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GENETIC FACTORS OF HETEROSIS FOR YIELD-ASSOCIATED TRAITS IN BREAD WHEAT (*TRITICUM AESTIVUM* L.)

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SUMMARY

The genetic architecture of yield components and effective exploitation of a diverse gene pool are crucial to improve the productivity of wheat (*Triticum aestivum* L.). The related study aimed to tap the genetic potential and heterotic effects by crossing eight diverse wheat lines, i.e., Gulzar 19, Shahkar 13, Wadan 17, Fatehjang 16, Fahim 19, Pirsabak 19, Khaista 17, and Pirsabak 15 with four testers, viz., Zincol 16, Akbar 19, PR 128, and Zinc Shakthi. This line-by-tester mating design took place in 2022–2023 at the Cereal Crops Research Institute (CCRI), Pirsabak-Nowshera, Pakistan. Analysis of variance showed significant ($p \leq 0.01$) differences among genotypes, parents, crosses, and line-by-tester populations for most traits. Based on the mean performance, the F_1 wheat hybrid Gulzar 19 × Zincol 16 had the highest tiller count, grain spike^{-1}, biological yield, and grain yield. The general combining ability (GCA) to specific combining ability (SCA) variance ratios and degree of dominance implied non-additive gene action, suggesting delayed selection in F_2 generations. Zincol 16 showed positive GCA for tillers, grains spike^{-1}, biological yield, and grain yield; Akbar 19 also had positive GCA for 1000-grain weight; and PR 128 remained a common parent in multiple heterotic hybrids. Gulzar 19 × Zincol 16 had the highest SCA and heterosis for grain yield, proving it as the most promising candidate for future breeding.

Keywords: Bread wheat (*T. aestivum* L.), F_1 hybrids, line-by-tester mating design, heterosis, yield components, mean performance

Key findings: This study assessed eight lines and four testers to evaluate mean performance, combining abilities, gene action, and heterotic potential of wheat (*T. aestivum* L.) hybrids targeting at high-yielding wheat cultivars. Four F_1 hybrids (Gulzar 19 × Zincol 16, Pirsabak 19 × PR 128, Fahim 19 × PR 128, and Pirsabak 15 × Zincol 16) showed distinction for their superior performance in multiple traits for enhancing yield.

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INTRODUCTION

Bread wheat (*Triticum aestivum* L.) (2n = 6x = 42, AABBDD), a self-pollinating crop of the family Poaceae, has become recognized as the golden grain and pillar of global food security and socioeconomic stability. Wheat, being a dominating crop of Pakistan for area and production, holds 70% of the Rabi crop and 37% of the total cropped area in Pakistan (Sikandar *et al*., 2024). In 2023–2024, Pakistan's wheat production showed an increase of 16.82%, with 31.44 million tons of production in an area of 9.63 million hectares (GOP, 2024).

Pakistan, ranking among the world's top wheat producers, has its wheat production contributing nearly 2% to the agricultural GDP each year (Shah *et al.,* 2024). By 2030, Pakistan's wheat production will need to grow by 1% annually to keep up with domestic consumption and export demands (Saeed *et al*., 2025). Wheat yield often falls extensively below the genetic potential of improved cultivars due to genotype-by-environment interactions influencing yield-related trait expression (Zubair *et al.,* 2026).

Sustainable wheat production necessitates effective genetic innovations and genetic diversity under fluctuating climatic conditions (Rakov *et al*., 2025; Voucko *et al*., 2025). The success of a wheat breeding program relies on understanding the breeding behavior, combining ability, and suitable gene actions, as assessed by line-×-tester analysis (Kempthorne, 1957), an effective strategy for predicting combining ability when selecting parents and crosses for pedigree manipulation (Jatav *et al*., 2014).

General combining ability (GCA) and specific combining ability (SCA) are invaluable for identifying superior parents and high-yielding wheat cultivars by revealing the genetic architecture governing various traits (Afridi *et al.,* 2017). Hybrid vigor enhances desirable traits via selected crosses to obtain superior segregants, whereas heterobeltiosis is a game-changing agricultural innovation, particularly in self-pollinating crops, to identify superior combinations for reaching transgressive genotypes in later generations (Dragov, 2023). The degree of heterosis through hybrid vigor exploitation and seed production addresses food security and sustainability (Kumar *et al*., 2021). This study proceeded to assess the genetic variation, GCA and SCA effects, heterosis, and gene action to identify valuable parents and hybrids for breeding.

MATERIALS AND METHODS

Breeding material and procedure

The generation of experimental materials continued by using a line-by-tester mating design by crossing eight wheat (*T. aestivum* L.) lines. These were Gulzar 19, Shahkar 13, Wadan 17, Fatehjang 16, Fahim 19, Pirsabak 19, Khaista 17, and Pirsabak 15, known for their yield potential. The four testers used were Zincol 16, Akbar 19, PR 128, and Zinc Shakthi, with the research conducted during the 2021–2022 Rabi season (Table 1). Moreover, 32 F_1 hybrids and their 12 parental genotypes received evaluation in a randomized complete block design with three replications during 2022–2023 at the Cereal Crops Research Institute (CCRI), Pirsabak-Nowshera, Pakistan.

Data recorded

Data recording comprised morphological parameters from 20 randomly selected plants per genotype. Average tillers plant^{-1} and grains spike^{-1} from 20 spikes per replication entailed counting. Furthermore, determining the 1000-grain weight used an electronic balance for each genotype. Average biological yield and grain yield plant^{-1} also got recorded per replication.

Statistical analysis

Data analysis employed the analysis of variance (Steel *et al*., 1997) through TUNSTATS software, with genotype means compared by the least significant difference ($LSD_{0.05}$) test. Based on significant variations, the line-by-tester combining ability analysis (Singh and Chaudhary, 1985) determined

Table 1. Parentage of wheat lines and testers used in the study.

S.No.	Lines	Parentage
1	Gulzar 19	VORB/3/T.DICOCCON PI94625/AE.SQUARROSA (372)//3*PASTOR
2	Shahkar 13	CMH84.3379/CMH78.578//MILAN)
3	Wadan 17	YAV79//DACK/RABI/3/SNIPE/4/ AE. SQUARROSA
4	Fatehjang 16	"ERA F 2000 /4/ FONG CHAN #3 / TRT'S'//VEE#9/3/ COOK/ VEE'S'// DOVE'S '/ SERI"
5	Fahim 19	MILAN/KAUZ//PRINIA/3/BAV92/4/2*SOKOL
6	Pirsabak 19	NAC/TH.AC//3*PVN/3/MIRLO/BUC/4/2*PASTOR/5/KACHU/6/KACHU
7	Khaista 17	KAUZ//ALTAR 84/AOS/3/MILAN/KAUZ/4/HUITES/7/ CAL/NH//H567.71/3/SERI/4/CAL/…
8	Pirsabak 15	MILAN/S87230//BABAX)
	Testers	Parentage
1	Zincol 16	OASIS/SKAUZ//4*BCN/3/2*PASTOR/4/T.SPELTA PI348449/5/BACEU #1/6/WBLL1*2/….
2	Akbar 19	BECARD/QUAIU # 1
3	PR 128	SALEEM-2000/PS-05
4	Zinc Shakthi	CROC1_/AE.SQUARRO- SA(210)//INQALAB 91*2/KUKUNA/3/ PBW3432/KUKUNA

Table 2. Analysis of variance of parental genotypes and their F_1 hybrids for tillers plant^{-1}, grains - spike^{-1}, 1000-grain weight, biological yield plant^{-1}, and grain yield plant^{-1} in wheat.

Source	d.f.	Tillers plant^{-1}	Grains spike^{-1}	1000-grain weight	Biological yield plant^{-1}	Grain yield plant^{-1}
Replications	2	7.56	89.17	2.27	622.68	4.17
Genotypes	43	29.38**	249.54**	273.72**	961.67**	150.23**
Parents (P)	11	10.58**	377.59**	51.14**	1095.06**	76.03**
Crosses (C)	31	34.99**	198**	361.0**	933.75**	147.34**
Parents vs crosses	1	62.27**	438.46*	15.98ns	359.62ns	1056.18**
Lines (L)	7	48.98**	199.29**	591.63**	1203.12**	141.12**
Testers (T)	3	23.65**	279.25**	327.34**	1354.02**	104.2**
L × T	21	31.95**	185.97**	288.95**	783.93**	155.58**
Error	86	4.64	47.05	10.70	115.42	16.05

*, **: Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively, ns: Nonsignificant

variances due to GCA and SCA additive and dominance genetic effects. Alongside, the F_1 heterobeltiosis calculation followed Sharma and Singh (1978).

RESULTS AND DISCUSSION

The analysis of variance showed significant ($p \leq 0.01$) differences among genotypes, parents, and crosses for all traits in wheat (*T. aestivum* L.). The mean square of the contrast parents versus crosses was significant ($p \leq 0.01$) for all traits, except 1000-grain weight and biological yield plant^{-1}. Likewise, lines, testers, and their interactions also had significant variations for all studied traits (Table 2).

Mean performance of the parental genotypes, hybrids, and their heterotic effects

Tillers plant^{-1}

The mean value for parental tillers' production ranged from -9 to 16, with Fatehjang 16 and Zinc Shakthi exhibiting maximum genetic potential for tillering. However, F_1 hybrids demonstrated heterotic vigor, producing -9 to 22 tillers plant^{-1} (Table 3). Tilley *et al*. (2019) support the breeding value of high tillering hybrids to enhance yield. Dwivedi *et al*. (2023) and Ali *et al*. (2024) also highlighted a positive correlation between the number of tillers and grain yield. Similarly, Fatehjang 16,

Table 3. Mean performance of the parental genotypes and F_1 hybrids for various traits in wheat.

Parental genotypes & F_1 hybrids	Tillers plant^{-1}	Grains spike^{-1}	1000-grain weight (g)	Biological yield plant^{-1} (g)	Grain yield plant^{-1} (g)
Gulzar 19	10	45	43	54	14
Shahkar 13	11	67	45	66	25
Wadan 17	11	53	48	86	26
Fatehjang 16	16	65	48	89	30
Fahim 19	12	65	53	61	22
Pirsabak 19	10	57	50	54	20
Khaista 17	10	73	45	106	23
Pirsabak 15	12	82	40	77	33
Zincol 16	13	66	50	100	26
Akbar 19	12	61	48	83	28
PR 128	9	83	55	48	28
Zinc Shakthi	13	75	48	66	27
F_1 hybrids					
Gulzar 19 × Zincol 16	22	86	45	117	47
Gulzar 19 × Akbar 19	15	70	58	85	30
Gulzar 19 × PR 128	12	78	50	72	26
Gulzar 19 × Zinc Shakthi	13	61	40	75	29
Shahkar 13 × Zincol 16	9	63	48	39	15
Shahkar 13 × Akbar 19	11	76	50	64	31
Shahkar 13 × PR 128	14	74	43	74	28
Shahkar 13 × Zinc Shakthi	10	63	35	54	34
Wadan 17 × Zincol 16	15	71	45	114	36
Wadan 17 × Akbar 19	12	60	40	72	26
Wadan 17 × PR 128	9	62	28	58	19
Wadan 17 × Zinc Shakthi	18	74	53	73	25
Fatehjang 16 × Zincol 16	21	75	50	74	32
Fatehjang 16 × Akbar 19	18	66	53	75	35
Fatehjang 16 × PR 128	15	61	43	91	30
Fatehjang 16 × Zinc Shakthi	10	54	50	71	27
Fahim 19 × Zincol 16	10	62	48	71	29
Fahim 19 × Akbar 19	15	68	63	86	38
Fahim 19 × PR 128	13	73	53	94	42
Fahim 19 × Zinc Shakthi	13	69	50	77	32
Pirsabak 19 × Zincol 16	12	76	50	81	31
Pirsabak 19 × Akbar 19	16	67	50	97	34
Pirsabak 19 × PR 128	18	60	50	110	43
Pirsabak 19 × Zinc Shakthi	12	75	55	73	34
Khaista 17 × Zincol 16	11	86	53	83	34
Khaista 17 × Akbar 19	10	70	55	70	31
Khaista 17 × PR 128	9	61	50	66	32
Khaista 17 × Zinc Shakthi	11	79	50	67	32
Pirsabak 15 × Zincol 16	16	82	55	108	46
Pirsabak 15 × Akbar 19	11	76	48	71	33
Pirsabak 15 × PR 128	12	78	50	76	36
Pirsabak 15 × Zinc Shakthi	10	67	38	53	19
$LSD_{0.05}$	4.17	11.3	5.31	23.9	12.26

Table 4. General and specific combining ability effects for various traits in wheat.

Lines, testers, & F_1 hybrids	Tillers plant^{-1}	Grains spike^{-1}	1000-grain weight (g)	Biological yield plant^{-1} (g)	Grain yield plant^{-1} (g)
Lines					
Gulzar 19	2.46**	3.50^{ns}	1.41^{ns}	9.35**	1.64^{ns}
Shahkar 13	-2.22**	-0.99^{ns}	-14.84**	-20.10**	-5.37**
Wadan 17	0.43^{ns}	-3.57^{ns}	-5.47**	1.34^{ns}	-4.93**
Fatehjang 16	2.50**	-5.99**	2.03*	-0.07^{ns}	-0.52^{ns}
Fahim 19	-0.43^{ns}	-2.11^{ns}	6.41**	4.13^{ns}	2.74**
Pirsabak 19	1.21^{ns}	-0.60^{ns}	4.53**	12.35**	3.80**
Khaista 17	-2.89**	3.88^{ns}	5.16**	-6.22^{ns}	0.69^{ns}
Pirsabak 15	-1.07^{ns}	5.88**	0.78^{ns}	-0.78^{ns}	1.96^{ns}
S.E.	0.62	1.98	0.94	3.1	1.16
Testers					
Zincol 16	1.15*	5.07**	-3.59**	8.00**	1.88*
Akbar 19	0.41^{ns}	-1.07^{ns}	5.16**	-0.26^{ns}	0.66^{ns}
PR 128	-0.43^{ns}	-1.81^{ns}	-1.09^{ns}	2.25^{ns}	0.45^{ns}
Zinc Shakthi	-1.13*	-2.19^{ns}	-0.47^{ns}	-10.00**	-2.98**
S.E.	0.44	1.4	0.67	2.19	0.82
F_1 hybrids					
Gulzar 19 × Zincol 16	4.87**	6.86^{ns}	0.47^{ns}	21.59**	11.74**
Gulzar 19 × Akbar 19	-0.61^{ns}	-2.70^{ns}	4.22*	-1.60^{ns}	-3.79^{ns}
Gulzar 19 × PR 128	-3.08*	5.83^{ns}	2.97^{ns}	-17.60^{ns}	-7.18**
Gulzar 19 × Zinc Shakthi	-1.18^{ns}	-9.99*	-7.66**	-2.39^{ns}	-0.76^{ns}
Shahkar 13 × Zincol 16	-3.40*	-11.16*	-28.28**	-27.12**	-12.71**
Shahkar 13 × Akbar 19	-0.03^{ns}	8.36^{ns}	12.97**	6.39^{ns}	3.96^{ns}
Shahkar 13 × PR 128	3.74**	6.57^{ns}	11.72**	14.08*	1.57^{ns}
Shahkar 13 × Zinc Shakthi	-0.30^{ns}	-3.78^{ns}	3.59*	6.64^{ns}	7.17**
Wadan 17 × Zincol 16	0.23^{ns}	-0.98^{ns}	7.34**	26.77**	7.81**
Wadan 17 × Akbar 19	-1.58^{ns}	-5.68^{ns}	-6.41**	-7.27^{ns}	-0.89^{ns}
Wadan 17 × PR 128	-4.21**	-2.77^{ns}	-12.66**	-23.49**	-8.18**
Wadan 17 × Zinc Shakthi	5.56**	9.43*	11.72**	4.00^{ns}	1.25^{ns}
Fatehjang 16 × Zincol 16	3.87**	6.26^{ns}	4.84**	-11.46^{ns}	-0.77^{ns}
Fatehjang 16 × Akbar 19	1.65^{ns}	2.99^{ns}	-1.41^{ns}	-2.42	3.14^{ns}
Fatehjang 16 × PR 128	-0.51^{ns}	-1.48^{ns}	-5.16**	10.85^{ns}	-1.62^{ns}
Fatehjang 16 × Zinc Shakthi	-5.01**	-7.77^{ns}	1.72^{ns}	3.03^{ns}	-0.75^{ns}
Fahim 19 × Zincol 16	-4.03**	-11.13*	-2.03^{ns}	-18.99**	-10.19**
Fahim 19 × Akbar 19	2.18^{ns}	0.60^{ns}	4.22*	4.76^{ns}	2.85^{ns}
Fahim 19 × PR 128	0.52^{ns}	7.14^{ns}	0.47^{ns}	9.66^{ns}	6.92**
Fahim 19 × Zinc Shakthi	1.32^{ns}	3.39^{ns}	-2.66^{ns}	4.57^{ns}	0.42^{ns}
Pirsabak 19 × Zincol 16	-3.81**	1.65^{ns}	2.34^{ns}	-17.36*	-6.13**
Pirsabak 19 × Akbar 19	0.94^{ns}	-1.51^{ns}	-6.41**	6.61^{ns}	-2.33^{ns}
Pirsabak 19 × PR 128	3.70**	-7.84^{ns}	-0.16^{ns}	17.71*	6.84**
Pirsabak 19 × Zinc Shakthi	-0.83^{ns}	7.70^{ns}	4.22*	-6.96^{ns}	1.62^{ns}
Khaista 17 × Zincol 16	-0.20^{ns}	7.15^{ns}	4.22**	3.30^{ns}	-0.01^{ns}
Khaista 17 × Akbar 19	-0.96^{ns}	-3.39^{ns}	-2.03^{ns}	-1.04^{ns}	-2.24^{ns}
Khaista 17 × PR 128	-0.72^{ns}	-11.32*	-0.78^{ns}	-7.47^{ns}	-0.43^{ns}
Khaista 17 × Zinc Shakthi	1.88^{ns}	7.56^{ns}	-1.41^{ns}	5.21^{ns}	2.67^{ns}
Pirsabak 15 × Zincol 16	2.48^{ns}	1.35^{ns}	11.09**	23.27**	10.26**
Pirsabak 15 × Akbar 19	-1.58^{ns}	1.33^{ns}	-5.16**	-5.44^{ns}	-0.71^{ns}
Pirsabak 15 × PR 128	0.55^{ns}	3.86^{ns}	3.59*	-3.75^{ns}	2.08^{ns}
Pirsabak 15 × Zinc Shakthi	-1.45^{ns}	-6.54^{ns}	-9.53**	-14.09*	-11.62**
S.E.	0.44	1.4	0.67	2.19	0.82

*, **: Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively, ns: Nonsignificant

Gulzar 19, and Zincol 16 showed a significant positive GCA, reflecting an additive gene action (Table 4). Five F_1 hybrids had a positive SCA with the highest SCA value of 5.56 (Wadhan 17 × Zinc Shakthi). Karikor *et al*. (2022) observed significant GCA and SCA for tillering. Shah *et al*. (2020) identified good, poor, and average SCA for tillers plant^{-1}, supporting our finding of variable SCA among crosses.

Better parent heterobeltiosis ranged from -38.71% to 79.93% in accordance with Dudhat *et al.* (2022), who observed a heterobeltiosis range of −47.58% to 62.72% across 32 wheat hybrids. Our 10 F_1 hybrids showed significant heterobeltiosis, particularly Pirsabak 19 × PR 128 and Gulzar 19 × Zincol 16, suggesting true hybrid vigor (Table 5). Likewise, Fareed *et al*. (2024) reported heterosis in several wheat hybrids, including Benazir-2013 × TD-1, TD-1 × Benazir-2013, TD-1 × Hamal, and Kiran-95 × Benazir-2013. Variance component analysis confirmed the prevalence of non-additive gene action for tillers plant^{-1} (Table 6). Breeding methods, such as reciprocal recurrent selection or biparental mating, are suitable for traits like tillers plant^{-1}, where non-additive gene effects predominate (Ishaq *et al.,* 2018).

Table 5. Better-parent heterotic effects for various traits in wheat.

F_1 hybrids	Tillers plant^{-1}	Grains spike^{-1}	1000-grain weight (g)	Biological yield plant^{-1} (g)	Grain yield plant^{-1} (g)
Gulzar 19 × Zincol 16	65.14**	29.49**	-10.00^{ns}	17.00^{ns}	78.05**
Gulzar 19 × Akbar 19	28.33^{ns}	13.96^{ns}	21.05**	3.35^{ns}	8.56^{ns}
Gulzar 19 × PR 128	16.35^{ns}	-6.28^{ns}	-9.09^{ns}	34.2*	-6.38^{ns}
Gulzar 19 × Zinc Shakthi	-0.00^{ns}	-18.49*	-15.79**	13.45^{ns}	8.35^{ns}
Shahkar 13 × Zincol 16	-33.59*	-5.83^{ns}	-4.00^{ns}	-61.32**	-41.75**
Shahkar 13 × Akbar 19	-5.83^{ns}	14.17^{ns}	5.26^{ns}	-22.62*	11.34^{ns}
Shahkar 13 × PR 128	25.96^{ns}	-10.81^{ns}	-22.73**	12.96^{ns}	-0.12^{ns}
Shahkar 13 × Zinc Shakthi	-28.57*	-16.20*	-26.32**	-17.50^{ns}	11.79^{ns}
Wadan 17 × Zincol 16	14.25^{ns}	6.93^{ns}	-10.00^{ns}	14.16^{ns}	36.86**
Wadan 17 × Akbar 19	3.33^{ns}	-2.45^{ns}	-15.79**	-17.15^{ns}	-4.70^{ns}
Wadan 17 × PR 128	-16.51^{ns}	-25.20**	-50.00**	-33.00**	-33.22**
Wadan 17 × Zinc Shakthi	35.34**	-2.09^{ns}	10.53^{ns}	-15.38^{ns}	-8.48^{ns}
Fatehjang 16 × Zincol 16	33.33**	14.22^{ns}	0.00^{ns}	-25.55**	7.84^{ns}
Fatehjang 16 × Akbar 19	14.19^{ns}	1.93^{ns}	10.53^{ns}	-15.96^{ns}	16.91^{ns}
Fatehjang 16 × PR 128	-5.16^{ns}	-26.57**	-22.73**	1.68^{ns}	0.11^{ns}
Fatehjang16 × Zinc Shakthi	-38.71**	-28.14**	5.26^{ns}	-20.81*	-8.40^{ns}
Fahim 19 × Zincol 16	-24.94^{ns}	-6.22^{ns}	-9.52^{ns}	-28.89**	-1.27^{ns}
Fahim 19 × Akbar 19	25.4^{ns}	3.21^{ns}	19.05**	4.73^{ns}	36.55**
Fahim 19 × PR 128	4.92^{ns}	-11.47^{ns}	-4.55^{ns}	53.46**	47.52**
Fahim 19 × Zinc Shakthi	-3.01^{ns}	-8.16^{ns}	-4.76^{ns}	16.08^{ns}	16.83^{ns}
Pirsabak 19 × Zincol 16	-10.69^{ns}	15.41^{ns}	0.00^{ns}	-19.04*	18.15^{ns}
Pirsabak 19 Akbar 19	30.83*	9.22^{ns}	0.00^{ns}	16.92^{ns}	21.71^{ns}
Pirsabak 19 × PR 128	79.93**	-27.74**	-9.09^{ns}	105.22**	51.06**
Pirsabak 19 × Zinc Shakthi	-6.77^{ns}	-0.43^{ns}	10.00^{ns}	11.08^{ns}	25.06*
Khaista 17 × Zincol 16	-14.50^{ns}	18.32*	5.00^{ns}	-22.14**	29.70*
Khaista 17 × Akbar 19	-19.17^{ns}	-4.58^{ns}	15.79**	-33.97**	10.74^{ns}
Khaista 17 × PR 128	-9.90^{ns}	-26.53**	-9.09^{ns}	-37.63**	14.18^{ns}
Khaista 17 × Zinc Shakthi	-17.29^{ns}	5.32^{ns}	5.26^{ns}	-37.26**	17.57^{ns}
Pirsabak 15 × Zincol 16	20.10^{ns}	0.92^{ns}	10.00^{ns}	8.52^{ns}	37.76**
Pirsabak 15 × Akbar 19	-11.38^{ns}	-6.64^{ns}	0.00^{ns}	-13.57^{ns}	0.91^{ns}
Pirsabak 15 × PR 128	-0.81^{ns}	-5.80^{ns}	-9.09^{ns}	-2.03^{ns}	8.76^{ns}
Pirsabak 15 × Zinc Shakthi	-28.57*	-17.63*	-21.05**	-31.34**	-43.00**

*, **: Significant at p≤0.05 and p≤0.01, respectively, ns: Nonsignificant

Table 6. Genetic components for various traits in wheat.

Genetic components	Traits				
	Tillers plant^{-1}	Grains spike^{-1}	1000-grain weight (g)	Biological yield plant^{-1} (g)	Grain yield plant^{-1} (g)
σ^2_a	0.49	1.53	6.48	11.62	1.34
σ^2_d	9.10	46.31	92.75	222.84	46.51
σ^2_e	4.64	47.05	10.70	115.42	16.05
σ^2_{GCA}	0.25	0.76	3.24	5.81	0.67
σ^2_{SCA}	9.10	46.30	92.75	222.84	46.51
σ^2_{GCA}/ σ^2_{SCA}	0.03	0.02	0.04	0.03	0.01
CV (%)	16.95	9.59	6.97	13.99	13.46

σ^2a = Additive variance, σ^2d = Dominance variance, σ^2e = Environmental variance, σ^2GCA = General combining ability variance, σ^2SCA = Specific combining ability variance, σ^2GCA/σ^2SCA = Ratio of general combining ability variance to specific combining ability variance, and CV = Coefficient of variation.

Grains spike^{-1}

The mean value for parental genotypes for grains spike^{-1} varied from 45 (Gulzar 19) to 83 (PR 128). The F_1 hybrids showed a heterotic boost from 54 to 86 grains spike^{-1} (Table 3). Philip *et al*. (2018) and Abro *et al*. (2024) suggested more grains spike^{-1} directly relate to grain yield, which is similar to this study's findings for Gulzar 19 × Zincol 16. It had the maximum grains spike^{-1} and grain yield plant^{-1}. Parental genotypes Pirsabak 15 and Zincol 16 emerged as potential parents based on a significant positive GCA (Table 4). Only one hybrid, Wadhan17 × Zinc Shakthi, showed a positive SCA (9.43). Presented results align with Saeed *et al.* (2021) for significant GCA and SCA for grains spike^{-1}; unlike with Abro *et al*. (2021), they observed 10 significant crosses out of 15. Parental genotypes with a significant GCA and their resulting SCA hybrids hold potential to enhance wheat yield for food security (Karikor *et al*., 2022).

Heterobeltiosis varied from -28.14% to 29.49% with 12 of 21 F_1 hybrids having positive values. Only two crosses, i.e., Gulzar 19 × Zincol 16 (29.49%) and Khaista 17 × Zincol 16 (18.32%), expressed true hybrid vigor, indicating that heterosis for grains spike^{-1} is apparent only in specific genetic combinations. Our highest heterosis of 29.49% aligns with Khokhar *et al*. (2019), who documented up to 28.0% heterosis (Janbaz × Marvi-2000), and with Roy *et al*. (2021), who reported significant heterosis in HPBW 01 × PBW 725.

1000-grain weight

The parental 1000-grain weight ranged from 40 to 55 g, with the highest value in PR 128 (55 g). F_1 hybrids Fahim 19 × Akbar 19 (63 g) surpassed the best parent and demonstrated positive heterosis. Moreover, Karaman (2020) mentioned that thousand grain weight had a positive impact on grain yield and grain weight spike^{-1}, which was similar to the results of the present study.

Parental genotypes, i.e., Fahim 19, Khaista 17, Pirsabak 19, Fatehjang 16, and Akbar 19, indicated superior general combining ability in the line × tester analysis. The SCA effect ranged from -28.28 to 12.97 with 11 positive cross combinations (Table 4). The best specific combination, Shahkar 13 × Akbar 19, involved parents with poor × good GCA effects, suggesting a complementary gene action. Our findings align with Khan *et al.* (2020) and Dawwam *et al*. (2024), who also identified parents with high GCA and hybrids with significant SCA. Saeed *et al.* (2021) reported significant specific combiners, including Galaxy-13 × Yr-10 (40.2 g), supporting this study's finding of 11 positive SCA crosses, with the top hybrid Shahkar13 × Akbar19.

Heterobeltiosis varied from -50.00% to 21.05% (Table 5). Fifteen F_1 cross combinations had positive values with a significant heterosis in Gulzar 19 × Akbar 19

(21.05%), confirming Akbar 19 as a key parent for hybrid wheat. Deverin *et al*. (2024) reported a modest heterobeltiosis range (3.89% to 10.03%), while Fouad and Mohamad (2023) observed significant heterosis (6.50% to 23.83%), which corresponds to the concerned study findings. Non-additive gene action for 1000-grain weight aligns with Ahmad and Gupta (2024), who reported a non-additive genetic action for all traits in wheat (Table 6).

Biological yield plant^{-1}

Parental biological yield ranged from 48 to 106 g plant^{-1} indicating genetic diversity. The maximum biological yield emerged for parental genotypes Khaista 17 (106 g) and Zincol 16 (100 g), while PR 128 revealed the minimum biological yield (48 g). The F_1 hybrids varied from 39 to 117 g, with the maximum biological yield shown by Gulzar 19 × Zincol 16, followed by Wadhan 17 × Zincol 16 (Table 3). Ali *et al*. (2017) and Ahmad and Gupta (2023) reported that biological yield had a positive effect on grain yield, which was also consistent with the existing study for Gulzar 19 × Zincol 16. It had the greater biological yield along with grain yield.

Parental line Pirsabak 19 (12.35) and tester Zincol 16 (8.00) were remarkable as the best general combiners for biological yield plant^{-1}. The SCA effects ranged from -27.12 to 26.77 with five significant crosses, including the top hybrid Wadan 17 × Zincol 16, resulting from a poor × good GCA pattern (Table 4). The selection of specific parental combinations for biological yield is noteworthy for producing superior offspring (Ishaq *et al.*, 2018; Bajaniya *et al.*, 2019; Roy *et al.*, 2021).

The heterobeltiosis varied from -61.32% to 105.22%. Significant positive better parent heterosis was evident in six F_1 crosses, including key hybrids, viz. Pirsabak 19 × PR 128, Wadan 17 × PR 128, and Fahim 19 × PR 128, yielding important insights for utilization in wheat breeding programs (Table 5). The latest heterosis range exceeded that as reported by Dudhat *et al*. (2022), who observed 29.68% to 37.79% in 13 significant hybrids. In accordance with Roy *et al*. (2021), the study findings confirm that specific cross combinations could potentially have substantial heterosis for biological yield.

Grain yield plant^{-1}

The grain yield plant^{-1} varied among parental lines and testers from 14 to 33 g. The maximum grain yield resulted in Pirsabak 15. The F_1 hybrids ranged from 15 to 47 g, with Gulzar 19 × Zincol 16 exceeding the best parent by 14 g and demonstrating a strong heterosis (Table 3). Ullah *et al*. (2021) and Attri *et al*. (2021) revealed that grain yield is a complex polygenic trait affected by tillers plant^{-1}, grains spike^{-1}, and 1000 grain weight, which was similar to the results of this study. It showed grain yield gained direct effects from the aforementioned traits.

Positive GCA was notable in Pirsabak 19, Fahim 19, and Zincol 16. SCA effects ranged from -11.62 to 11.74, with the best SCA hybrid (Gulzar 19 × Zincol 16) resulting from a poor × good GCA combination (Table 4). Promising findings support the view that complementary alleles exist across diverse parents. As suggested by Jatav *et al.* (2014), inter-mating of selected genotypes in early generations could help break undesirable linkages and unlock further genetic variability.

Heterobeltiosis varied from -43.0% to 78.05%, aligning with the heterotic range observed by Hama-Amin and Towfiq (2019). Meanwhile, it was higher than observations from Kaur and Kumar (2023) and Fareed *et al.* (2024), mentioning heterotic values of 37.93% and 11.22%, respectively (Table 5). Eleven F_1 crosses showed significant heterobeltiosis with the top three heterotic hybrids as Gulzar 19 × Zincol 16 (78.05%), followed by Pirsabak 19 × PR 128 (51.06%), and Fahim 19 × PR 128 (47.52%). Likewise, Baiumy *et al*. (2024) documented significant estimates of heterosis in multiple crosses. The significantly higher σ^2SCA than σ^2GCA demonstrates a major role of a non-additive gene action (Table 6), supporting the findings of Dawwam *et al.* (2024).

CONCLUSIONS

The analysis of variance revealed significant differences among genotypes, parental genotypes, lines, testers, crosses, and line-by-tester interactions for most traits in wheat (*T. aestivum* L.). Based on mean performances, combining ability, and heterotic potential, F_1 hybrids, viz., Gulzar 19 × Zincol 16, Pirsabak 19 × PR 128, Fahim 19 × PR 128, and Pirsabak 15 × Zincol 16, consistently exhibited superior performance for multiple traits, including tillers plant^{-1}, grains spike^{-1}, biological yield plant^{-1}, and grain yield plant^{-1}. These promising hybrids need further evaluation for effective utilization in wheat breeding programs targeting at high-yielding wheat cultivars.

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