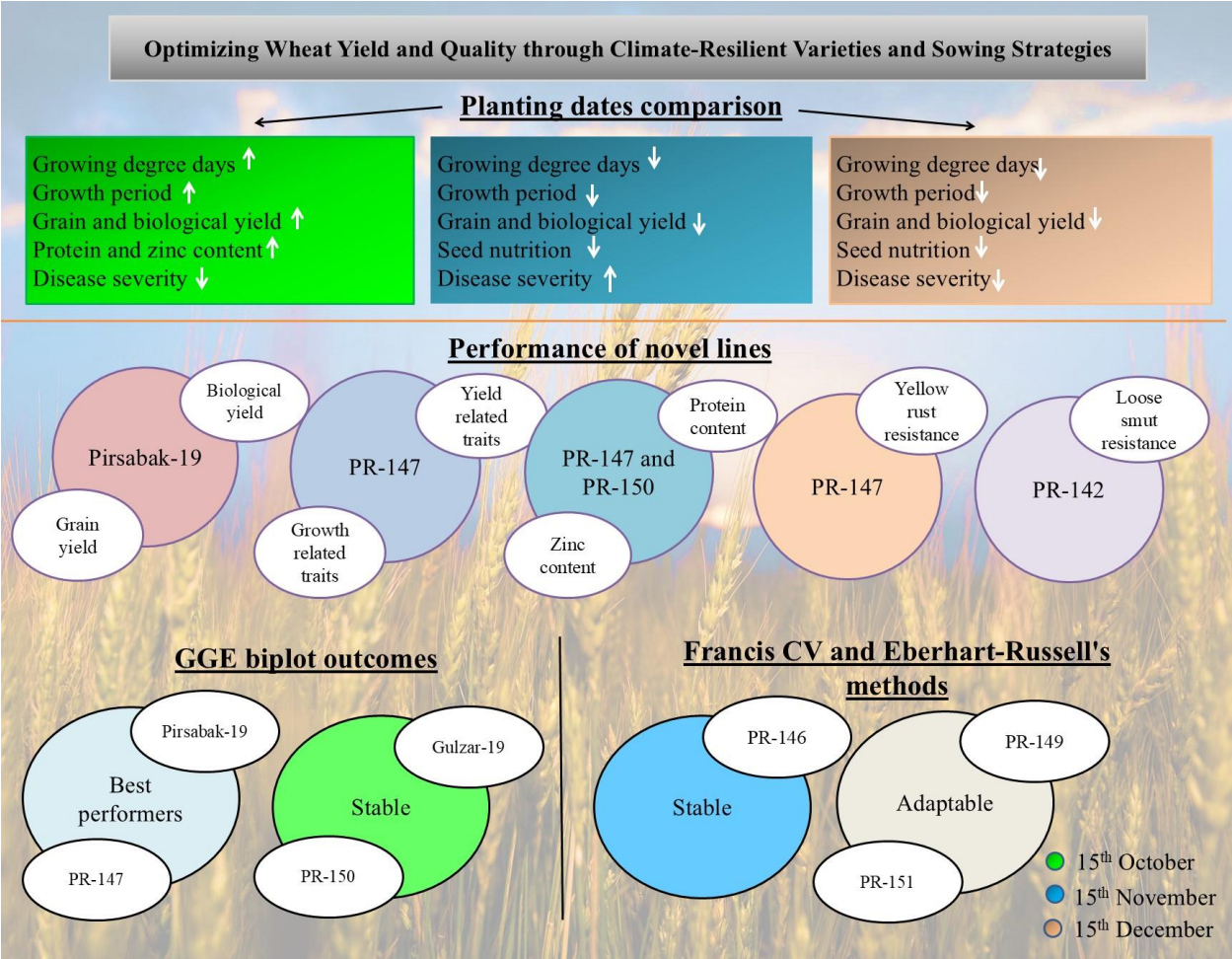[3]Department of Environmental Sciences, COMSATS University Islamabad, Vehari campus, Pakistan; farhansaeed@cuivehari.edu.pk (M.F.S)

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Optimizing Wheat Yield and Quality through Climate-Resilient Varieties and Sowing Strategies

Planting dates comparison

Growing degree days ↑
Growth period ↑
Grain and biological yield ↑
Protein and zinc content ↑
Disease severity ↓

Growing degree days ↓
Growth period ↓
Grain and biological yield ↓
Seed nutrition ↓
Disease severity ↑

Growing degree days ↓
Growth period ↓
Grain and biological yield ↓
Seed nutrition ↓
Disease severity ↓

Performance of novel lines

Pirsabak-19 — Biological yield, Grain yield

PR-147 — Yield related traits, Growth related traits

PR-147 and PR-150 — Protein content, Zinc content

PR-147 — Yellow rust resistance

PR-142 — Loose smut resistance

GGE biplot outcomes

Best performers — Pirsabak-19, PR-147

Stable — Gulzar-19, PR-150

Francis CV and Eberhart-Russell's methods

Stable — PR-146

Adaptable — PR-149, PR-151

● 15ᵗʰ October
● 15ᵗʰ November
○ 15ᵗʰ December

Graphical abstract

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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

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62 climate change and a growing population (Mottaleb et al., 2023). Consequently, food insecurity

63 remains a challenge in several regions.

64 Climate change threatens agriculture with increased temperatures, erratic weather, and emerging

65 pests and diseases, contributing to decreased yields and diminishing crop quality (Habib-ur-

66 Rahman et al., 2022). Adaptation is required to maintain production. Optimizing the planting

67 schedule is an efficient method for increasing wheat productivity by providing improved

68 conditions for growth and yield (Yusuf et al., 2019). Late planting exposes wheat crops to

69 unfavorably low temperatures at germination and excessive temperatures during the reproductive

70 phase, resulting in poor yields (Smita Gupta et al., 2017). Early planting results in stunted growth

71 and poor root development, which impact development, yield, and quality (Nahar et al., 2010).

72 Thus, adjusting planting dates has a substantial impact on the timing and length of vegetative and

73 reproductive growth stages, which are critical for optimizing the yields of small-grain cereals such

74 as wheat (El-Sarag and Ismaeil, 2013). Optimal planting time is highly significant for improving

75 wheat grain yield and baking quality because it establishes appropriate phenological,

76 environmental, and physiological conditions for adaptation (Qiao et al., 2023). Additionally,

77 choosing the right planting date controls the crop's access to vital resources, such as water, heat,

78 and sunlight (Silva et al., 2014). Thus, strategic plantation date management and cultivation of

79 corresponding varieties can boost wheat grain yield by 8% to 27% (Wang et al., 2020).

80 From an agricultural economics perspective, planting dates and varietal selection play critical roles

81 in influencing farm profitability and risk mitigation (Sánchez et al., 2022). Decisions regarding

82 input timing and crop choice affect not only yields, but also cost efficiency, resource allocation,

83 and resilience to market fluctuations (Mihrete and Mihretu, 2025). In particular, timely sowing can

84 reduce the need for late-stage interventions, thereby optimizing labor and fertilizer use (Tlatlaa et

85 al., 2024). Furthermore, climate-resilient varieties improve productivity stability, which is an

86 essential factor in ensuring income security for smallholder farmers under volatile weather

87 conditions (Acevedo et al., 2020). Integrating agronomic strategies with economic considerations

88 provides a comprehensive approach to address food security and sustainability (Mihrete and

89 Mihretu, 2025).

90 Increasing climate-resilient wheat varieties has the potential to increase yields, as variety

91 performance is influenced by genetic potential and environmental flexibility, whereas poor

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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 Fig. 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.

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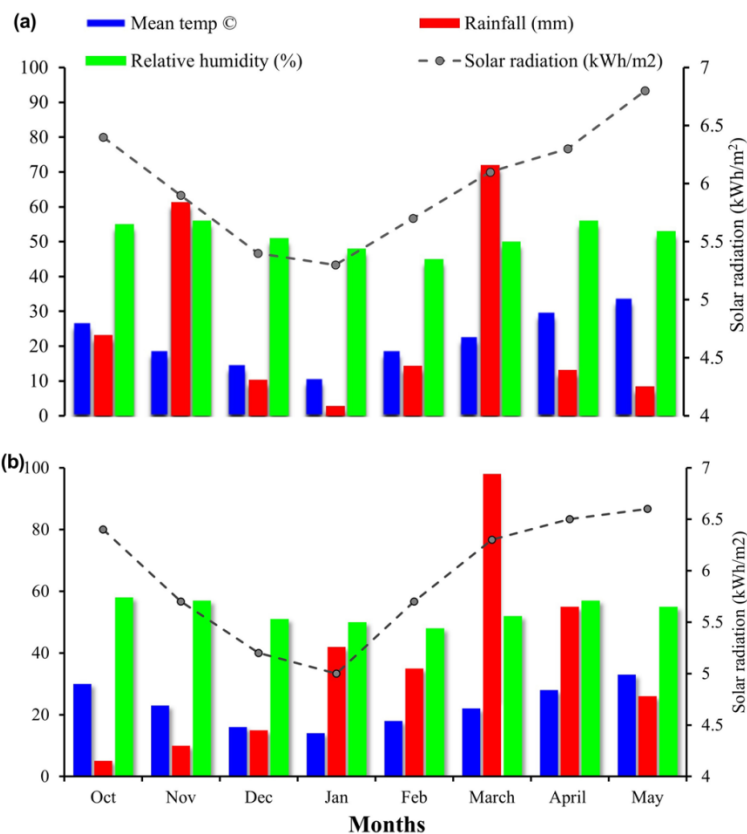
Figure 1: Meteorological data recorded during the 2021-22 (a) and 2022-23 (b) growing season.

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

Variety/	Pedigree	Origin
PR-142	KAUZ/ALTAR84/AOS/3/MILAN/KAUZ/4/…. /	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	SAWYT V-4 (2018-19)
PR-147	MUNAL*2/WESTONIA/4/KACHU/3/WHEAR//2*	ESWYT V-30 (2020-21)
PR-148	Pirsabak-13/ Khaista-17	FIX Line
PR-149	BORL14*2/8/REH/HARE//2*BCN/3/CROC_1/AE.SQUARROSA(213)//PGO/4/HUITES/5/T.DICOCCON PI94624/AE.SQUARROSA	SABWGPYT-5 V-35 (2019-20)
PR-150	WHEAR/VIVITSI//WHEAR/3/FRNCLN/5/SHORTENED SR26	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/	SRNV-113 (2011-12)
Gulzar-19	VORB/3/T.DICOCCONPI94625/AE.SQUARROSA	SAWYT V-15 (2012-13)
Pirsabak-	NAC/TH.AC//3*PVN/3/MIRLO/BUC/4/2*PASTO	ESWYTV-17

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130   *2.2 Agronomic management*

131   The field was initially organized by plowing with a cultivator, followed by the use of a rotavator

132   to create a consistent seedbed. The plot size was 3.2 m². Each plot was comprised four rows, each

133   3 m in length and spaced 30 cm apart. The same layout as in the first experiment was maintained

134   for the following year. Seeds of all the lines and varieties were planted in lines with the help of a

135   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

136   based on the percentage of nitrogen present in urea and was applied to plots in divided doses at the

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137 necessary growth stages. Half of the calculated amount was applied at sowing, and the remaining
138 half was applied at the tillering stage. The field received basal doses of phosphorus (P) and
139 potassium (K) at rates of 90 and 60 kg ha^{-1}, respectively, using single super phosphate and
140 potassium sulfate. Manual weeding was conducted at the boot stage in all plots. Furthermore,
141 irrigation was applied four times during the first year and five times during the second year using
142 flood irrigation across all the plots to ensure an adequate water supply.

2.3. Soil physiochemical analysis

144 Soil samples were collected from a depth of 5-15 cm using a soil auger for pre- plantation analysis
145 of soil physiochemical properties. The soil samples were then oven- dried and finely ground for
146 analysis of soil texture, pH, moisture, bulk density, electric conductivity, organic matter, organic
147 carbon, and available N, P, and K. The texture of the soil was determined using the method
148 described by Foth (1991), while pH and electric conductivity were determined by following the
149 procedures described by Herrera (2000). The method described by Alexander (1978) was used to
150 analyze the percentages of sand, silt, and clay by employing different sieves and measuring their
151 settling rates in a water solution using a hydrometer. soil organic matter and carbon were
152 determined using the wet oxidation method outlined by Walkley and Black (1934). Finally, the
153 available N, P, and K contents (mg kg^{-1}) were recorded using the Olsen extractant NaHCO$_3$
154 procedure (Olsen, 1954). The soil type, classified as Calcaric Luvisols according to the World
155 Reference Base (WRB) system of soil taxonomy, exhibited a sandy clay loam texture (39.4% sand,
156 29.4% silt, and 29.8% clay), an alkaline pH (7.68), and non-saline conditions (electrical
157 conductivity of 0.84 dS m^{-1}). It showed a low organic matter content (1.52 g kg^{-1}) and organic
158 carbon content (11.14 g kg^{-1}). The moisture content was 8.47%, and the soil bulk density was 1.68
159 gcm$^{-1.}$. Nutrient analysis revealed an available nitrogen content of 3.08 mg kg^{-1}, AB-DTPA
160 assimilable phosphorus content of 4.54 mg kg^{-1}, and potassium content of 79 mg kg^{-1}.

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2.4 Wheat physiology

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

$$GDD = (\text{Tmax} + \text{Tmin}) - \text{Tbase} \div 2$$

167 Here, Tmax is the daily maximum temperature.

168 Tmin is the daily minimum temperature.

169 Tbase is the base temperature specific to the crop.

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

175 ### *2.5. Growth and yield and its attributes*

176 The height of the three plants at maturity was measured using a meter stick. Grain spike^{-1} data
177 were determined by counting the grains in randomly selected spikes from each plot. Similarly, the
178 number of spikes m^{-2} was calculated by counting the spikes within randomly chosen 1m² areas in
179 each plot. Thousand-grain weight was measured for each subplot by weighing 1000 seeds per
180 subplot. To calculate the grain yield (kg ha^{-1}), the grains from the central two rows were harvested
181 in each plot, weighed using an electronic scale, and then converted using equation 1 (Saeed et al.,
182 2021). Biological yield was determined by harvesting four rows from each subplot, drying the
183 material in the sun for five days, and subsequently weighing and converting the data to kg ha^{-1}
184 using equation 2 (Saeed et al., 2021).

185 Grain yield (kg ha^{-1})

186 $$= \frac{\text{Biological yield in 4 central rows}}{\text{R} - \text{R distance (m)} \times \text{Row length(m)} \times \text{No. of rows}} \times 10000 \text{ m}^2 \quad (1)$$

187 Biological yield (kg ha^{-1})

188 $$= \frac{\text{Total plant weight in 4 central rows}}{\text{R} - \text{R distance (m)} \times \text{Row length(m)} \times \text{No. of rows}} \times 10000 \text{m}^2 \quad (2)$$

189 ### *2.6. Grain quality*

190 For grain protein content (%), a Micro-kjeldahl (C, 1883) setup was used to convert digestion and
191 distillation samples into a saturated boric acid solution, from which the total nitrogen content was

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192 determined. The percentage of protein was calculated by applying a constant factor of 6.25 to the

193 grain nitrogen content. For the zinc content analysis, grains were randomly selected from all plots,

194 oven-dried, finely ground, and digested in HNO_3. The zinc content in the digest samples was

195 subsequently analyzed using an atomic absorption spectrophotometer and expressed in mg kg^{-1}.

196 ### 2.7. Disease incidence

197 Yellow rust (during anthesis) and loose smut severity (during grain filling) assessments were

198 conducted for all evaluated wheat lines/varieties across various treatments using the Modified

199 Cobb Scale (Peterson et al., 1948). This visual observation method employs a percentage-based

200 scoring system to assess disease incidence. Specifically, disease severity was categorized as

201 follows: 0-5% indicating a high level of resistance, 6-10 % representing resistance, 11-20 %

202 denoting moderate resistance, 21-30 % reflecting moderate susceptibility, 31-50 % indicating

203 susceptibility, and 51-100% signifying a high level of susceptibility to the diseases.

204 ### 2.8 Statistical analysis

205 The collected data were statistically analyzed using analysis of variance (ANOVA) as appropriate

206 for split-plot RCBD using the statistical package Statistix8.1 (Statistix8.1, Tallahassee, FL, USA)

207 (Steel and Torrie, 1960). If the F values were significant, the means were compared using the Least

208 Significant Difference (LSD) test at p = 0.05 probability levels.

209 ## 3. Results

210 ### 3.1. Wheat physiology

211 The growing degree days (GDD) required for different physiological stages of wheat varied

212 significantly based on planting date (PD). Earlier planting (15th October) demanded significantly

213 higher GDD for tiller initiation, anthesis, and maturity stages than later plantings (15th November

214 and 15th December) in both years (Fig.2). For PD1, representing October 15th, the crop required

215 455 and 432 GDD for tiller initiation, 896 and 898 GDD for the anthesis stage, and 1870 and 1890

216 GDD for maturity. PD2, corresponding to planting on November 15th, required 342 and 315 GDD

217 for tiller initiation, 832 and 843 GDD for anthesis, and 1609 and 1619 GDD for reaching maturity.

218 Lastly, wheat planted late in both seasons (15th December) progressed through these stages more

219 swiftly, likely due to warmer conditions, that recorded 271 and 279 GDD for tiller initiation, 813

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and 823 GDD for anthesis, and 1549 and 1510 GDD for maturity in 2021-22 and 2022-23, respectively (Fig. 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 ± 0 days) as compared to early planting (6 ± 1 days). The number of days plants took to produce anthers was significantly reduced as planting was delayed (ranging from 116 ± 3 to 136 ± 3 days). Among the tested lines and checks, late anthesis was recorded for Gulzar-19 and Pirsabak-19 (129 ± 8 days), and early anthesis was noted for PR-151 and PR-152 (126 ± 9 and 126 ± 10 days). Early Planting extended the maturity period (170 ± 3 days) in October compared to December (146 ± 2 days) (Table 2). Moreover, a prolonged growth period leading to maturity was observed in Khaista-17 and PR-152 (164 ± 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 (Fig 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.

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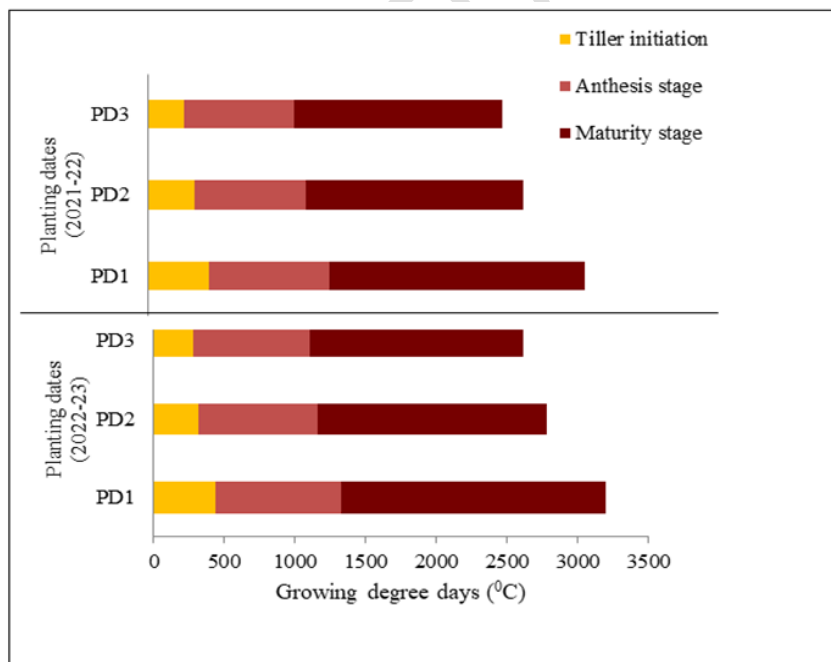
238   **Figure 2.** Variation in GDD among different planting dates for Physiological stages of wheat lines

239   during 2021-22 and 2022-23.

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244 **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$\pm$1 c	6$\pm$1c	6$\pm$1 c	134$\pm$2 a	139$\pm$2 a	136$\pm$3 a	170$\pm$2 a	173$\pm$3 a	170$\pm$3 a
15th Nov	9$\pm$0 b	9$\pm$1b	9$\pm$0 b	126$\pm$3 b	132$\pm$2 b	129$\pm$4 b	163$\pm$3 b	164$\pm$3 b	163$\pm$3 b
15th Dec	12$\pm$0 a	13$\pm$1a	13$\pm$0 a	114$\pm$3 c	117$\pm$1 c	116$\pm$3 c	147$\pm$2 c	145$\pm$2 c	146$\pm$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$\pm$3	9$\pm$3	9$\pm$2	125$\pm$11 c	129$\pm$10	127$\pm$11 c	159$\pm$9 e	159$\pm$11 g	159$\pm$10 e
PR-146	9$\pm$2	9$\pm$3	9$\pm$3	125$\pm$7 c	129$\pm$10	127$\pm$9 c	158$\pm$9 f	158$\pm$13 f	158$\pm$11 f
PR-147	9$\pm$2	9$\pm$3	9$\pm$2	125$\pm$9 c	129$\pm$10	127$\pm$9 c	158$\pm$10 f	158$\pm$12 f	158$\pm$11 f
PR-148	9$\pm$2	10$\pm$3	9$\pm$3	125$\pm$9 c	129$\pm$9 bc	127$\pm$9 c	159$\pm$11 e	159$\pm$13 e	159$\pm$11 e
PR-149	9$\pm$3	9$\pm$3	9$\pm$3	124$\pm$8 d	129$\pm$10	127$\pm$9 c	160$\pm$11 d	161$\pm$12 c	161$\pm$11 c
PR-150	9$\pm$3	9$\pm$3	9$\pm$2	126$\pm$7 b	129$\pm$8 bc	128$\pm$7 b	158$\pm$10 f	157$\pm$13 h	158$\pm$11 f
PR-151	9$\pm$2	9$\pm$3	9$\pm$3	124$\pm$8 d	128$\pm$9 c	126$\pm$9 d	161$\pm$11 c	163$\pm$13 b	162$\pm$12 b
PR-152	9$\pm$2	9$\pm$3	9$\pm$3	124$\pm$10 d	128$\pm$11 c	126$\pm$10 d	163$\pm$11 b	165$\pm$14 a	164$\pm$12 a
Khaista-17	9$\pm$2	9$\pm$3	9$\pm$3	125$\pm$9 c	131$\pm$11 a	128$\pm$10 b	164$\pm$11 a	165$\pm$13 a	164$\pm$12 a
Gulzar-19	9$\pm$2	10$\pm$3	9$\pm$3	127$\pm$12 a	131$\pm$10 a	129$\pm$11 a	160$\pm$10 d	160$\pm$12 d	160$\pm$11 d
Pirsabak-19	9$\pm$2	9$\pm$3	9$\pm$2	127$\pm$7 a	130$\pm$9 b	129$\pm$8 a	160$\pm$10 d	161$\pm$12 c	161$\pm$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			1.6			0.8	

245 ***= very highly significant at P ≤ 0.05, **= highly significant at P ≤ 0.05 and *= significant at P ≤ 0.05;

246 NS= non-significant. The data are reported as means of 3 replicates ± standard deviation. Means followed

247 by the same letter do not significantly differ at p ≤ 0.05 according to Tukey's test.

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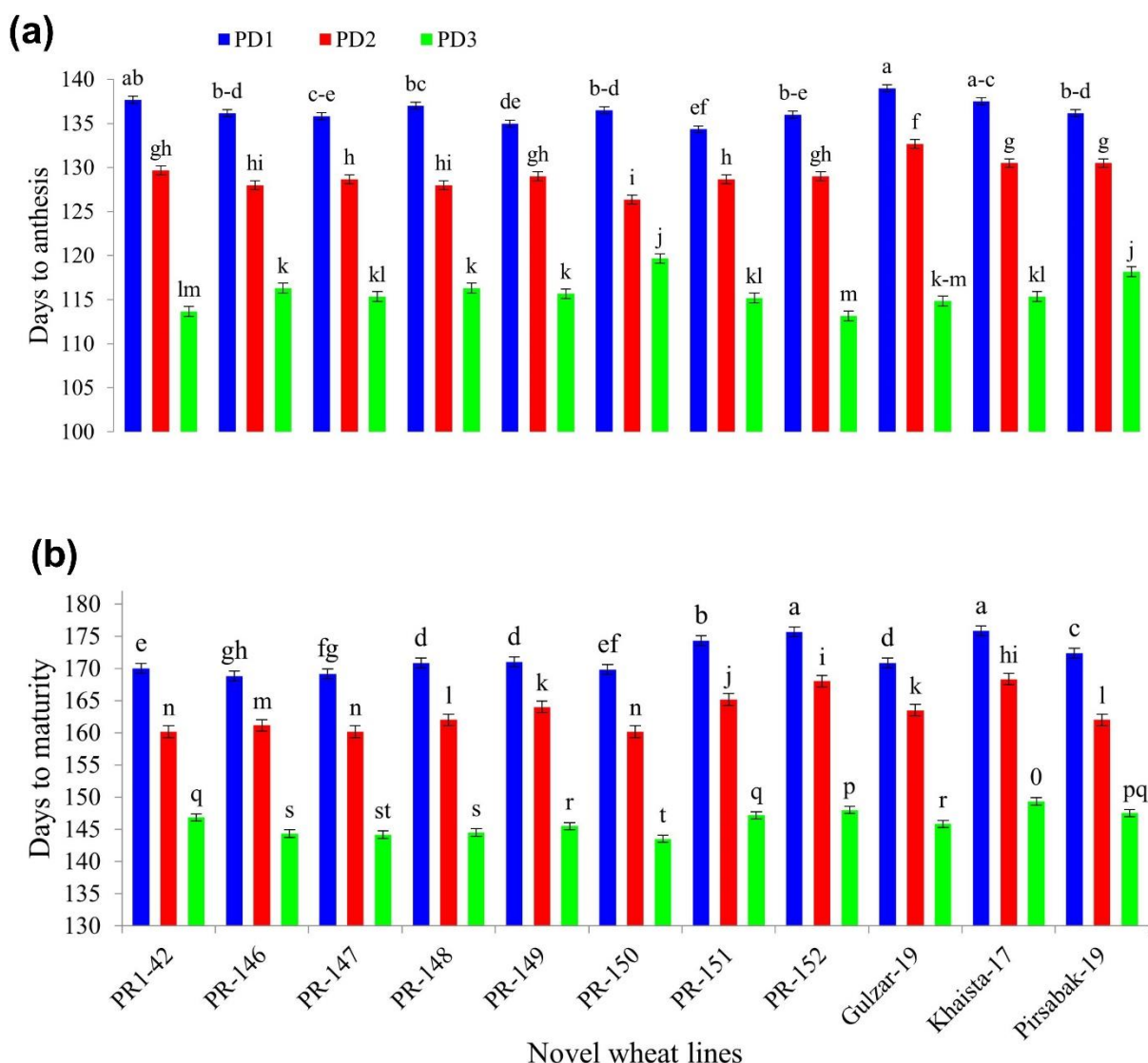
Figure 3. Interactive effect of planting dates and wheat lines on days to anthesis (a) and days to maturity (b) of wheat in 2021-22 and 2022-23. The data are reported as a means of 3 replicates. Means followed by the same letter do not significantly differ at p ≤ 0.05 according to Tukey's test. The bars 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$\pm$9 cm), while December 15th planting resulted in the shortest (90$\pm$8 cm) in successive years. Among the wheat lines, PR-149

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258 displayed the tallest plants (110$\pm$7 cm), whereas PR-142 had the shortest (81$\pm$5 cm) (Table 3). The

259 interaction between (PD $\times$ L) indicated a decrease in plant height for all wheat lines when planting

260 was delayed beyond October 15th (Fig 4a). Specifically, PR-149 plants were tallest when the crop

261 was planted on October 15th.

262 In terms of planting dates, October 15th yielded the highest grains spike^{-1} (45$\pm$7), while the lowest

263 was observed on December 15th (30$\pm$4). Among the wheat lines, PR-147 and Pirsabak-19

264 demonstrated the highest grains spike^{-1} (46$\pm$10), whereas a lower grains spike^{-1} (33$\pm$5) was

265 recorded for PR-142 in both years. These results were also reflected in the interactive effect of

266 PD$\times$L (Fig. 4b).

267 Among the planting dates, October 15th produced the highest number of spikes m^{-2} (350$\pm$15)

268 compared to December 15th (278$\pm$14). Similarly, spikes m^{-2} was observed the highest for Pirsabak-

269 19 (328$\pm$33) and statistically at par with PR-147 (324$\pm$32). In contrast, spike m^{-2} was the lowest

270 for PR-142 (304$\pm$38) as shown in Table 3. Thousand grain weight displayed notable differences

271 with 15th October producing better results (41.7$\pm$3.6 g) than the rest of the planting dates. Among

272 the wheat lines, the heaviest grains were recorded for Pirsabak-19 (40.6$\pm$5.3 g) and PR-147

273 (41.1$\pm$5.3 g), while lighter grains were produced by PR-142 (33.1$\pm$3.2 g) (Table 4). The interactive

274 effects (PD $\times$ L) showed that the thousand- grain weights of PR-147 and Pirsabak-19 were higher

275 on 15th October compared on other dates (Fig 4c).

276   The grain yield of wheat lines was influenced by both PD and L. For planting dates, October 15th

277 resulted in the highest grain yield (4270$\pm$604 kg ha^{-1}), and December 15th had the lowest yield

278 (2001$\pm$465 kg ha^{-1}). The highest grain yield was noted for Pirsabak-19 (3875$\pm$1138 kg ha^{-1}) and

279 the lowest for Khaista-17 (2729$\pm$1152 kg ha^{-1}), PR-148 (2573$\pm$1092 kg ha^{-1}), and PR-152

280 (2748$\pm$1074 kg ha^{-1}), as presented in Table 4. Among the PD, October 15th yielded the highest

281 biological yield (11851$\pm$1579 kg ha^{-1}) and the lowest was recorded on December 15th (6571$\pm$1101

282 kg ha^{-1}). The highest biological yield was observed for Pirsabak-19 (10791$\pm$2528 kg ha^{-1}) and the

283 lowest for PR-148 (7620$\pm$2548 kg ha^{-1}). The interaction between (PD$\times$L) indicated that as planting

284 was delayed, both grain and biological yields decreased for all wheat lines (Fig. 5a and 5b).

285 Specifically, Pirsabak-19 and PR-149 recorded maximum grain yield, with only Pirsabak-19

286 attaining the highest biological yield on 15th October compared to other planting dates.

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-	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	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	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	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	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	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.

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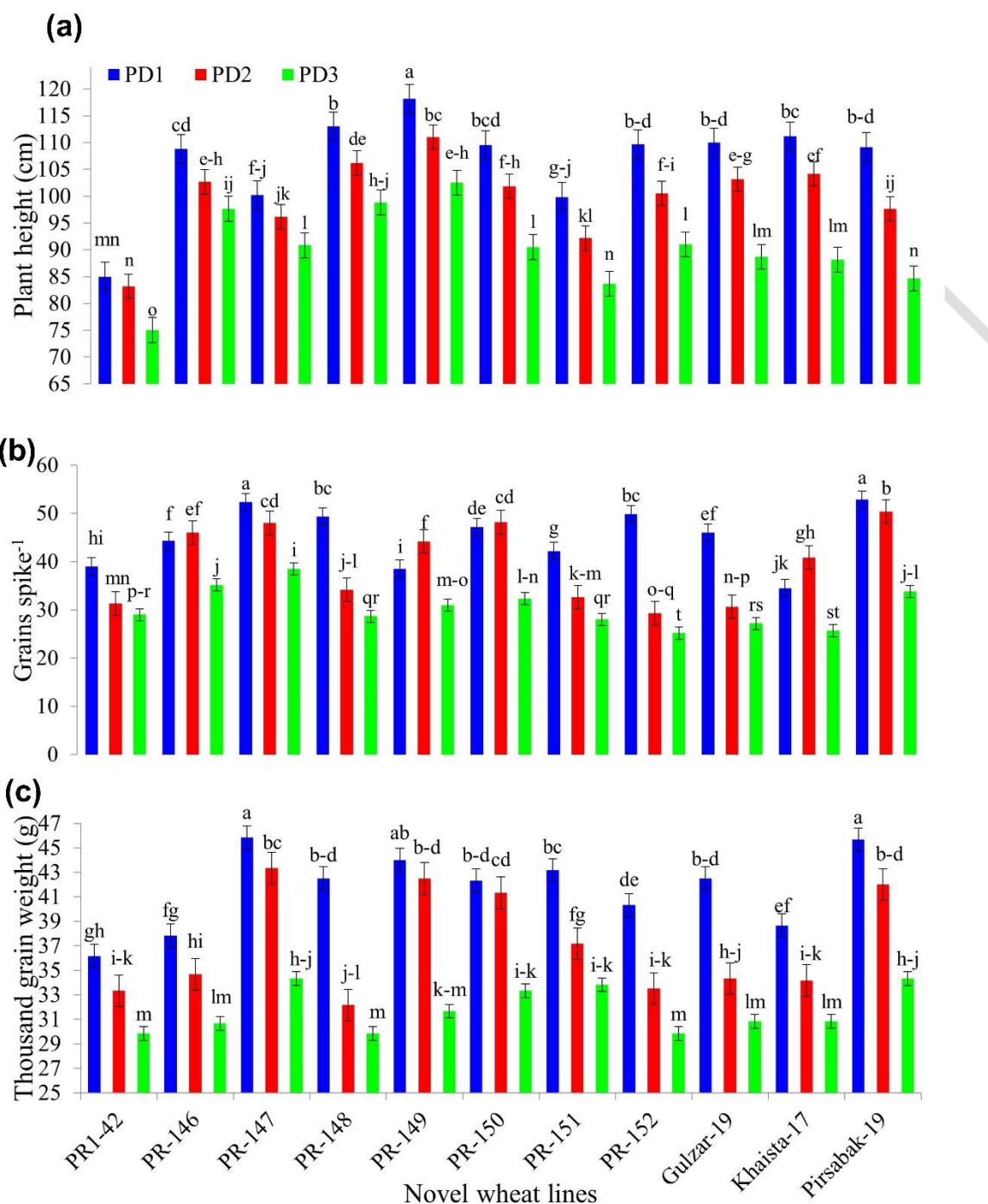
Figure 4: Interactive effect of planting dates and wheat lines on plant height (a), grains spike^{-1} (b) and thousand grain weight (c) of wheat in 2021-22 and 2022-23. The data are reported as means of 3 replicates. Means followed by the same letter do not significantly differ at p ≤ 0.05 according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

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299   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±127	12119±181	11851±157
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	7509±1228	7540±1122
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	6505±1089	6571±1101
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	3202±953 d	3027±781	7725±1352	7692±1358	7708±1315
PR-146	33.6±3.6 d	35.2±3.3 e	34.4±3.5 e	3140±715	3230±920	3235±806 c	8020±1460	8114±1487	8067±1430
PR-147	40.7±4.8 a	41.6±6.0	41.1±5.3 a	3533±776 b	3716±892	3625±817 b	9776±2089	9917±2135	9847±2051
PR-148	34.3±5.7 c	35.3±6.4	34.8±5.9	2575±1100	2572±1151	2573±1092	7859±2728	7381±2495	7620±2548
PR-149	39.2±5.4 b	39.5±6.8	39.4±6.0 b	3318±1195	3619±1274	3468±1208	8952±1976	9625±2818	9288±2386
PR-150	38.9±4.5 b	39.1±5.9 c	39.0±5.1	3043±1082	3220±1019	3182±1030	8062±1868	8132±1939	8097±1847
PR-151	38.8±3.5 b	37.3±6.6	38.0±5.2 c	2879±1124	3139±1366	3009±1221	8198±3554	8142±3749	8170±3544
PR-152	34.0±4.9	35.1±4.9	34.5±4.8 e	2655±1088	2841±1116	2748±1074	8189±3054	8333±3683	8261±3283
Khaista-17	34.2±3.3 c	34.2±4.3 e	34.5±3.8 e	2709±1216	2749±1159	2729±1152	8306±3328	8698±4418	8502±3800
Gulzar-19	34.4±5.1 c	37.3±5.8	35.8±5.5 d	3126±1035	3301±988	3214±985	8810±1678	8879±1626	8845±1603
Pirsabak-	39.2±5.1 b	42.1±5.5 a	40.6±5.3 a	3785±1125	3966±1212	3875±1138	10675±212	10906±300	10791±252
LSD $_{(0.05)}$	0.6	2.4	1.2	204	336	140	228	197	149
Year		Ns			*			**	
PD×L		2.3			390			267	

300   ***= very highly significant at P ≤ 0.05, **= highly significant at P ≤ 0.05 and *= significant at P ≤ 0.05;

301   NS= non-significant. The data are reported as a means of 3 replicates ± standard deviations. Means ± standard

302   error followed by the same letter are not significantly different for p ≤ 0.05 according to Tukey's test.

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(a)

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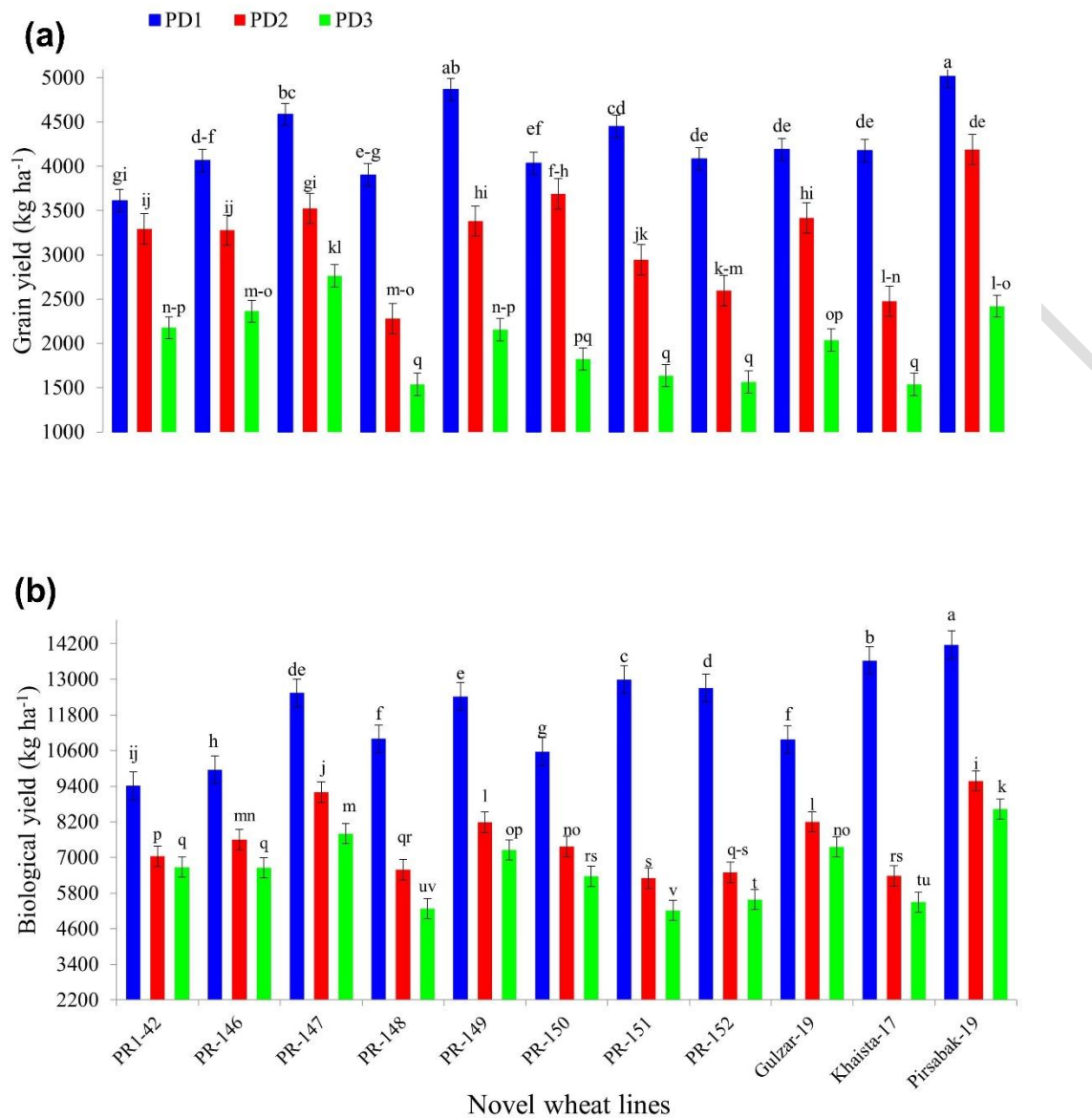
Figure 5: Interactive effect of planting dates and wheat lines on grain yield (a) and biological yield (b) of wheat in 2021-22 and 2022-23. The data are reported as a means of 3 replicates. Means followed by the same letter do not significantly differ at $p \leq 0.05$ according to Tukey's test. The bars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

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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$\pm$1.24 %) was observed in crops sown on October 15[th], followed by those planted on November 15[th] (11.09$\pm$0.95 %). The lowest grain protein content was recorded in crops sown on December 15[th] (8.67$\pm$1.45 %). Regarding wheat lines, PR-147 (11.57$\pm$1.69 %) and PR-150 (11.94$\pm$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$\pm$1.65 mg kg^{-1}) concentration, which was statistically similar to those sown on November 15[th] (31.17$\pm$1.87 mg kg^{-1}). The lowest zinc (28.58$\pm$0.84 mg kg^{-1}) content was observed in crops sown on December 15[th] (Table 5). Among the wheat lines, PR-150 had the highest (33.92$\pm$3.42 mg kg^{-1}) zinc content, while, PR-152 (29.26$\pm$1.43 mg kg^{-1}), Pirsabak-19 (29.36$\pm$1.27 mg kg^{-1}) and PR-146 (29.39$\pm$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 (Fig. 6a), whereas PR-150 recorded the highest zinc content when sown on both October 15th and November 15th (Fig 6b).

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329 **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		

330 ***= very highly significant at P ≤ 0.05, **= highly significant at P ≤ 0.05 and *= significant at P ≤ 0.05.

331 The data are reported as a means of 3 replicates ± standard deviations. Means ± standard error followed by

332 the same letter are not significantly different for p ≤ 0.05 according to Tukey's test.

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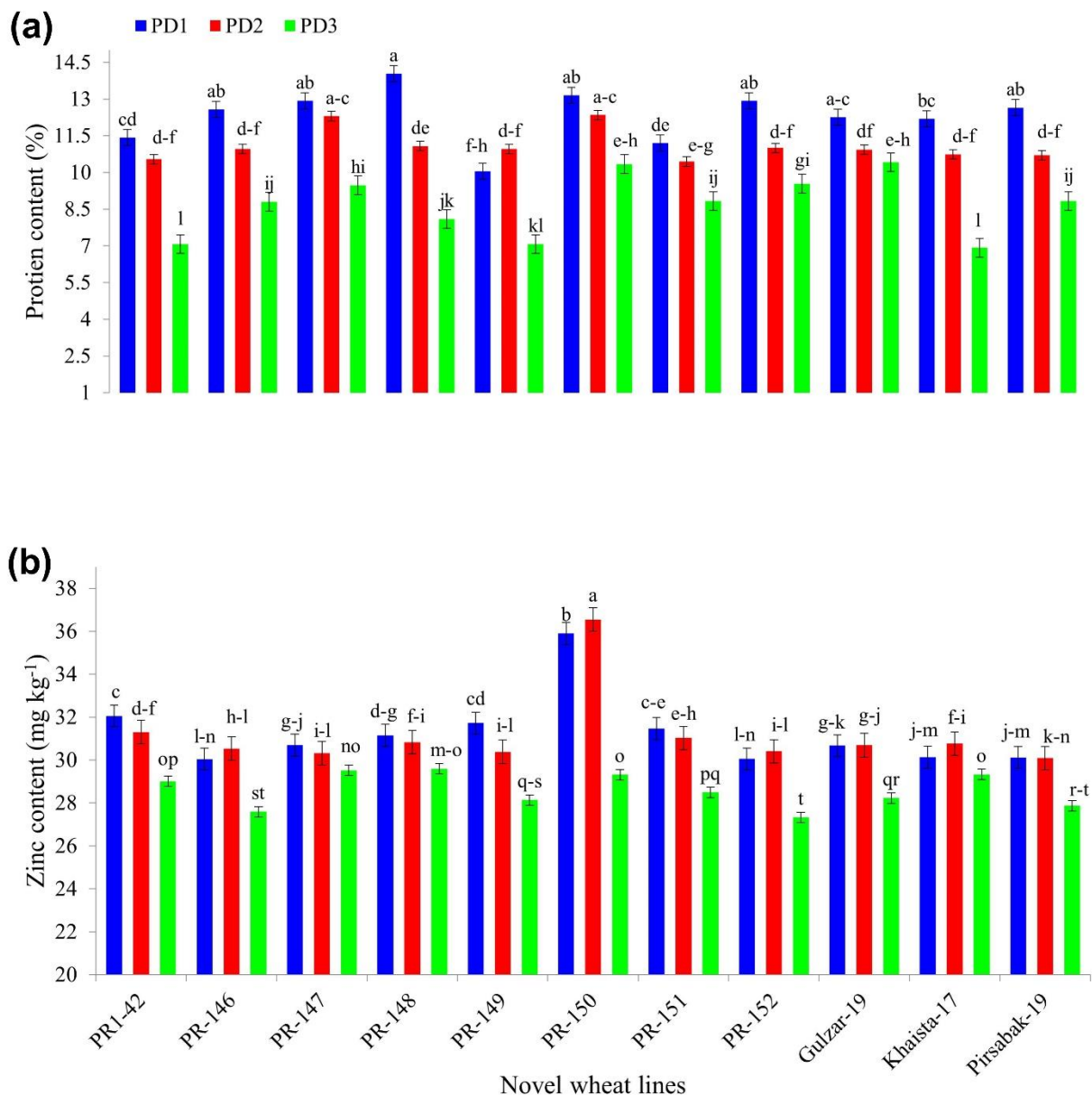
Figure 6: Interactive effect of planting dates and wheat lines on grain protein (a), and grain zinc (b) content of wheat in 2021-22 and 2022-23. The data are reported as a means of 3 replicates. Means followed by the same letter do not significantly differ at p ≤ 0.05 according to Tukey's test. The bars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

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343   15th (20.9$\pm$4.3 %) and November 15th (23.3$\pm$4.1 %). Among the wheat lines, PR-147 was classified

344   as resistant to yellow rust (15.5$\pm$3.0 %), while PR-150 exhibited the highest susceptibility

345   (23.3$\pm$5.9 %) (Table 6).

346   Similarly, the incidence of loose smut showed significant variations based on both planting dates

347   and wheat lines. The highest severity was recorded in crops sown on October 15th and November

348   15th, whereas the lowest severity (14.1$\pm$4.1 %) was observed in crops planted on December 15th.

349   Among the wheat lines, PR-142 and PR-152 showed the highest resistance to loose smut (15.7$\pm$3.2

350   and 15.7$\pm$2.9 %, respectively), while PR-149 was the most susceptible (27.1$\pm$1.8%) (Table 6).

351   The interaction between planting dates and wheat lines (PD×L) revealed that the severity of both

352   yellow rust and loose smut was higher in early (October 15th) and mid-early (November 15th)

353   sowings, whereas late planting (December 15th) consistently resulted in the lowest disease

354   severity across all wheat lines and check varieties (Fig 7a and 7b).

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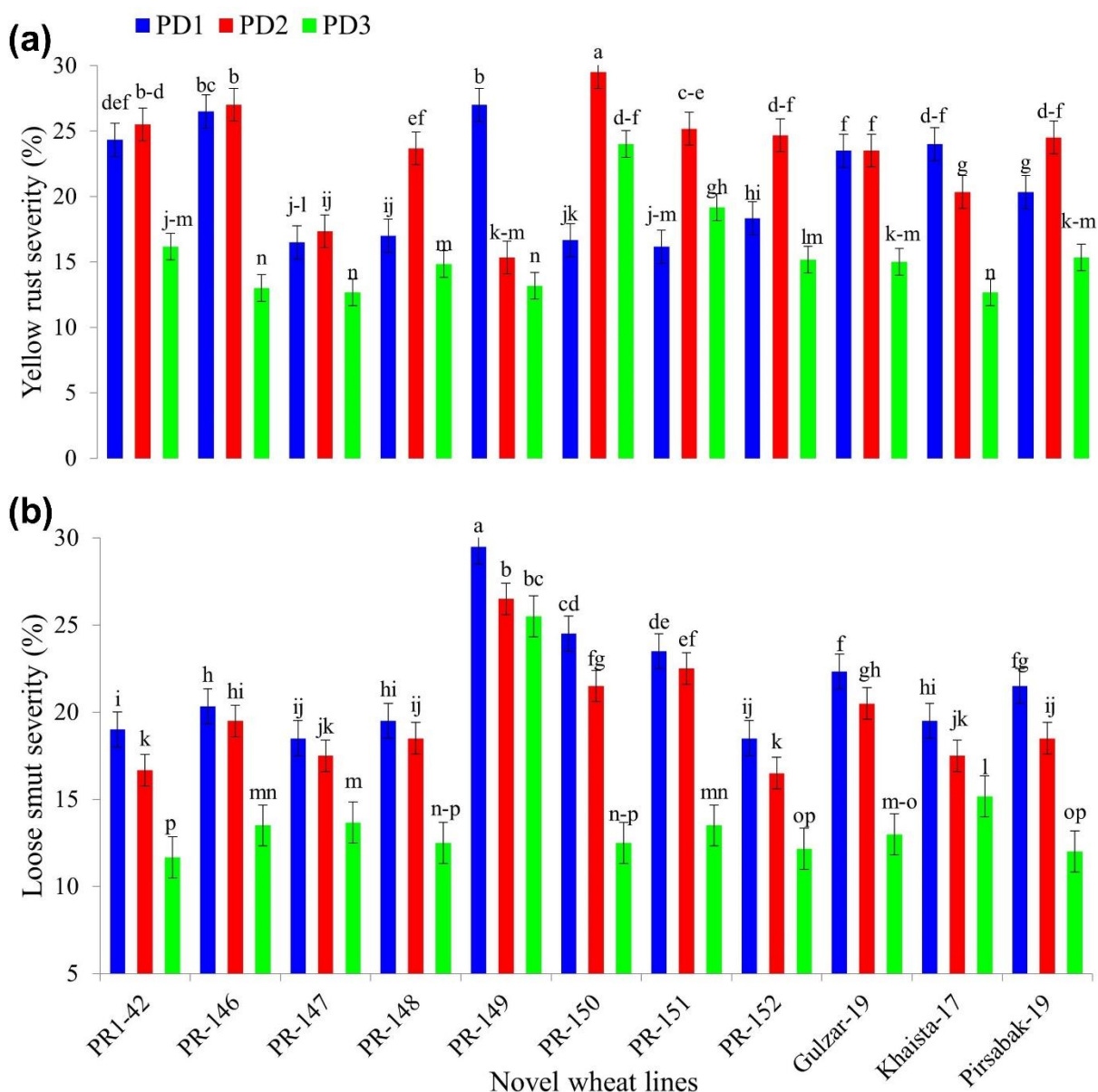
Figure 7: Interactive effect of planting dates and wheat lines on disease incidence, yellow rust (a) and loose smut (b) of wheat in 2021-22 and 2022-23. The data are reported as means of 3 replicates. Means followed by the same letter do not significantly differ at $p \leq 0.05$ according to Tukey's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

3.4. 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

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382 (centering, 2) and dual-metric-preserving (SVP, 2) methods in GEA-R software, with no scaling
383 applied. The resulting biplots accounted for 92% of the total variation, with the first principal
384 component (PC1) explaining 73.26% and the second principal component (PC2) explaining
385 18.93%.

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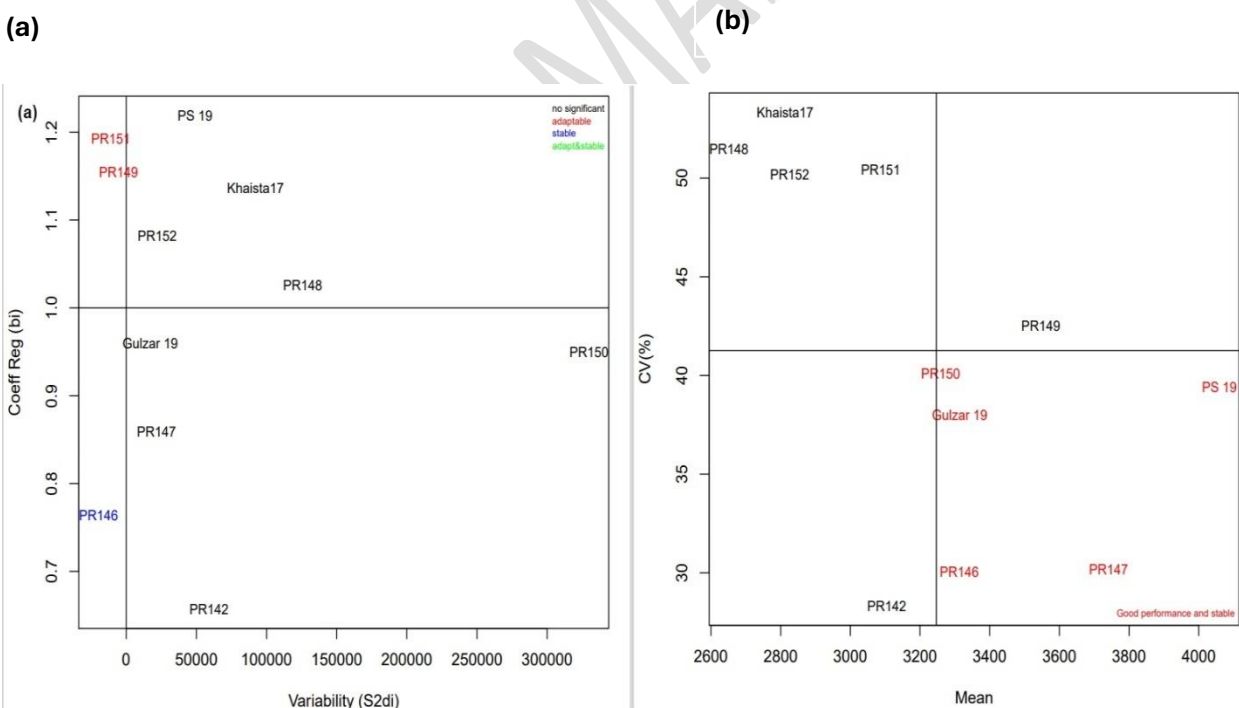393 planting dates .

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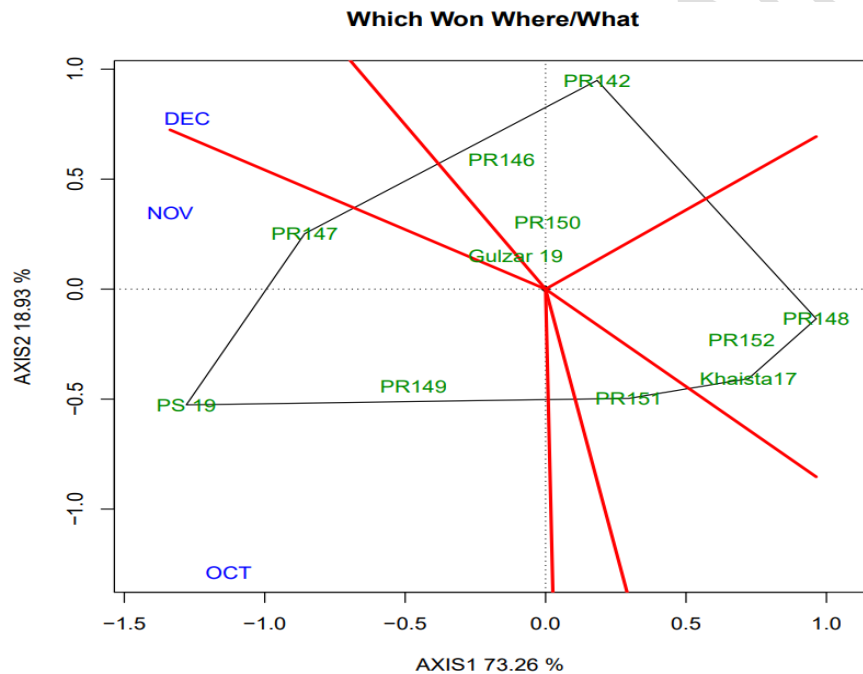
395 **Figure 8:** Polygon view of GGE biplot for wheat lines across three planting dates in terms of
396 grain yield.

397 *3.5. Stability analysis*

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

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

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411 **(a)**   **(b)**

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

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: 15th 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 15th) 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 15th resulted in a longer anthesis period, while later planting on December 15th 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).

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 15th) 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 15th planting produced the highest number of grains per spike, while delayed plantation reduced emergence and impaired grain development (Shah et al., 2020).

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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

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474 lowest in December 15th planting and greatest on November 15th, since delayed planting minimized
475 exposure to favorable conditions (Singh et al., 2009). PR-142 was the most resistant, whereas PR-
476 149 was greatly affected, consistent with the observations of Kharina and Amunova (2020).

477 GGE biplot analysis (Yan and Tinker, 2006) revealed that Pirsabak-19, PR-147, and PR-149 were
478 the most stable and highest yielding genotypes across different planting dates. The genotype-
479 environment interaction (GEI) had a significant effect on yield, with the environment contributing
480 the largest portion of t variation (Ghazy et al., 2023). PR-146 demonstrated stability across planting
481 dates, consistent with the Eberhart and Russell (E-R) model, where regression values greater than
482 1 indicate genotypic stability across environments (Ibrahim HA, 2021).

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

492 **5. Conclusions**

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

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References

ABDELKHALIK, S. A. M. & HAGRAS, A. A. E.-A. 2021. Behavior of some Egyptian bread wheat genotypes under different natural photo-thermal environments. *Egypt J Agric Res* 99**,** 142-157.http://dx.doi.org/10.21608/ejar.2021.62280.1081

ACEVEDO, E., SILVA, P. & SILVA, H. 2002. Wheat growth and physiology.Bread wheat, improvement and production. *CIMMYT,* 30**,** 39-70

ACEVEDO, M., PIXLEY, K., ZINYENGERE, N., MENG, S., TUFAN, H., CICHY, K., BIZIKOVA, L., ISAACS, K., GHEZZI-KOPEL, K. & PORCIELLO, J. 2020. A scoping review of adoption of climate-resilient crops by small-scale producers in low-and middle-income countries. *Nature plants,* 6**,** 1231-1241.https://doi.org/10.1038/s41477-020-00783-z

AFZAL, A., IJAZ, N., ASHRAF, S., NAWAZ, H. H., IQBAL, J., ALTAF, R. & SYED, S. 2022. Determination of relationship of environmental factors with stripe rust in wheat. *Plant Prot. Sci,* 6**,** 151-159.https://doi.org/10.33804/pp.006.02.4256

AHMED, S. F., AHMED, J. U., HASAN, M. & MOHI-UD-DIN, M. 2023. Assessment of genetic variation among wheat genotypes for drought tolerance utilizing microsatellite markers and morpho-physiological characteristics. *Heliyon,* 9.https://doi.org/10.1016/j.heliyon.2023.e21629

ALEXANDER, M. 1978. Introduction to soil microbiology. *Soil Sci* 125**,** 331

ANDERSON, J. R. & DILLON, J. L. 1992. *Risk analysis in dryland farming systems*, Food & Agriculture Org.

ASLAM, M. A., AHMED, M., STÖCKLE, C. O., HIGGINS, S. S., HASSAN, F. U. & HAYAT, R. 2017. Can growing degree days and photoperiod predict spring wheat phenology? *Front Environ Sci* 5**,** 57.https://doi.org/10.3389/fenvs.2017.00057

C, K. 1883. A new method for the determination of nitrogen in organic matter. . *Z Anal Chem,* 22**,** 366

CAO, J., SHANG, Y., XU, D., XU, K., CHENG, X., PAN, X., LIU, X., LIU, M., GAO, C. & YAN, S. 2020. Identification and validation of new stable QTLs for grain weight and size by multiple mapping models in common wheat. *Front Genet* 11**,** 584859.https://doi.org/10.3389/fgene.2020.584859

561 CHOUDHARY, L., GOYAL, V., PANDEY, S., MOITRA, P. & SHUKLA, R. 2020. Assessment of
562   genetic variability in advance breeding lines of wheat. *Pharma Innov J* 9**,** 239-244

563 DESTA, B. T., GEZAHEGN, A. M., ESHETU, S. & TAKELE, A. 2020. Optimizing sowing date
564   for the productivity of durum wheat (*Triticum turgidum* L. var. Durum) in Central Highland
565   of Ethiopia. *Agric Forestry Fish* 9**,** 28-32.https://doi.org/10.11648/j.aff.20200902.12

566 DEV, W.-S., GENG, X.-L., HU, D.-W., MEMON, S., ABRO, A. A. & MEMON, S. 2019.
567   Screening of bread wheat genotypes on physiological and agronomical traits in high
568   temperature at different planting.

569 E, H. 2000. *Soil Test Interpretations Guide A-122.*, New Mexico State University Board of
570   Regents.

571 EL-SARAG, E. I. & ISMAEIL, R. I. 2013. Evaluation of some bread wheat cultivars productivity
572   as affected by sowing dates and water stress in semi-arid region. *Asian J Crop Sci* 5**,** 167-
573   178.https://doi.org/10.3923/ajcs.2013.167.178

574 FARHAD, M., KUMAR, U., TOMAR, V., BHATI, P. K., KRISHNAN J, N., BAREK, V.,
575   BRESTIC, M. & HOSSAIN, A. 2023. Heat stress in wheat: a global challenge to feed
576   billions in the current era of the changing climate. *Front Sustainable Food Syst,* 7**,**
577   1203721.https://www.doi.org/10.3389/fsufs.2023.1203721

578 FOTH, H. D. 1991. *Fundamentals of soil science,* USA, John Wiley & Sons, Inc., Hoboken, NJ, .

579 GHAZY, M. I., ABDELRAHMAN, M., EL-AGOURY, R. Y., EL-HEFNAWY, T. M., EL-NAEM,
580   S. A., DAHER, E. M. & REHAN, M. 2023. Exploring Genetics by Environment
581   Interactions in Some Rice Genotypes across Varied Environmental Conditions. *Plants,* 13**,**
582   74.https://doi.org/10.3390/plants13010074

583 HABIB-UR-RAHMAN, M., AHMAD, A., RAZA, A., HASNAIN, M. U., ALHARBY, H. F.,
584   ALZAHRANI, Y. M., BAMAGOOS, A. A., HAKEEM, K. R., AHMAD, S. & NASIM, W.
585   2022. Impact of climate change on agricultural production; Issues, challenges, and
586   opportunities in Asia. *Front Plant Sci,* 13**,**
587   925548.https://doi.org/10.3389/fpls.2022.925548

588 HOPKINS, B. G. & HANSEN, N. C. 2019. Phosphorus management in high-yield systems. *J.*
589   *Environ. Qual,* 48**,** 1265-1280.https://doi.org/10.2134/jeq2019.03.0130

590 HUSSAIN, I., IJAZ, M., UL-ALLAH, S., SATTAR, A., SHER, A., NAWAZ, A., GHAFFAR, A.,
591   RAHMAN, M. H. U., AHMAD, S. & RASHEED, I. 2023. Optimum zinc fertilization and

33

sowing date improved growth, yield components, and grain Zn contents of bread wheat under different tillage systems. *J Soil Sci Plant Nutr* 23**,** 2344-2353.http://dx.doi.org/10.1007/s42729-023-01185-8

HUSSAIN, L. S., AHMED, S., HISBANI, M. A., MIHAS, A. A., AHMED, A., CHANDIO, M. A. & KUMBHAR, S. 2018. Effect of different sowing dates on growth and yield of candidate wheat varieties. *Natl J Adv Res* 4**,** 41-46

IBRAHIM HA, I. A., ALI KA 2021. Genotype by environment interaction and stability analyses of grain yield of selected maize (*Zea mays* L.) genotypes in eastern and central Sudan. . *Gezira J Agric Sci* 17**,** 294–312.

JAMAL, A., SAEED, M. F., MIHOUB, A., HOPKINS, B. G., AHMAD, I. & NAEEM, A. 2023. Integrated use of phosphorus fertilizer and farmyard manure improves wheat productivity by improving soil quality and P availability in calcareous soil under subhumid conditions. *Front Plant Sci,* 14**,** 1034421.10.3389/fpls.2023.1034421

JAT, A., PRASAD, S. S., AMBATI, D., SINGH, J., GAUTAM, A. & DUBEY, V. 2018. Genetic variability, heritability and diversity for yield contributing traits in reference varieties of wheat. *Indian J Plant Genet Resour* 31**,** 11-16.https://doi.org/10.5958/0976-1926.2018.00002.5

JUST, R. E. & POPE, R. D. 1979. Production function estimation and related risk considerations. *American Journal of Agricultural Economics,* 61**,** 276-284.https://doi.org/10.2307/1239732

KALWAR, Z. A., TUNIO, A., SHAIKH, M. Y., KHAN, I. & JOGI, J. 2018. Impact of sowing dates on the growth and yield of wheat variety benazir-2013, Sindh Province, Pakistan. *Int. J. Agron. Agric. Res,* 12**,** 65-71

KAMROZZAMAN, M., KHAN, M., AHMED, S. & SULTANA, N. 2016. Growth and yield of wheat at different dates of sowing under chrland ecosystem of Bangladesh. *Journal of the Bangladesh Agricultural University,* 14**,** 147-154.http://dx.doi.org/10.3329/jbau.v14i2.32688

KHAN, I., AMANULLAH, JAMAL, A., MIHOUB, A., FAROOQ, O., FARHAN SAEED, M., ROBERTO, M., RADICETTI, E., ZIA, A. & AZAM, M. 2022. Partial substitution of chemical fertilizers with organic supplements increased wheat productivity and

profitability under limited and assured irrigation regimes. *Agriculture,* 12**,** 1754.https://doi.org/10.3390/agriculture12111754

KHARINA, A. & AMUNOVA, O. 2020. Loose smut resistance and adaptability of spring soft wheat varieties of VIR collection. *Agricultural Science Euro-North-East,* 21**,** 18-27.https://doi.org/10.30766/2072-9081.2020.21.1.18-27

KHOKHAR, J. S., SAREEN, S., TYAGI, B. S., SINGH, G., WILSON, L., KING, I. P., YOUNG, S. D. & BROADLEY, M. R. 2018. Variation in grain Zn concentration, and the grain ionome, in field-grown Indian wheat. *PLoS One,* 13**,** e0192026.https://doi.org/10.1371/journal.pone.0192026

MASHIQA, P., PULE-MEULENBERG, F. & NGWAKO, S. 2022. Wheat Growth As Affected By Planting Density, Planting Time And Nitrogen Application. *Res Sq* 6**,** 24-58.http://dx.doi.org/10.21203/rs.3.rs-1276650/v1

MCMASTER, G. S. & WILHELM, W. 1997. Growing degree-days: one equation, two interpretations. *Agric For Meteorol* 87**,** 291-300

MEGAHED, E. M., AWAAD, H. A., RAMADAN, I. E., ABDUL-HAMID, M. I., SWEELAM, A. A., EL-NAGGAR, D. R. & MANSOUR, E. 2022. Assessing performance and stability of yellow rust resistance, heat tolerance, and agronomic performance in diverse bread wheat genotypes for enhancing resilience to climate change under Egyptian conditions. *Front Plant Sci* 13**,** 1014824.https://doi.org/10.3389/fpls.2022.1014824

MIHRETE, T. B. & MIHRETU, F. B. 2025. Crop Diversification for Ensuring Sustainable Agriculture, Risk Management and Food Security. *Global Challenges***,** 2400267.https://doi.org/10.1002/gch2.202400267

MOSLETH, E. F., LILLEHAMMER, M., PELLNY, T. K., WOOD, A. J., RICHE, A. B., HUSSAIN, A., GRIFFITHS, S., HAWKESFORD, M. J. & SHEWRY, P. R. 2020. Genetic variation and heritability of grain protein deviation in European wheat genotypes. *Field Crops Res* 255**,** 107896.https://doi.org/10.1016/j.fcr.2020.107896

MOTTALEB, K. A., KRUSEMAN, G., FRIJA, A., SONDER, K. & LOPEZ-RIDAURA, S. 2023. Projecting wheat demand in China and India for 2030 and 2050: Implications for food security. *Front Nutr* 9**,** 1077443.https://doi.org/10.3389/fnut.2022.1077443

MUHSIN, M., NAWAZ, M., KHAN, I., CHATTHA, M. B., KHAN, S., ASLAM, M. T., IQBAL, M. M., AMIN, M. Z., AYUB, M. A. & ANWAR, U. 2021. Efficacy of Seed Size to Improve

Field Performance of Wheat under Late Sowing Conditions. *Pak J Agric Res* 34.http://dx.doi.org/10.17582/journal.pjar/2021/34.1.247.253

NAHAR, K., AHAMED, K. U. & FUJITA, M. 2010. Phenological variation and its relation with yield in several wheat (*Triticum aestivum* L.) cultivars under normal and late sowing mediated heat stress condition. *Not Sci Biol* 2**,** 51-56.https://doi.org/10.15835/nsb234723

NANDINI, K. & SRIDHARA, S. 2019. Heat use efficiency, Helio thermal use efficiency and photo thermal use efficiency of foxtail millet (*Setaria italica* L.) genotypes as influenced by sowing dates under southern transition zone of Karnataka. *J Pharmacog Phytochem* 8**,** 284-290

OLSEN, S. R. 1954. *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*, US Department of Agriculture.

PETERSON, R. F., CAMPBELL, A. & HANNAH, A. 1948. A diagrammatic scale for estimating rust intensity on leaves and stems of cereals. *Can J Res* 26**,** 496-500

QIAO, S., HARRISON, S. P., PRENTICE, I. C. & WANG, H. 2023. Optimality-based modelling of wheat sowing dates globally. *Agric Syst* 206**,** 103608.https://doi.org/10.1016/j.agsy.2023.103608

SAEED, M. F., JAMAL, A., MUHAMMAD, D., SHAH, G. M., BAKHAT, H. F., AHMAD, I., ALI, S., IHSAN, F. & WANG, J. 2021. Optimizing phosphorus levels in wheat grown in a calcareous soil with the use of adsorption isotherm models. *J Soil Sci Plant Nutr* 21**,** 81-94.https://doi.org/10.1007/s42729-020-00344-5

SÁNCHEZ, A. C., KAMAU, H. N., GRAZIOLI, F. & JONES, S. K. 2022. Financial profitability of diversified farming systems: a global meta-analysis. *Ecological Economics,* 201**,** 107595.https://doi.org/10.1016/j.ecolecon.2022.107595

SATTAR, A., NANDA, G., SINGH, G., JHA, R. K. & BAL, S. K. 2023. Responses of phenology, yield attributes, and yield of wheat varieties under different sowing times in Indo-Gangetic Plains. *Front Plant Sci* 14**,** 1224334.https://doi.org/10.3389/fpls.2023.1224334

SHAH, F., COULTER, J. A., YE, C. & WU, W. 2020. Yield penalty due to delayed sowing of winter wheat and the mitigatory role of increased seeding rate. *Eur J Agron* 119**,** 126120.https://doi.org/10.1016/j.eja.2020.126120

SHAYKHUTDINOV F, S. I., SERZHANOVA AR, GARAEV RI, HAMITOVA AR 2022. The yield and quality of spring wheat grain depending on the timing of sowing, the depth of

seeding and the background of nutrition in the northern part of the Middle Volga region. *Agrobiotechnol Digital Farm* 2**,** 28-32.https://doi.org/10.12737/2782-490X-2022-22-26

SHAZMA ANWAR, S. A., KHATTAK, W., INAMULLAH, I., MUHAMMAD ISLAM, M. I., SAQIB BASHIR, S. B., MUHAMMAD SHAFI, M. S. & JEHAN BAKHT, J. B. 2015. Effect of sowing dates and seed rates on the agro-physiological traits of wheat. *J Environ Earth Sci* 5**,** 135-141

SILVA, R. R., BENIN, G., ALMEIDA, J. L. D., FONSECA, I. C. D. B. & ZUCARELI, C. 2014. Grain yield and baking quality of wheat under different sowing dates. *Acta Sci Agron* 36**,** 201-210.https://doi.org/10.4025/actasciagron.v36i2.16180

SINGH, R., BENIWAL, M., KARWASRA, S. & SAHARAN, H. S. 2009. Effect of sowing date on the incidence of loose smut, flag smut and seed gall of wheat. *Bangladesh J Agric Res* 34**,** 1-4.http://dx.doi.org/10.3329/bjar.v34i1.5746

SMITA GUPTA, S. G., SINGH, R., SINHA, N., AJIT SINGH, A. S. & SHAHI, U. 2017. Effect of different sowing dates on growth and yield attributes of wheat in Udham Singh Nagar District of Uttarakhand, India. *Plant Arch* 17**,** 232-236

STEEL, R. G. D. & TORRIE, J. H. 1960. Principles and procedures of statistics.

SWAMI, S., BAZAYA, B. & GURJAR, G. 2019. Performance of durum wheat (Triticum durum) genotypes under variable sowing dates in sub-tropical zone of Jammu, Jammu & Kashmir. *Int J Curr Microbiol Appl Sci* 8**,** 760-765.http://dx.doi.org/10.20546/ijcmas.2019.803.093

TAHIR, S., AHMAD, A., KHALIQ, T. & CHEEMA, M. J. M. 2019. Evaluating the impact of seed rate and sowing dates on wheat productivity in semi-arid environment. *Int. J. Agric. Biol,* 22**,** 57-64.http://dx.doi.org/10.17957/IJAB/15.1033

TIAN, X., XIA, X., XU, D., LIU, Y., XIE, L., HASSAN, M. A., SONG, J., LI, F., WANG, D. & ZHANG, Y. 2022. Rht24b, an ancient variation of TaGA2ox-A9, reduces plant height without yield penalty in wheat. *New Phytol* 233**,** 738-750.https://doi.org/10.1111/nph.17808

TLATLAA, J. S., TRYPHONE, G. M. & NASSARY, E. K. 2024. Impact of sowing date and level of phosphorus application on economic returns in cotton. *Frontiers in Plant Science,* 15**,** 1402731.https://doi.org/10.3389/fpls.2024.1402731

UPADHYAYA, N. & BHANDARI, K. 2022. Assessment of different genotypes of wheat under late sowing condition. *Heliyon,* 8.https://doi.org/10.1016/j.heliyon.2022.e08726

715 WALKLEY, A. & BLACK, I. A. 1934. An examination of the Degtjareff method for determining
716   soil organic matter, and a proposed modification of the chromic acid titration method. *Soil*
717   *Sci* 37**,** 29-38

718 WANG, C., FENG, L., WU, L., CHENG, C., LI, Y., YAN, J., GAO, J. & CHEN, F. 2020.
719   Assessment of genotypes and management strategies to improve resilience of winter wheat
720   production. *Sustainability,* 12**,** 1474.https://doi.org/10.3390/su12041474

721 YAN, W. & TINKER, N. A. 2006. Biplot analysis of multi-environment trial data: Principles and
722   applications. *Can J Plant Sci* 86**,** 623-645.https://doi.org/10.4141/P05-169

723 YUSUF, M., KUMAR, S., DHAKA, A., SINGH, B. & BHUKER, A. 2019. Effect of sowing dates
724   and varieties on yield and quality performance of wheat (*Triticum aestivum* L.). *Agric Sci*
725   *Digest* 39**,** 306-310.http://dx.doi.org/10.18805/ag.D-4977

726 ZHANG, W., BOYLE, K., GAO, P., POLLEY, B., BROST, J. M., FRANCIS, T., SIDEBOTTOM,
727   C., MCCALLUM, B. D., KUTCHER, H. R. & RANDHAWA, H. 2023. Systematic
728   Characterization of Multi-Rust Resistance Genes from a 'Parula× Thatcher'Population
729   with   a   High-Density   Genetic   Map. *Phytopathology,* 113**,** 847-
730   857.https://doi.org/10.1094/phyto-06-22-0238-fi

731 ZOHAIB, A., YOUSAF, S., ANJUM, S. A., TABASSUM, T., ABBAS, T., MUZAFFAR, W. &
732   IKRAM, W. 2019. Growth, allometry and dry matter yield of soybean genotypes in
733   response to seed inoculation with plant growth promoting rhizobacteria. *Pak J Agric Res*
734   32**,** 102.http://dx.doi.org/10.17582/journal.pjar/2019/32.1.102.109

735