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Study of Nature of Gene Action, Combining Ability and Heterosis in F_2 Half-Diallel Crosses for Grain Yield and Its Components in Bread Wheat

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Bread wheat, Combining Ability, heterosis, half-diallel, F_2generation

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ABSTRACT

This study aimed to evaluated seven bread wheat genotypes and their 21 F_2 hybrids derived from a half-diallel mating design to estimate mean performance, general and specific combining ability, heterosis, and some genetic parameters. The parental genotypes (SK 95, Side 14, Side 12, SK 94, Giemiza 9, Giemiza 7, and Al-Fayadh) and their hybrids were grown at the Agricultural Research Station, University of Kirkuk, using a randomized complete block design with three replications. Analysis of variance revealed significant differences among parents for most traits, except days to flowering (129.67–131.67 days). Side 14 genotype was surpassed in flag leaf area (70.79 cm^2), whereas SK 94 showed higher mean for number of grains per spike (83.73) and grain yield per plant (31.54 g). Significant variation was also observed among F_2 hybrids for all traits, with several hybrids surpassing the better parent; as the hybrid SK 95 *x* Side 12 produced the highest number of grains per spike (95.73), while Side 14 *x* Side 12 achieved the highest grain yield per plant (37.85 g). Heterosis results showed that Side 14 *x* Side 12 genotype surpassed by greatest heterotic effects for grain yield, number of spikes per plant, and grains per spike, whereas SK 95 *x* Side 14 consistently excelled in thousand-grain weight, spikes per plant, and grain yield. Genetic parameter estimates showed that genetic variance exceeded environmental variance, with high broad-sense heritability but low narrow-sense heritability and expected genetic advance, emphasizing the importance of selection in advanced generations to achieve stable genetic improvement.

دراسة طبيعة الفعل الجيني والمقدرة على الائتلاف وقوة الهجين في تهجينات نصف تبادلية في الجيل الثاني F_2 لصفات حاصل الحبوب ومكوناته في حنطة الخبز

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المستخلص:
هدفت هذه الدراسة إلى تقييم سبعة تراكيب وراثية من حنطة الخبز و21 هجين في الجيل الثاني (F_2) الناتجة من نظام التهجين التبادلي النصفي، وذلك لتقدير متوسطات الأداء، والمقدرة العامة والخاصة على الائتلاف، وقوة الهجين، وبعض المعالم الوراثية. نُفذت التجربة في محطة البحوث الزراعية/جامعة كركوك باستخدام تصميم القطاعات العشوائية الكاملة بثلاث مكررات. أظهر تحليل التباين وجود فروق معنوية بين الآباء في معظم الصفات المدروسة، باستثناء صفة عدد الأيام إلى الإزهار التي تراوحت بين 129.67–131.67 يوماً. تفوق التركيب Side 14 في مساحة ورقة العلم (70.79 سم^2)، في حين أظهر التركيب SK 94 أعلى متوسط لعدد الحبوب في السنبلة (83.73 حبة) وحاصل الحبوب للنبات (31.54 غم). كما سُجل تباين معنوي بين هجن الجيل الثاني في جميع الصفات، وتجاوزت بعض الهجن أفضل الآباء؛ إذ حقق الهجين Side 12 *x* SK 95 أعلى عدد حبوب في السنبلة (95.73 حبة)، بينما سجل الهجين Side 14 *x* Side 12أعلى حاصل حبوب للنبات (37.85 غم). وأظهرت نتائج قوة الهجين أن الهجين Side 12 *x* Side 14 تفوق بأعلى قيم لقوة الهجين في حاصل الحبوب وعدد السنابل للنبات وعدد الحبوب في السنبلة، في حين تميز الهجين Side 14 *x* SK 95 بتفوق ثابت في وزن 1000 حبة وعدد السنابل للنبات وحاصل الحبوب. وبينت تقديرات المعالم الوراثية زيادة قيم التباين الوراثي على التباين البيئي، مع تسجيل قيم مرتفعة للتوريث بالمعنى الواسع وقيم منخفضة للتوريث بالمعنى الضيق والتحسين الوراثي المتوقع، مما يؤكد أهمية الانتخاب في الأجيال المتقدمة لتحقيق تحسن وراثي ثابت ومستقر.

الكلمات المفتاحية: حنطة الخبز، المقدرة الائتلافية، قوة الهجين، التهجين التبادلي النصفي، الجيل الثاني.

INTRODUCTION

Bread wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide, serving as the primary food source for millions and contributing directly to food security, particularly in arid and semi-arid regions. Wheat production, however, faces increasing challenges due to climate change, water scarcity, and environmental fluctuations, which necessitate the development of high-yielding and stable cultivars across diverse environments (Omar & Al-Layla, 2024; Hindi *et al*., 2025). Achieving effective genetic improvement in grain yield and its components depends on the available genetic variation among parental genotypes, as well as a thorough understanding of the nature of gene action controlling these traits (Al-Mafarji *et al*., 2024; Mohammed & Al Hamdani, 2025).

Full and half-diallel mating designs are among the most efficient methods for studying the inheritance of quantitative traits in self-pollinated crops like wheat, as they allow the estimation of general combining ability (GCA) and specific combining ability (SCA), which provide key indicators of additive and non-additive gene effects (Griffing, 1956; Al-Mafarji & Al-Jubouri, 2023a). There have been numerous studies that proved the complex nature of genetic interactions for yield as well as its components in the study of grains (Abdullah & Abdul Karim, 2019), thereby emphasizing the need for the use of combining ability in the selection of better parents as well as promising hybrids.

Heterosis is another very important technique used in assessing the performance of genotypes based on the degree to which hybrids excel above the mean or better parent. As the degree of heterosis tends to be greater in F1 generations due to dominance and overdominance, the F2 generation plays a very important role in self-pollinated crops because it enables the determination of true genetic segregation and variation so that better hybrids can be selected that can give better offspring in future generations (Al-Mafarji & Al-Jubouri, 2023b ; Mohammed, 2025).

Genetic parameters, including genetic, environmental, and phenotypic variances, broad and narrow-sense heritability, expected genetic advance, and degree of dominance,

are essential for interpreting the inheritance of quantitative traits and guiding effective selection. High heritability values indicate strong genetic control over phenotypic variation, while narrow-sense heritability and expected genetic advance provide insights into the efficiency of direct selection in segregating generations (Madab, 2024; Hindi *et al*., 2025).

Despite numerous studies on combining ability and heterosis in F_1 wheat hybrids, information on gene action in the F_2 generation-particularly the integrated analysis of mean performance, GCA, SCA, heterosis, and genetic parameters-remains limited. Therefore, this study aimed to investigate gene action in F_2 hybrids derived from a half-diallel cross of seven bread wheat genotypes to identify better parents and hybrids and support breeding programs with more precise and effective selection strategies.

MATERIALS AND METHODS

Plant Materials

Seven bread wheat genotypes were used in this study, as listed in Table 1. These genotypes differed in pedigree and origin and were selected to represent a wide range of genetic diversity for yield and its components. Six genotypes (SK 95, Giemiza 9, Side 14, Side 12, SK 94, and Giemiza 7) originated from Egypt, while Al-Fayyad originated from Iraq.

Table 1. The names and pedigree of seven wheat genotypes.

No.	Genotypes	Pedigree	Origin
1	SK 95	PASTOR// SITE// MO/3/ CHEN/ AEGILOPSSQUARROSA (TAUS)// BCN/4/ WBLL1 * CMA01Y00158S- 040POY- 040M- 030ZTM- 040SY- 26M- 0Y- 0SY-0S.	Egypt
2	Giemiza 9	Ald " S " / Huac " S " // CMH77A . 630 / Sx *CGM4583 – 5GM – 1GM – 0 GM.	Egypt
3	Side 14	SW8488*2/KUKUNA.	Egypt
4	Side 12	BUC // 7C / ALD /5/ MAYA74 /ON // 1160.147 /3/ BB/ GLL /4/ CHAT " S " /6/ MAYA/ VUL// CMH74A.630/ 4 * SX. SD7096 - 4SD - 1SD - 1SD - 0SD	Egypt
5	SK 94	OPATA/ RAYON// KAUZ .* CMBW90Y3180 - 0TOM -3Y - 010M - 010Y - 10M - 015Y - 0Y - 0AP - 0S.	Egypt
6	Giemiza 7	CMH74A.630/SX//SERI82 /Agent* CGM4611- 2GM- 3GM- 1GM- 0GM	Egypt
7	Al-Fayyad	ACSAD 875 // URES *2 / PRIS	Iraq

Experimental Site and Crop Management

The experiment was conducted at the Agricultural Research and Experimental Station, College of Agriculture, University of Kirkuk, Iraq, during the 2024–2025 growing season. The experimental field was prepared by disc plowing followed by leveling and soil smoothing. Diammonium phosphate fertilizer (DAP; 46% P_2O_5 + 18% N) was applied once before sowing at a rate of 200 kg ha^{-1}. Urea fertilizer (46% N) was applied in two equal splits at a total rate of 200 kg ha^{-1}, with the first application at the tillering stage and the second at stem elongation **(**Kadhim, 2023)**.** Sowing was carried out in mid-November 2024. Standard agronomic practices, including irrigation and weed control, were applied as required throughout the growing season.

Crossing Program and Experimental Design

The seven parental genotypes and their 21 F_2 hybrids derived from a half-diallel

mating design were evaluated using a randomized complete block design (RCBD) with three replications. Each replication consisted of 28 experimental units in which genotypes were randomly assigned. The spacing between plants was 0.05 m, between rows 0.30 m, and between replications 1.00 m. Each experimental unit comprised three rows, each 2.00 m long.

Data Collection

Harvesting was carried out on 1 June 2025. Ten plants were randomly selected from each experimental unit after excluding border plants. The following traits were recorded: days to 50% flowering (days), flag leaf area (cm^2), number of spikes per plant, number of grains per spike, thousand-grain weight (g), and grain yield per plant (g).

Statistical and Genetic Analysis

Data were subjected to analysis of variance using SAS software. Mean comparisons were performed using Duncan's Multiple Range Test at 5% probability. General combining ability (GCA) and specific combining ability (SCA) effects and their sums of squares were estimated according to Griffing's Method II, fixed model (Griffing, 1956). Phenotypic variance components (V_P), including additive variance (V_A), dominance variance (V_D), and environmental variance (V_E), as well as broad-sense heritability ($H^2_{b.s}$), narrow-sense heritability ($h^2_{n.s}$) and average degree of dominance ($\bar{a}$), were estimated using expected mean squares (EMS) for the fixed model assuming pure parental lines, with calculations performed using OPSTAT software. Heterosis was estimated as the percentage deviation of F_2 hybrids from mid-parent and better-parent values, and the significance of heterosis was tested using the t-test at 1% and 5% probability levels according (Al-Zubaidy & Al-Jubory 2016).

RESULT AND DISCUSSION

Table 2 shows highly significant differences ($P \leq 0.01$) among the parental genotypes for several traits, particularly flag leaf area, number of grains per spike, thousand-grain weight, and grain yield per plant, reflecting clear genetic variation among the studied genotypes. The number of spikes per plant exhibited significant differences at $P \leq 0.05$, whereas days to flowering did not differ significantly ($P > 0.05$), indicating that parents were relatively uniform for this trait compared to the others.

Table 3 presents the performance of F_2 half-diallel hybrids, revealing highly significant differences ($P \leq 0.01$) for all studied traits without exception. This indicating a wide genetic variation in the F_2 generation resulting from segregation and recombination. The higher significance observed in hybrids compared to parents highlights the effectiveness of the crosses in generating broader genetic variability, particularly for yield-related traits, which facilitates the identification of superior lines in subsequent generations and enhances the potential for effective selection in advanced generation.

Table 2. Analysis of variance of parental wheat genotypes for yield and related traits.

S.o.V	D.F	DFF	FLA	NSPP	NGPS	TGW	PY
Replicate	2	2.04	5.42	0.53	4.59	0.07	5.42
Parents	6	1.42	530.17**	1.12*	115.83**	10.80**	42.83**
Error	12	0.54	1.42	0.30	4.20	0.26	4.29

S.o.V: Sources of variation; **D.F:** Degrees of freedom; **DFF:** Days to 50% flowering; **FLA:** Flag leaf area (cm^2); **NSPP:** Number of spikes per plant; **NGPS:** Number of grains per spike; **TGW:** Thousand-grain weight (g); **PY:** Plant yield (g); *and ** indicate significance at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Table 3. Analysis of variance of F_2 half-diallel wheat hybrids for yield and related traits.

S.o.V	D.F	DFF	FLA	NSPP	NGPS	TGW	PY
Replicate	2	0.82	83.47	3.45	3.47	0.87	41.10
Hybrids	20	9.78^{**}	178.00^{**}	4.37^{**}	202.96^{**}	42.75^{**}	50.85^{**}
Error	40	1.19	2.16	0.50	11.33	1.79	6.32

Tables 4 and 5 depict the magnitude of genetic variability among the parental genotypes and F2 hybrids for the studied traits. The parents were relatively homogeneous for days to flowering ($P > 0.05$) with means within the range of 129.67 to 131.67 days, while F2 hybrids showed higher variability because of genetic segregation. It is worth mentioning that the hybrids SK 95 *x* Giemiza 9, SK 95 *x* Side 12, and Giemiza 9 *x* Side 12 had shown earlier flowering, with an average of 126.00 days, revealing that some combinations of parents can disrupt the uniformity of the parents and produce early-maturing hybrids. This is an important aspect that needs attention for improving adaptation in dry environments. These results are in agreement with those reported by Kumar *et al*. (2017) Shah *et al*. (2018) and Hindi *et al.* (2026).

During vegetative growth, flag leaf area ranged from 70.79 cm2 for Side 14 as the highest among parents to 32.26 cm2 for SK 95 as the lowest, while in F2 hybrids, the range was from the highest for Side 14 *x* Al-Fayyad, with a mean of 71.55 cm2, to the lowest for SK 95 *x* Side 12, with a mean of 38.81 cm2. The latter agrees with the conclusions of Mohammed, (2025), that flag leaf area contributes to physiological efficiency.

For spikes per plant, parental values ranged from 7.03 to 8.79 with Giemiza 9 and Giemiza 7 having the highest of 8.79 and Side 14 having the lowest of 7.03. During F2 generation, variability extended, with Side 14 *x* Side 12 having the highest mean of 11.60, followed by Giemiza 9 *x* Al-Fayyad with a mean of 10.20, while Giemiza 9 *x* Giemiza 7 had one of the lowest means of 6.83 in agreement with previous reports on increased spike number variability due to segregation (Raza *et al*. (2025).

Among the parents, SK 94 had the highest value for grains per spike, with a mean of 83.73, followed by Giemiza 9, with a mean of 78.00, while Side 12 had the lowest value, 69.20. During F2 generation, SK 95 *x* Side 12 reached 95.73 grains, followed by Giemiza 9 *x* Side 12, which attained 91.10, whereas the SK 95 *x* SK 94 cross had the lowest mean, 63.27, reflecting partial dominance breakdown in F2. These results correspond with the results Raza *et al*. (2025), Bibi *et al*. (2024).

The TSW of the parents ranged from 40.52 to 46.18 g, with SK 94 having the highest and Giemiza 7 the lowest. In the F2 hybrids, the highest mean was achieved by SK 95 *x* Side 14, with 49.12 g, closely followed by SK 95 *x* SK 94, with 48.49 g, while Giemiza 9 *x* Side 12 was the lowest, at 38.75 g. This is in agreement with the reports on the sensitivity of this trait to additive gene effects Bilgin *et al*. (2022), Rwaida & Hama-Amin, (2024).

Grain yield per plant also reflected this variation, with parents ranging from 20.89 to 31.54 g (SK 94 highest, Side 14 lowest). Several F_2 hybrids surpassed the better parent, with Side 14 *x* Side 12 producing 37.85 g, SK 95 *x* Side 14 35.11 g, and Giemiza 9 *x* Side 12 the lowest (24.49 g), indicating the potential for transgressive segregants in subsequent generations. These observations are consistent with the findings of Abro *et al*. (2021), and Ribeiro *et al*. (2025).

Table 4. Mean performance of parental wheat genotypes for yield and related traits.

Genotypes	DFF	FLA	NSPP	NGPS	TGW	PY
SK 95	129.67 a	32.26 g	8.39 a	76.07 b	43.69 b	27.89 ab
Giemiza 9	130.00 a	65.09 b	8.79 a	78.00 b	43.47 b	29.77 a
Side 14	131.00 a	70.79 a	7.03 b	70.33 c	42.21 c	20.89 c
Side 12	131.67 a	48.92 e	7.83 ab	69.20 c	43.78 b	23.78 c
SK 94	130.67 a	43.22 f	8.16 a	83.73 a	46.18 a	31.54 a
Giemiza 7	130.67 a	52.09 d	8.79 a	67.13 c	40.52 d	23.93 c
Al-Fayyad	130.00 a	60.41 c	7.99 ab	67.87 c	45.47 a	24.66 bc

Means for each trait followed by similar letters do not differ in terms of statistical significance, based on DMRT at $P \leq 0.05$.

Table 5. Mean performance of F_2 half-diallel wheat hybrids for yield and related traits.

Hybrids	DFF	FLA	NSPP	NGPS	TGW	PY
SK 95 *x* Giemiza 9	126.00 a	63.51 bc	8.39 d-g	73.87 de	46.17 bcd	28.57 c-f
SK 95 *x* Side 14	131.33 b	60.09 d	9.19 b-e	77.73 bcd	49.12 a	35.11 ab
SK 95 *x* Side 12	126.00 a	38.81 k	7.03 gh	95.73 a	38.31 i	25.79 ei
SK 95 *x* SK 94	130.33 b	49.57 i	7.59 fgh	63.27 h	48.49 ab	23.27 hi
SK 95 *x* Giemiza 7	130.33 b	65.46 b	9.20 b-e	74.60 de	46.07 cd	31.67 bc
SK 95 *x* Al-Fayyad	131.00 b	61.54 cd	8.39 d-g	81.20 bc	34.22 j	23.24 hi
Giemiza 9 *x* Side 14	131.33 b	55.25 efg	7.60 fgh	77.40 bcd	41.95 fgh	24.55 f-i
Giemiza 9 *x* Side 12	126.00 a	63.21 bc	6.97 h	91.10 a	38.75 i	24.49 f-i
Giemiza 9 *x* SK 94	131.67 b	52.73 gh	9.80 bc	71.67 d-g	40.37 ghi	28.32 c-g
Giemiza 9 *x* Giemiza 7	130.67 b	57.08 e	10.20 b	74.47 de	40.67 ghi	30.79 bcd
Giemiza 9 *x* Al-Fayyad	131.33 b	59.64 d	10.20 b	65.67 gh	39.43 i	26.40 d-i
Side 14 *x* Side 12	130.33 b	48.90 i	11.60 a	75.13 cde	43.46 ef	37.85 a
Side 14 *x* SK 94	131.67 b	56.21 ef	8.59 c-f	66.80 fgh	43.36 ef	24.90 f-i
Side 14 *x* Giemiza 7	129.67 b	56.57 e	8.59 c-f	82.67 b	42.34 e-h	30.07 cde
Side 14 *x* Al-Fayyad	130.67 b	71.55 a	9.39 bcd	67.13 fgh	41.97 fgh	26.63 d-i
Side 12 *x* SK 94	130.67 b	61.80 cd	8.03 d-h	76.40 b-e	44.76 de	27.47 d-i
Side 12 *x* Giemiza 7	131.00 b	63.79 bc	6.83 h	81.87 b	39.02 i	21.77 i
Side 12 *x* Al-Fayyad	130.00 b	46.06 j	7.96 e-h	70.60 efg	39.91 hi	22.53 hi
SK 94 *x* Giemiza 7	131.00 b	65.30 b	7.59 fgh	73.83de	48.16 abc	27.04 d-i
SK 94 *x* Al-Fayyad	130.33 b	50.39 hi	8.60 c-f	64.40 h	42.66 efg	23.60 ghi
Giemiza 7 *x* Al-Fayyad	131.33 b	53.66 fg	8.16 d-h	72.73 def	44.33 def	26.27 d-i

Means for each trait followed by similar letters do not differ in terms of statistical significance, based on DMRT at $P \leq 0.05$.

Table 6 demonstrates the extent of heterosis as deviation of F2 from mid-parent values for all studied traits, with several hybrids exhibiting highly significant effects ($P \leq 0.01$), reflecting clear dominance and non-additive genetic effects. For days to flowering, the greatest negative heterosis-indicating earliness-was observed in Giemiza 9 *x* Side 12 (-3.69%), SK 95 *x* Side 12 (-3.57%), and SK 95 *x* Giemiza 9 (-2.95%).

For vegetative traits, flag leaf area showed the highest heterosis in SK 94 *x* Giemiza 7 (37.04%), Side 12 *x* SK 94 (34.15%), and SK 95 *x* Giemiza 9 (30.46%), with additional significant hybrids including SK 95 *x* Side 14 (16.62%), SK 95 *x* SK 94 (31.35%), SK 95 *x* Giemiza 7 (55.20%), SK 95 *x* Al-Fayyad (32.80%), and Giemiza 9 *x* Side 12 (10.87%).

With respect to spikes per plant, the greatest heterosis values was found in Side 14 x Side 12 (56.16%), followed by Side 12 x Giemiza 7 (26.30%), Giemiza 9 *x* Al-Fayyad (21.55%), Giemiza 9 *x* Giemiza 7 (16.06%), Giemiza 9 *x* SK 94 (15.59%), Side 14 *x* Giemiza 7 (13.05%), and SK 95 *x* Side 14 (19.12%).

As for grains per spike, the highest heterosis values was found in the cross of Giemiza 9 *x* Side 12 (23.78%), followed by Side 14 *x* Giemiza 7 (20.27%), Side 12 *x* Giemiza 7 (20.10%), as well as Side 14 *x* Side 12 (7.69%), Giemiza 7 *x* Al-Fayyad (7.75%), SK 95 *x* Giemiza 7 (12.83%), and SK 95 *x* Side 14)

Thousand grain weight e*x*hibited the highest heterosis values in SK 95 *x* Side 14 (14.37%), SK 94 *x* Giemiza 7 (11.08%), SK 95 *x* SK 94 (7.91%), and SK 95 *x* Giemiza 7 (9.41%), while some values were negative but significant: Giemiza 9 *x* Side 12.(%11.16-)

The most important trait of grain yield per plant exhibited high heterosis of 69.48% with Side 14 *x* Side 12, followed by SK 95 *x* Side 14 (43.95%), Side 14 *x* SK 94 (34.21%), SK 95 *x* Giemiza 7 (31.67%), Side 14 *x* Giemiza 7 (16.95%), and Giemiza 9 *x* Giemiza 7 (14.67%), which significantly exceeded the means of their parents at $P \leq 0.01$. Other significant hybrids that could play a role in stabilizing the trait in succeeding generations included Giemiza 9 *x* Al-Fayyad for number of flowers (1.03%), Giemiza 7 *x* Al-Fayyad for number of grains per spike (7.75%), and SK 94 *x* Al-Fayyad for thousand-grain weight (11.08%), which were significant at $P \leq 0.01$

In particular, Side 14 *x* SK 95 was one of the most exemplary F2 hybrids in showing high positive heterosis in terms of five important traits: flag leaf area, number of spikes per plant, grains per spike, weight of a thousand grains, and grain yield, starting with plant vegetation and ending with grain production ,. The significant heterotic effects observed in hybrid (Side 14 *x* SK 95) for the evaluated traits confirm the occurrence of heterosis, likely resulting from dominance and/or overdominance gene action. The superior performance of the hybrid as deviation of F2 from mid-parent or better-parent values reflects the efficiency of its genetic constitution and emphasizes the importance of selecting genetically diverse parents to achieve maximum heterotic response. Consequently, this hybrid could be considered a promising candidate for inclusion in crop improvement programs. The superiority of some hybrids in heterosis over the mid is consistent with the results reported by Shah *et al*. (2018), Joshi & Kumar, (2020), Askander *et al* (2021), Al-Mafarji and Al-Jubouri (2023b) , Ahmed *et al*. (2023), Deviren *et al*. (2024), and Raza *et al*. (2025), indicating a clear role of dominance effects.

Table 6. Heterosis as deviation of F2 from mid-parent values for yield and related traits in F_2 wheat hybrids.

Hybrids	DFF	FLA	NSPP	NGPS	TGW	PY
SK 95 *x* Giemiza 9	-2.95**	30.46**	-2.40	-4.11	5.95**	-0.91
SK 95 *x* Side 14	0.77	16.62**	19.12**	6.19*	14.37**	43.95**
SK 95 *x* Side 12	-3.57**	-4.38	-13.27*	31.80**	-12.41**	-0.18
SK 95 *x* SK 94	0.13	31.35**	-8.28	-20.82**	7.91**	-21.71**
SK 95 *x* Giemiza 7	0.13	55.20**	7.08	4.19	9.41**	22.23**
SK 95 *x* Al-Fayyad	0.90	32.80**	2.37	12.83**	-23.25**	-11.57*
Giemiza 9 *x* Side 14	0.64	-18.68**	-3.93	4.36	-2.09	-3.06
Giemiza 9 *x* Side 12	-3.69**	10.87**	-16.13**	23.78**	-11.16**	-8.52
Giemiza 9 *x* SK 94	1.02	-2.64	15.59**	-11.38**	-9.93**	-7.64
Giemiza 9 *x* Giemiza 7	0.26	-2.57	16.06**	2.62	-3.17	14.67*
Giemiza 9 *x* Al-Fayyad	1.03*	-4.96**	21.55**	-9.96**	-11.35**	-3.00
Side 14 *x* Side 12	-0.76	-18.31**	56.16**	7.69**	1.09	69.48**
Side 14 *x* SK 94	0.64	-1.39	13.05*	-13.28**	-1.88	-5.01
Side 14 *x* Giemiza 7	-0.89	-7.92**	8.58	20.27**	2.36	34.21**
Side 14 *x* Al-Fayyad	0.13	9.07**	25.04**	-2.85	-4.26*	16.95*
Side 12 *x* SK 94	-0.38	34.15**	0.45	-0.09	-0.48	-0.69

Hybrids	DFF	FLA	NSPP	NGPS	TGW	PY
Side 12 *x* Giemiza 7	-0.13	26.30**	-17.73**	20.10**	-7.42**	-8.73
Side 12 *x* Al-Fayyad	-0.89	-0.03	-0.39	-7.67**	-11.27**	-18.55**
SK 94 *x* Giemiza 7	0.26	37.04**	-10.39*	-2.12	11.08**	-2.50
SK 94 *x* Al-Fayyad	0.00	-2.74	6.43	-15.04**	-6.92**	-16.01*
Giemiza 7 *x* Al-Fayyad	0.77	-4.60*	-2.71	7.75**	3.09	8.11
$S.E_{(s_{ij})}$	0.74	1.23	0.48	2.17	0.84	1.71

*and ** indicate significance at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Table 7 illustrates the extent of heterobeltiosis, hybrid performance relative to the better parent, for all studied traits, with several hybrids showing highly significant effects ($P \leq 0.01$). For earliness in flowering, SK 95 *x* Giemiza 9 (-2.83%), SK 95 *x* Side 12 (-2.83%), and Giemiza 9 *x* Side 12 (-3.08%) flowered earlier than the better parent, indicating their ability to shorten the growth period.

For vegetative traits, flag leaf area showed the highest heterobeltiosis in Side 12 *x* SK 94 (26.33%), followed by SK 95 *x* Giemiza 7 (25.67%), SK 94 *x* Giemiza 7 (25.37%), and Side 12 *x* Giemiza 7 (22.46%), whereas Giemiza 7 *x* Al-Fayyad exhibited a significant negative effect (-11.17%)

Regarding spikes per plant, the most pronounced heterobeltiosis occurred in Side 14 *x* Side 12 (48.26%) and Side 14 *x* Al-Fayyad (17.54%), along with Giemiza 9 *x* Giemiza 7 (16.04%), Giemiza 9 *x* Al-Fayyad (16.04%), and Giemiza 9 *x* SK 94 (11.45%), highlighting the role of non-additive gene effects.

For grains per spike, notable heterobeltiosis was observed in Side 12 *x* Giemiza 7 (18.30%), Side 14 *x* Giemiza 7 (17.54%), Giemiza 9 *x* Side 12 (16.79%), SK 95 *x* Side 12 (25.85%), SK 95 *x* Giemiza 7 (6.75%), Side 14 *x* Side 12 (6.82%), and Giemiza 7 *x* Al-Fayyad.(%7.17)

In thousand-grain weight, SK 95 *x* Side 14 showed the highest positive heterobeltiosis (12.43%), followed by SK 95 *x* Giemiza 9 (5.69%), SK 95 *x* SK 94 (5.00%), and SK 95 *x* Giemiza 7 (5.45%), whereas Giemiza 9 *x* SK 94 (-12.57%) and Side 12 *x* Giemiza 7 (-10.86%) displayed significant negative effects.

Grain yield per plant, the most critical trait, was highest in Side 14 *x* Side 12 (59.18%), followed by SK 95 *x* Side 14 (25.87%) and Side 14 *x* Giemiza 7 (25.67).

Overall, only a limited number of hybrids excelled simultaneously in multiple traits, making them the most promising genetically. Side 14 *x* Side 12 and Side 14 *x* Giemiza 7 consistently showed high heterobeltiosis for grain yield, spikes per plant, and grains per spike, indicating superior reproductive performance, while SK 95 *x* Side 14 excelled in three key traits-thousand-grain weight, spikes per plant, and yield-reflecting strong genetic compatibility and a genotype capable of enhancing final productivity. The superiority of some hybrids in heterosis over the mid- and better-parent is consistent with the results reported by Shah *et al*. (2018), Joshi & Kumar, (2020), Askander *et al* (2021), Al-Mafarji and Al-Jubouri (2023b) , Ahmed *et al*. (2023), Deviren *et al*. (2024), Raza *et al*. (2025), and El-Karamity *et al*. (2025), indicating a clear role of dominance effects.

Table 7. Heterobeltiosis as deviation of F2 from better parent for yield and related traits in F_2 wheat hybrids.

Hybrids	DFF	FLA	NSPP	NGPS	TGW	PY
SK 95 *x* Giemiza 9	-2.83**	-2.44	-4.59	-5.30	5.69**	-4.04
SK 95 *x* Side 14	1.29*	-15.12**	9.47	2.19	12.43**	25.87**
SK 95 *x* Side 12	-2.83**	-20.66**	-16.20**	25.85**	-12.49**	-7.54
SK 95 *x* SK 94	0.51	-23.84**	-13.62**	-24.44**	5.00*	-26.24**
SK 95 *x* Giemiza 7	0.51	25.67**	4.69	-1.93	5.45**	13.55*
SK 95 *x* Al-Fayyad	1.03	1.86	-0.08	6.75*	-24.76**	-16.69*
Giemiza 9 *x* Side 14	1.03	-21.95**	-13.52**	-0.77	-3.51	-17.53**
Giemiza 9 *x* Side 12	-3.08**	-2.90	-20.73**	16.79**	-11.47**	-17.73**
Giemiza 9 *x* SK 94	1.28*	-19.00**	11.45*	-14.41**	-12.57**	-10.23
Giemiza 9 *x* Giemiza 7	0.51	-12.31**	16.04**	-4.53	-6.45**	3.43
Giemiza 9 *x* Al-Fayyad	1.03	-8.38**	16.04**	-15.81**	-13.30*	-11.32*
Side 14 *x* Side 12	-0.51	-30.93**	48.26**	6.82*	-0.71	59.18**
Side 14 *x* SK 94	0.77	-20.59**	5.25	-20.22**	-6.10**	-21.06**
Side 14 *x* Giemiza 7	-0.77	-20.08**	-2.26	17.54**	0.31	25.67**
Side 14 *x* Al-Fayyad	0.51	1.08	17.54**	-4.55	-7.70**	8.00
Side 12 *x* SK 94	0.00	26.33**	-1.61	-8.76**	-3.07	-12.92*
Side 12 *x* Giemiza 7	0.26	22.46**	-22.23**	18.30**	-10.86**	-9.03
Side 12 *x* Al-Fayyad	0.00	-23.76**	-0.38	2.02	-12.23**	-8.65
SK 94 *x* Giemiza 7	0.26	25.37**	-13.58**	-11.82**	4.28*	-14.26*
SK 94 *x* Al-Fayyad	0.26	-16.58**	5.33	-23.09**	-7.63**	-25.17**
Giemiza 7 *x* Al-Fayyad	1.03	-11.17**	-7.11	7.17*	-2.52	6.51
$S.E_{(s_{ij})}$	0.86	1.42	0.56	2.51	0.97	1.98

*and ** indicate significance at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Table 8 shows highly significant mean square ($P \leq 0.01$) of genotypes for all studied traits, reflecting the substantial genetic variability present in the F_2 generation, which confirms the potential of these traits to respond to selection. Significant mean square of both general combining ability (GCA) and specific combining ability (SCA), were also observed for all traits indicating that both additive and non-additive gene actions contribute to the inheritance of these traits, consistent with the principles described by Kempthorne (1957) in the genetic analysis of crosses.

The effect of SCA was higher than GCA for all traits, as indicated by the low ratio σ^2GCA / σ^2SCA (0.16 for days to flowering, 0.19 for flag leaf area, 0.03 for spikes per plant, 0.13 for grains per spike, 0.12 for thousand-grain weight, and 0.05 for grain yield), The significant and desirable general combining ability effects observed in some wheat parents indicate the presence of favorable additive genes contributing positively to the expression of the studied traits, confirming their effectiveness and suitability for use in wheat breeding programs. This aligns with Griffing (1956), who emphasized the role of SCA in explaining variation among genetically diverse hybrids, and with Falconer & Mackay (1996), who highlighted the contribution of gene interactions in quantitative traits.

Collectively, these indicators suggest that breeding programs based on hybridization followed by individual selection in advanced generations are appropriate for exploiting non-additive variation and converting it into stable variation in promising, high-yielding lines.

Table 8. Analysis Results for general (GCA) and specific combining ability (SCA).

S.o.V	D.F	DFF	FLA	NSPP	NGPS	TGW	PY
Replicate	2	0.08	59.16	3.36	4.89	0.47	39.74
Genotypes	27	7.66**	258.73**	3.59**	178.34**	34.74**	47.89**
GCA	6	9.64**	380.61**	1.55*	194.88**	35.92**	28.77*
SCA	21	7.09**	223.91**	4.18**	173.62**	34.40**	53.35**
Error	54	1.11	3.02	0.47	9.45	1.41	5.89
σ^2GCA/σ^2SCA		0.16	0.19	0.03	0.13	0.12	0.05

Table 9 shows that several parents exhibited significant general combining ability (GCA) effects, confirming the role of additive gene action in the inheritance of traits, as highlighted by Kempthorne (1957) and its importance for direct selection in segregating generations. Parent SK 95 showed a desirable effect for earliness in flowering (-0.83) at $P \leq 0.05$, indicating the presence of genes that reduce vegetative growth duration, a trait beneficial in dry environments as noted by Hassan & Al Jubouri, (2023).

For vegetative traits, Side 14 exhibited the highest significant effect on flag leaf area (4.50), followed by Giemiza 9 (3.55), Giemiza 7 (1.82), and Al-Fayyad (1.55), demonstrating that these parents possess genetic potential to enhance vegetative growth, which is strongly associated with increased photosynthetic efficiency Bibi *et al*., (2024).

Regarding reproductive traits, Side 12 showed the highest significant GCA effect for grains per spike (3.55), making it an outstanding parent for improving spike productivity, consistent with findings by Bilgin *et al*. (2022) on the importance of parents with desirable effects for reproductive traits. SK 94 exhibited the highest desirable effect for thousand-grain weight (1.96) at $P \leq 0.01$, reflecting its genetic ability to improve grain size and quality. Conversely, Al-Fayyad showed negative and significant effects on grains per spike (-4.43) and thousand-grain weight (-1.01), indicating limited genetic potential for enhancing reproductive traits, highlighting the importance of selecting parents with desirable GCA effects as recommended by Rwaida & Hama-Amin, (2024).

Overall, these results indicate that Side 14, Giemiza 9, and Giemiza 7 are strong sources for improving vegetative traits, Side 12 is better for enhancing grain number, and SK 94 excels in improving grain quality traits, making these parents key components in breeding programs aimed at increasing the productivity of subsequent generations through early and advanced line selection.

Table 9. General combining ability effects of parents for studied traits.

Parents	DFF	FLA	NSPP	NGPS	TGW	PY
SK 95	-0.83*	-5.13**	-0.12	2.36	0.80	0.93
Giemiza 9	-0.53	3.55**	0.34	1.43	-0.92	0.84
Side 14	0.58	4.50**	0.15	-1.09	0.46	0.64
Side 12	-0.50	-3.25**	-0.40	3.55**	-1.20*	-0.85
SK 94	0.58	-3.03**	-0.13	-1.50	1.96**	0.29
Giemiza 7	0.39	1.82*	0.05	-0.32	-0.10	0.04
Al-Fayyad	0.32	1.55*	0.11	-4.43**	-1.01*	-1.90
$S.E_{(g_i)}$	0.50	0.82	0.32	1.45	0.56	1.14

Table 10 illustrates the wide variation in specific combining ability (SCA) effects among the hybrids, reflecting the prominent role of non-additive gene action (dominance and overdominance) in controlling quantitative traits, as highlighted by Griffing (1956) and confirmed by Kempthorne (1957) in quantitative genetics principles.

For flowering, the hybrids SK 95 *x* Giemiza 9 (-2.86), SK 95 *x* Side 12 (-2.90), and Giemiza 9 *x* Side 12 (-3.19) showed significant negative values at $P \leq 0.01$, indicating their ability to accelerate flowering compared to the expected genetic mean, a pattern previously reported in dry environments (Mohammed., 2025).

Regarding vegetative traits, large positive SCA effects were observed in SK 95 *x* Giemiza 7 (12.56), Side 12 *x* SK 94 (11.87), SK 94 *x* Giemiza 7 (10.30), and Side 12 *x* Giemiza 7 (9.01), confirming the potential of these genetic combinations to enhance photosynthetic efficiency via the flag leaf, consistent with Sulaiman *et al*. (2024). Negative significant effects were detected in Giemiza 7 *x* Al-Fayyad (-5.92) and Side 12 *x* Al-Fayyad (-8.45), indicating poor parental genetic compatibility, as also noted by Mohammed. (2025) for weak vegetative traits.

For spikes per plant, desirable significant SCA effects were observed in SK 95 *x* Giemiza 7, Giemiza 9 *x* SK 94, Giemiza 9 *x* Giemiza 7, Giemiza 9 *x* Al-Fayyad, and Side 14 *x* Side 12, demonstrating their efficiency in enhancing productive branching, a common feature in hybrids with strong gene interaction (Ribeiro *et al*., 2025). Several hybrids also excelled in grains per spike, notably SK 95 *x* Side 12 (15.16), Giemiza 9 *x* Side 12 (11.46), Side 14 *x* Giemiza 7 (9.41), and Side 12 *x* Giemiza 7 (3.98), reflecting partial or complete dominance in this trait. The results of this study are consistent with Bilgin *et al*. (2022).

For thousand-grain weight, the highest desirable SCA effects were observed in SK 95 *x* Side 14 (5.05), SK 94 *x* Giemiza 7 (3.48), and SK 95 *x* Giemiza 9 (3.47), indicating their potential to improve grain quality, whereas Giemiza 9 *x* SK 94 (–3.49) and Side 12 *x* Giemiza 7 (-2.50) showed significant negative effects. The findings of this trait align with the general trend observed in the studies of Abro *et al*., (2021)

For grain yield per plant, Side 14 *x* Side 12 (11.16), SK 95 *x* Side 14 (6.65), SK 95 *x* Giemiza 7 (3.81), and Giemiza 9 *x* Giemiza 7 (3.02) were the top-performing hybrids, consistent with the concept of "genetically superior combinations" described by Ribeiro *et al*., (2025).

Overall, hybrids with superior SCA particularly SK 95 *x* Giemiza 7, Side 14 *x* Side 12, SK 94 *x* Giemiza 7, and Side 12 *x* SK 94 exhibit the highest genetic compatibility between parents and represent the better genetic options for breeding programs aimed at increasing productivity and improving quantitative traits in subsequent generations.

Hybrids showing significant and desirable specific combining ability effects indicate the involvement of non-additive gene action in the expression of the studied traits, resulting from favorable genetic interactions between parental lines. Such hybrids are valuable for exploiting heterosis and for identifying superior parental combinations in breeding programs targeting overall genetic improvement. Across all studied traits, hybrids derived from parents exhibiting significant and desirable general combining ability effects highlight the major role of additive gene action in trait inheritance. The presence of significant specific combining ability in some of these hybrids further indicates the contribution of non-additive gene effects, such as dominance and epistatic interactions, arising from favorable parental combinations. In contrast, the lack of significant specific combining ability in other hybrids, despite the desirable general combining ability of one or both parents, suggests the predominance of additive gene effects in the stable expression of the evaluated traits.

Table 10. Specific combining ability effects of F2 hybrids for studied traits.

Hybrids	DFF	FLA	NSPP	NGPS	TGW	PY
SK 95 *x* Giemiza 9	-2.86**	8.88**	-0.29	-4.58*	3.47**	-0.09
SK 95 *x* Side 14	1.36*	4.51**	0.70	1.80	5.05**	6.65**
SK 95 *x* Side 12	-2.90**	-9.01**	-0.90*	15.16**	-4.12**	-1.18
SK 95 *x* SK 94	0.36	1.52	-0.62	-12.26**	2.91**	-4.83**
SK 95 *x* Giemiza 7	0.55	12.56**	0.81*	-2.10	2.55**	3.81*
SK 95 *x* Al-Fayyad	1.29*	8.91**	-0.06	8.61**	-8.39**	-2.68
Giemiza 9 *x* Side 14	1.06	-9.00**	-1.35**	2.39	-0.41	-3.82*
Giemiza 9 *x* Side 12	-3.19**	6.70**	-1.43**	11.46**	-1.95**	-2.39
Giemiza 9 *x* SK 94	1.40*	-4.00**	1.13**	-2.93	-3.49**	0.30
Giemiza 9 *x* Giemiza 7	0.58	-4.49**	1.35**	-1.31	-1.13	3.02*
Giemiza 9 *x* Al-Fayyad	1.32*	-1.67	1.29**	-6.00**	-1.47*	0.57
Side 14 *x* Side 12	0.03	-8.56**	3.39**	-1.99	1.39*	11.16**
Side 14 *x* SK 94	0.29	-1.47	0.11	-5.28**	-1.87*	-2.92*
Side 14 *x* Giemiza 7	-1.53*	-5.95**	-0.07	9.41**	-0.83	2.50
Side 14 *x* Al-Fayyad	-0.45	9.29**	0.67	-2.02	-0.29	1.00
Side 12 *x* SK 94	0.36	11.87**	0.10	-0.31	1.18	1.14
Side 12 *x* Giemiza 7	0.88	9.01**	-1.28**	3.98*	-2.50**	-4.31**
Side 12 *x* Al-Fayyad	-0.05	-8.45**	-0.21	-3.18	-0.70	-1.61
SK 94 *x* Giemiza 7	-0.19	10.30**	-0.79*	0.99	3.48**	-0.17
SK 94 *x* Al-Fayyad	-0.79	-4.34**	0.15	-4.34*	-1.11	-1.67
Giemiza 7 *x* Al-Fayyad	0.40	-5.92**	-0.46	2.82	2.62**	1.24
$S.E_{(S_{ij})}$	0.70	1.16	0.46	2.05	0.79	1.62

Analysis of genetic parameters in Table 11 indicates that genetic variance exceeded environmental variance for all studied traits, suggesting that most of the phenotypic variation is due to genetic factors. This reflects a broad genetic base that can be exploited in selection in subsequent generations. Moreover, dominance variance exceeded additive variance for all traits, resulting in high dominance degrees of 3.552 for days to flowering, 3.245 for flag leaf area, 7.861for spikes per plant, 3.992for grains per spike, 4.148 for thousand-grain weight, and 6.110for grain yield per plant. These values, all well above one, indicate the presence of overdominance and a strong influence of non-additive gene action, a natural pattern in the F_2 generation due to allele recombination and instability.

Broad-sense heritability (H^2) was very high for all traits, reaching 0.962 for flowering, 0.997 for flag leaf area, 0.970 for spikes per plant, 0.987 for grains per spike, 0.991 for thousand-grain weight, and 0.971 for grain yield, all within the high heritability category, indicating a clear predominance of genetic factors over environmental effects. In contrast, narrow-sense heritability (h^2) was very low for all traits, ranging from 0.030 to 0.159, reflecting weak additive gene action and limited response to direct selection within the F_2 generation, emphasizing the need to delay selection until advanced generations. The high heritability in the broad sense compared to the narrow sense is consistent with the findings of Bilgin *et al*. (2022), Mohammed & Al Hamdani, (2025) and Raza *et al*. (2025), and reflects the contribution of dominance and over-dominance to the inheritance of traits.

Expected genetic advance (ΔG%) was also low for all traits, at 0.55% for flowering, 9.34% for flag leaf area, 1.45% for spikes per plant, 4.10% for grains per spike, 2.99% for thousand-grain weight, and 2.68% for grain yield, indicating limited genetic progress in this generation. The low expected genetic gain values are in line with the low narrow-sense heritability, which is consistent with the reports of Lamara *et al*, (2022), Mohammed, (2025), Ribeiro *et al*. (2025) and Hindi *et al* (2025).

Collectively, these results suggest that the studied traits are mainly governed by non-additive gene action (dominance and overdominance), making selection in the F_2 generation inefficient, whereas subsequent generations provide a more suitable stage to convert this variation into stable and sustainable genetic improvement.

Table 11. Estimation of genetic parameters for F_2 Bread Wheat Hybrids.

Genetic Parameters	DFF	FLA	NSPP	NGPS	TGW	PY
V_E	0.369 ± 0.209	1.008 ± 0.571	0.156 ± 0.088	3.150 ± 1.786	0.469 ± 0.266	1.963 ± 1.113
V_G	9.238 ± 1.614	350.453 ± 63.437	5.110 ± 0.265	246.357 ± 32.504	49.100 ± 5.989	66.666 ± 4.860
V_P	9.608 ± 1.510	351.461 ± 55.227	5.266 ± 0.827	249.507 ± 39.206	49.569 ± 7.789	68.629 ± 10.784
V_A	1.264 ± 0.357	55.939 ± 14.097	0.160 ± 0.058	27.471 ± 7.219	5.113 ± 1.330	3.390 ± 1.069
V_D	7.974 ± 0.700	294.514 ± 22.010	4.950 ± 0.412	218.886 ± 17.076	43.987 ± 3.382	63.275 ± 5.257
$H^2_{b.s}$	0.962	0.997	0.970	0.987	0.991	0.971
$h^2_{n.s}$	0.132	0.159	0.030	0.110	0.103	0.049
$\bar{a}$	3.552	3.245	7.861	3.992	4.148	6.110
Genetic Advance ΔG	0.718	5.252	0.123	3.061	1.278	0.720
Genetic advance as percent ΔG%	0.55	9.34	1.45	4.10	2.99	2.68

CONCLUSION

The results of this study revealed clear genetic variation among the studied bread wheat genotypes, reflected in differences in mean performance, general and specific combining ability, and heterosis in the F_2 generation. Several parents demonstrated notable genetic potential, with Side 14, Giemiza 9, and Giemiza 7 excelling in vegetative traits, Side 12 in grains per spike, and SK 94 in thousand-grain weight, making them valuable genetic resources for breeding programs. Among the hybrids, Side 14 *x* Side 12, SK 95 *x* Side 14, SK 95 *x* Side 12, and Giemiza 9 *x* Side 12 showed clear superiority in mean performance, specific combining ability, and heterosis over both mid- and better-parent values, particularly for grain yield and its components. Genetic parameter analysis indicated the predominance of non-additive gene action, high broad-sense heritability, but low narrow-sense heritability and expected genetic advance, highlighting the limited effectiveness of direct selection in the F_2 generation. Therefore, the study recommends focusing on the superior hybrids mentioned above and performing selection in advanced generations to achieve stable and sustainable genetic improvement in bread wheat breeding programs.

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