Labyrinth: Fayoum Journal of Science and Interdisciplinary Studies 3 (2025)1; 89-98

Contents lists available at Egyptian Knowledge Bank

Labyrinth: Fayoum Journal of Science and Interdisciplinary Studies

Journal homepage: https://lfjsis.journals.ekb.eg/

Analysis of diallel crosses in wheat genotypes planted under different soil salinity levels

Kamal H. Ghallab [a,*], Ahmed A. M. Yassin [b], Ahmed E. Kalaf [a], Mohamed G. Aboud [a]

[a] ***Agronomy Department, Faculty of Agriculture, Fayoum University**, El Fayoum 63514, Egypt.*
[b] ***Genetics Department, Faculty of Agriculture, Fayoum University**, El Fayoum 63514, Egypt.*

A R T I C L E I N F O

Keywords:
Mean Performance,
Combining ability,
Heterosis,
Full diallel,
Bread Wheat

A B S T R A C T

Four genotypes of bread wheat were crossed in a full diallel scheme. The parents F_1's, and reciprocal crosses were evaluated. The study was conducted to determine the effects of salt stress on wheat varieties for yield traits, focusing on the performance of parents and F_1 crosses. The experiment was conducted in a randomized complete block design with three replications. The results cleared that salt stress caused high reduction in traits like heading date, plant height, spike length, No. tillers per plant, No. grains per spike, grain weight per spike, 100-grain weight, and grain yield per plant. Among the parents, P_4 displayed the greatest resilience, maintaining higher values for numerous traits under high salt conditions. Crosses involving P_4; $P_4 \times P_3$ and $P_4 \times P_2$, showed improved salt tolerance, exhibiting smaller reductions in crucial traits. The general combining ability (GCA), specific combining ability (SCA), reciprocal combining ability (RCA), and heterosis were evaluated. It was found that P_4 was a top combiner for yield traits, while higher yields under stress were maintained by crosses $P_2 \times P_3$ and $P_2 \times P_4$. Crosses like $P_1 \times P_4$, $P_4 \times P_3$, and $P_2 \times P_3$ showed large gains over parents without stress. $P_4 \times P_2$, $P_1 \times P_4$, and $P_3 \times P_2$ under medium and high stress. Heterosis was significant under specific conditions: P1×P4 displayed notable heterosis for heading date, plant height, and spike length under low saline salinity, while $P_4 \times P_2$ excelled for multiple traits, including grain yield under moderate stress. Under severe stress, $P_2 \times P_4$ and $P_4 \times P_2$ stood out for traits such as heading date, spike length, and tiller number. These results help the breeders to select the tolerance crosses to develop new promising lines or varieties for saline conditions.

1. Introduction

Wheat (*Triticum aestivum* L.) is a staple food for one-third of the global population, covering about 215 million hectares, making it the second most cultivated crop worldwide [1 , 2]. Global wheat production was 779 million metric tons in 2022/2023, slightly down from 781 million metric tons in 2021/2022 [3]. In Egypt, wheat has ancient roots and remains a crucial food source, producing about 9 million tons annually, though the demand is 18 million tons [4]. In 2021/2022, Egypt cultivated wheat on 3.4 million feddans, yielding 10 million tons, primarily in the Nile Delta (60%), with Middle and Upper Egypt contributing 22%, and the remainder in newly reclaimed areas [5 , 6].

Salinity stress is a major environmental challenge, significantly limiting global crop productivity [7]. It restricts yields and the economic use of land in arid and semiarid regions [8]. Over 900 million hectares, more than 7% of the world's total land area, are affected by salinity [9]. Enhancing salt tolerance in plants is essential for sustainable agriculture and improved crop yields [10].

The gene's role in combining traits for grain yield is essential for breeding lines and their performance across diverse environments. Evaluating parental strains through general combining ability (GCA) and specific combining ability (SCA) helps estimate genetic actions for adaptive traits. High SCA values suggest dominant gene effects, while high GCA values indicate additive gene effects. Complex agronomic traits in wheat, like plant height, tiller number, spikelets per spike, grains per spike, and thousand-seed weight, are influenced by both genetic actions. For abiotic stresses, parents with moderate to negative GCA effects are suitable for producing short progeny, while grain crop selection should focus on parents with higher positive GCA or crosses with high positive SCA [11 , 12].

* *Corresponding author.*
E-mail address: khg00@fayoum.edu.eg (*Kamal H. Ghallab*); Tel.: +201224922292

DOI: 10.21608/IFJSIS.2024321506.1091
Received 16 September 2024; Received in revised form 13 November 2024; Accepted 20 November 2024
Available online 23 November 2024

Diallel crosses are often employed in plant breeding to assess genetic features of parental lines, heritability, and general and specific combining abilities (GCA, SCA), [13-17]. By providing early insights into trait genetics in the first generation, this approach facilitates the selection of potential breeding materials [18], [19], [20], [21]. The distribution of positive and negative alleles in parent plants as well as the interaction of gene effects result in heterosis, also known as hybrid vigor, a complicated phenomenon. Its efficacy in self-pollinating crops, such as wheat, is dependent on direction and amplitude. Determining the possibility of heterosis and choosing the desired pure lines depend heavily on estimating gene activities. Practical value can be derived from crosses that perform better than the superior parent, particularly if the finest local cultivars are involved.

The study aims to assess the potential for genetic improvement in wheat breeding programs by identifying promising parental lines and hybrid combinations mediated evaluation heterosis relative to mid-parent, heterobeltiosis, GCA, SCA, and RCA effects in four bread wheat parents and their F1 crosses.

2. Experimental part

The present research studies were conducted at the Experimental Farm of Demo, Faculty of Agriculture, Fayoum University, Egypt, during wheat growing seasons 2019-20 and 2020-21 to determine the mean performance, general (GCA) and specific combining ability (SCA), reciprocal combining ability (RCA), and the heterosis relative to mid-parent and heterobeltiosis effects in F_1 crosses .Four promising wheat genotypes in the eighth generation designated as G1-4, G5-3, G5-8, and G5-9 in Table (1) were previously developed from a continuous breeding program [22], which have demonstrated tolerance to abiotic stresses such as salinity and drought, and were grown and tested under three sites of salinity, i.e., low salinity (3.56 dS/m), moderate (7.92 dS/m), and severe salinity (11.71 dS/m), the classification [23] shown in Table 2.

Table 1: Code number, genotypes and pedigree of wheat genotypes used in the study.

Code No.	Genotypes	Pedigree
P1	G1-4	Sakha93 / Gimmeiza5 – 4
P2	G5-3	Sakha93 / Sids1 – 3
P3	G5-8	Sakha93 / Sids1 – 8
P4	G5-9	Sakha93 / Sids1 – 9

In the first season of 2019-20, four parents (promising lines) were evaluated under three levels of soil salinity, in addition to a complete diallel cross between them to produce the first-generation (F1) crosses. In the second season of 2020-21, four parent and their (F1) crosses were evaluated under three levels of soil salinity.

Table 2: Analysis of the physicochemical properties of three location of the experimental soil.

Property	Unit	Location -1 low salinity	Location -2 Moderate salinity	Location -3 (Severe salinity
Physical				
Sand	(%)	75.50	73.40	76.30
Silt		12.00	12.90	11.90
Clay		12.50	13.70	11.80
Texture class		Sandy loam	Sandy loam	Sandy loam
Chemical				
pH		7.73	7.77	7.82
Ece	(dS m^{-1})	3.56	7.92	11.71
CEC	(cmol$_e$ kg^{-1})	11.36	11.85	12.05
$CaCO_3$	(%)	6.50	12.53	16.22
N		0.04	0.06	0.03
P	(mg kg^{-1} soil)	4.36	4.41	4.32
K		47.80	45.90	47.02

The Randomized Complete Block Design (RCBD) was used with three replications to minimizing the experimental errors and for reliability of the experiment. Plot size of 3m×3.5m (10.5 m2) having five rows of each parent and their F1 crosses.

Agronomic traits:

Heading date (HD) was recorded for ten plants, were randomly determined per plot. At harvest, ten representative plants were randomly taken as samples from each experimental unit to measure yield and its component traits, which included the following: Plant height, cm (PH), Number of total tiller (NTT), Spike length, cm (SL), Number of grains for the main stem spike, (GS), Grains weight / spike, g (GWS), 100-grain weight, g (HSW), Grain yield / plant, g (GYP).

Analysis of data.

The data was analyzed for determining the differences between the treatments, parental lines and F1 crosses using analysis of variance (ANOVA) [24]. The General Combining Ability (GCA), Specific Combining Ability (SCA), and reciprocal effects were analyzed following Griffing's (1956) Method 1, Model 1 which includes parents, F1 crosses, and reciprocals employing the following statistical model [25].

The heterosis relative to mid-parent (MPH) and relative to better-parent or (heterobeltiosis) (BPH) for F1 were estimated using the following equations [26]: $MPH=(F_1-MP)/MP*100$, $BPH=(F_1-BP)/BP*100$

3. Results

3.1. *Analysis of variance and mean performance of salinity tolerance traits*

Significant differences were found among genotypes for all the studied traits, in which estimates of variances for general combining ability (GCA), specific combining ability (SCA), and reciprocal effects (REC) in F1 diallel crosses of bread wheat under three salinity levels are presented in Table 3. The GCA, SCA, and REC were significant for all the studied traits in all environments, suggesting that additive, non-additive and cytoplasmic effects might have contributed to these differences. GCA/SCA ratios were 1.161 and 1.273 for the number of grains per spike and 100-grain weight under, low salinity 2.743 for the number of grains per spike under moderate salinity, and 1.301 for grain weight per spike under severe salinity. This indicates a major role of additive gene action in these mention traits' inheritance. Conversely, non-additive genes is a crucial part in the remaining traits.

Table (3): Analysis of variance for the full diallel cross (Griffing) for yield traits and yield components in wheat under three salinity levels.

S.V.	dF	Heading date	Plant height	Spike length	No. of total tillers	No. of grains /spike	Grains weight/ spike	100 grains weight	Grain yield/ plant
Low salinity condition (N)									
Rep.	2	0.152	1.5105	0.031	0.005	0.238	0.001	0.001	0.111
G.	15	57.19**	538.57**	12.16**	0.57**	16.94**	0.19**	0.23**	17.68**
GCA	3	3.95**	55.14**	0.80**	0.24**	16.99**	0.10**	0.22**	5.51**
SCA	6	133.49**	1304.84**	27.07**	0.62**	14.63**	0.38**	0.17**	17.24**
RE.	6	7.50**	14.06**	2.94**	0.69**	19.23**	0.05**	0.30**	24.21**
Error	30	0.201	0.435	0.025	0.021	0.461	0.003	0.002	0.221
GCA/SCA		0.030	0.042	0.029	0.394	1.161	0.258	1.273	0.320
Moderate salinity stress conditions (Sm)									
Rep.	2	0.623	0.387	0.024	0.001	0.336	0.001	0.001	0.049
G.	15	77.26**	402.10**	14.93**	0.59**	20.80**	0.30**	0.09**	19.63**
GCA	3	0.52**	47.06**	1.91**	0.37**	24.09**	0.18**	0.03**	15.75**
SCA	6	176.07**	967.74**	32.72**	0.51**	8.78**	0.45**	0.08**	18.39**
RE.	6	16.82**	14.02**	3.64**	0.77**	31.17**	0.22**	0.12**	22.81**
Error	30	0.063	0.148	0.035	0.011	0.380	0.003	0.002	0.164
GCA/SCA		0.003	0.049	0.058	0.733	2.743	0.393	0.309	0.856
Severe salinity stress conditions (Ss)									
Rep.	2	0.188	0.867	0.088	0.012	0.219	0.005	0.006	0.090
G.	15	83.73**	449.86**	16.21**	0.67**	33.91**	0.32**	0.12**	45.84**
GCA	3	0.50	166.04**	2.94**	0.36**	5.66**	0.46**	0.07**	15.49**
SCA	6	193.18**	1021.23**	33.10**	0.42**	48.07**	0.36**	0.14**	63.35**
RE.	6	15.92**	20.35**	5.95**	1.09**	33.88**	0.21**	0.13**	0.15**
Error	30	0.222	0.624	0.033	0.017	0.690	0.004	0.001	0.120
GCA/SCA		0.003	0.163	0.089	0.857	0.118	1.301	0.518	0.245

Where: S.V.: Source of variance, Rep: Replication, G: Genotypes, GCA, SCA: General and Specific combining ability, RE: Reciprocal Effect, SE: Standard error of mean, df: degree of freedom, * p> 0.05; ** p> 0.01

3.2. *Mean performances of parents and their F_1 crosses*

Fig. 1 presents the mean value traits for both parents and F_1 crosses, showing lower values under salinity stress compared to low salinity (N) condition. For the parents, heading date ranged from 79.12–80.63, 76.67–79.13, and 75.33–77.23 in low salinity, moderate and severe salinity conditions, respectively. Plant height varied from 120–123.53 cm low salinity, 112.90-118.90 cm (moderate salinity), to 106.17–110.50 cm (severe salinity). Spike length ranged from 15.03–17.63 cm (low salinity), 14.17–16.73 cm (moderate salinity), and 13.33–16.27 cm (severe salinity). The number of tillers showed ranges from 6.85–7.35 (low salinity), 6.38–6.90 (moderate salinity), and 5.88–6.27 (severe salinity). Grains per spike ranged from 65.98-67.42 (low salinity), 62.43-65.73 (moderate salinity), to 57.47-62.70 (severe salinity). Grain weight/spike ranged from 3.09–3.48 (low salinity), 2.90–3.17 (moderate salinity), and 2.97–3.17 (severe salinity). The 100-grain weight showed ranges from 4.57–5.16 g (low salinity), 4.61–4.88 g (moderate salinity), and 4.35–4.73 g (severe salinity). Grain yield per plant ranged from 20.33–22.22 g (low salinity), 18.25–20.22 g (moderate salinity), and 14.35–17.27 g (severe salinity).

The cross values ranged from 68.83 ($P_2 \times P_4$) to 75.05 ($P_2 \times P_1$), 64.32 ($P_2 \times P_4$) to 71.63 ($P_2 \times P_1$) and 62.17 ($P_2 \times P_4$) to 67.47 ($P_4 \times P_3$) days in low salinity, moderate and sever salinity conditions, respectively, for heading date, 87.96 ($P_3 \times P_1$) to 119.27 ($P_2 \times P_3$), 86.02 ($P_3 \times P_1$) to 112.17 ($P_3 \times P_2$) and 69.48 ($P_3 \times P_1$) to 108.77 ($P_3 \times P_2$) cm under low salinity, moderate and sever salinity conditions, respectively, for plant height. In addition to the above findings, it is important to note that the cross values for heading date and plant height exhibited significant variations across different salinity conditions. For spike length, the cross values ranged from 15.40 ($P_1 \times P_4$) to 20.88 ($P_2 \times P_4$) cm under low salinity conditions, from 13.77 ($P_1 \times P_4$) to 20.15 ($P_2 \times P_4$) cm under moderate salinity conditions, and from 12.27 ($P_1 \times P_4$) to 19.58 ($P_2 \times P_4$) cm under severe salinity conditions.

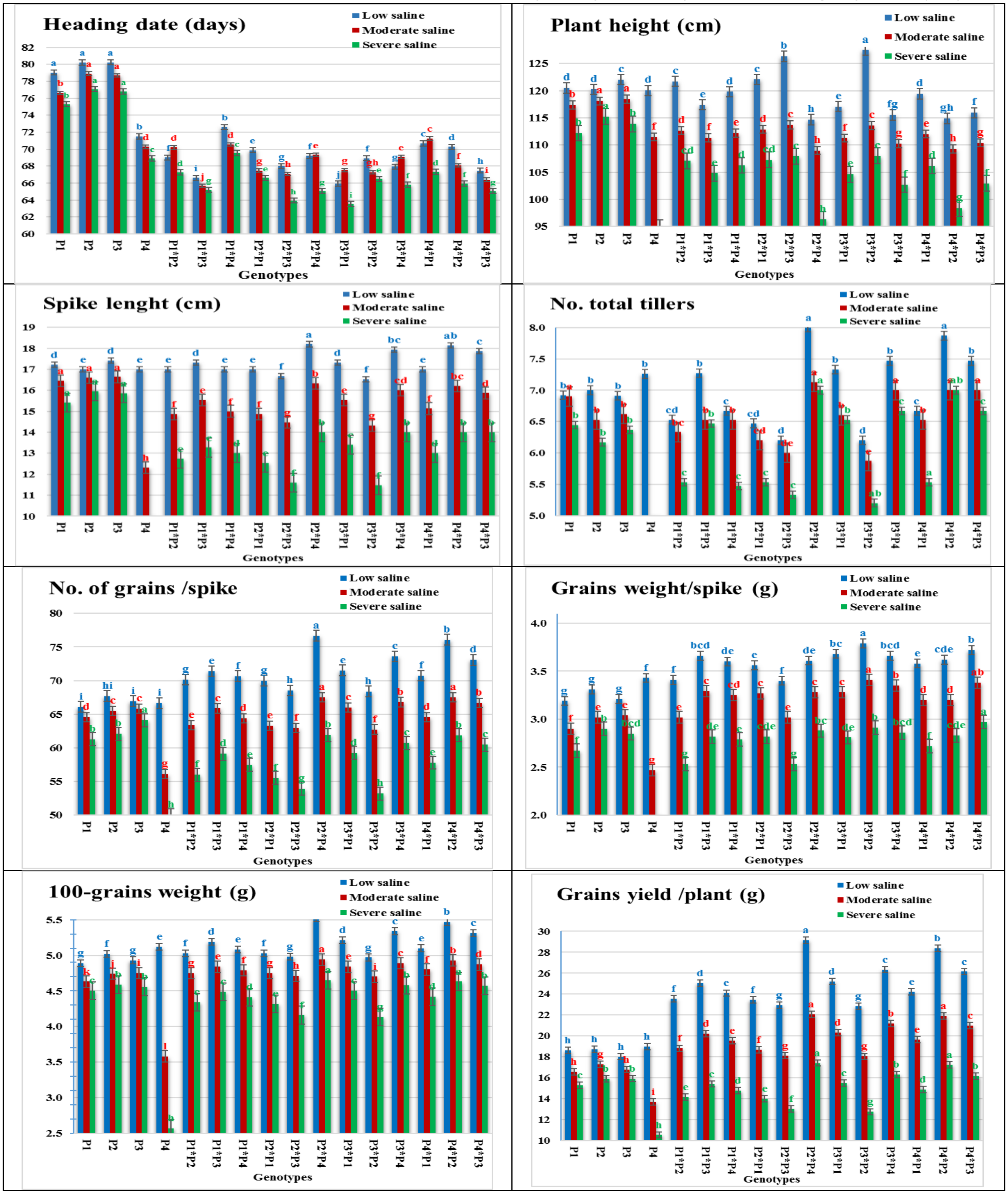


Fig. 1 Illustrates the mean performance of four parent and their F_1 crosses in complete diallel cross under three salinity levels (N, Sm and Ss) conditions.

Regarding tiller number/plant, under low salinity conditions, the hybrid values varied from 6.00 ($P_2 \times P_4$) to 7.63 ($P_4 \times P_3$). In moderate salinity conditions, the range was from 5.73 ($P_2 \times P_4$) to 7.33 ($P_4 \times P_3$). Under severe salinity conditions, the range extended from 5.33 ($P_3 \times P_4$) to 7.00 ($P_4 \times P_2$). For grain number/spike, the hybrid values ranged from 63.50 ($P_2 \times P_3$) to 73.02 ($P_4 \times P_3$) g under low salinity conditions. In moderate salinity conditions, the range was from 59.47 ($P_2 \times P_3$) to 68.93 ($P_3 \times P_1$) g. Under severe salinity conditions, the range extended from 57.70 ($P_4 \times P_1$) to 67.70 ($P_4 \times P_2$) g. For grain weight/ spike, the crosses values ranged from 3.01 ($P_3 \times P_2$) to 3.94 ($P_4 \times P_2$) g under normal salinity conditions, from 2.86 ($P_4 \times P_2$) to 3.97 ($P_1 \times$

P_2) g under moderate salinity conditions, and from 2.56 ($P_3 \times P_2$) to 3.89 ($P_3 \times P_1$) g under severe salinity conditions. The 100-grain weight and hybrid values ranged from 4.73 ($P_4 \times P_2$) to 5.40 ($P_1 \times P_4$) g under low salinity conditions, from 4.58 ($P_4 \times P_2$) to 5.14 ($P_3 \times P_2$) g under moderate salinity conditions, and from 4.47 ($P_4 \times P_1$) to 5.24 ($P_1 \times P_2$) g under severe salinity conditions. The cross values ranged from 18.23 (P2 × P_1) to 26.23 ($P_2 \times P_3$), 15.91 ($P_2 \times P_3$) to 25.13 ($P_4 \times P_1$), and 12.60 ($P_3 \times P_1$) to 24.03 ($P_3 \times P_4$) g in low salinity, moderate, and severe salinity conditions, respectively, for grains yield /plant.

3.3. *Estimates of general and specific combining ability as well as reciprocal effects*

The effects of general combining ability for parents, specific combining ability for diallel crosses and reciprocal combining ability for reciprocal crosses were estimated and represented in (Fig. 2). P4 gave the maximum positive and significant GCA effect values for the number of tillers/plant and the number of grains/spike at different salinity levels (N, Sm, and Ss) and under moderate salinity for grain weight, 100-grain weight, and grain yield/plant, and the highest negative GCA effect value for heading date under non- and moderate salinity and plant height under different salinity levels. P4 was found to be the best combiner for the previously mentioned. P3 recorded the highest positives for plant weight (severe salinity; Ss), spike length under three levels of salinity (N, Sm, and Ss), 100-grain weight, and grain yield per plant under normal salinity (N). P1 recorded the highest negative GCA effect value for spike length (under N, Sm, and Ss), grain/spike, grain weight/spike, grain yield, and plant under moderate salinity (Fig.2).

The cross P2×P3 exhibited the highest positive SCA effect values for spike length under N, Sm, and Ss conditions, 100-grain weight under N and Sm conditions, and grain yield per plant under both Sm and Ss conditions. Meanwhile, the cross P2×P4 showed the highest positive SCA effect values for the number of total tillers per plant under N, Sm, and Ss conditions, plant height, grain yield per plant under both Sm and Ss conditions, and grain weight per spike under non-stress salinity. In contrast, the cross P1×P3 exhibited the maximum negative effects for heading date, spike length, and the number of total tillers under all salinity stresses, as well as for plant height and grain yield per plant under Sm and Ss conditions (Fig. 2).

The reciprocal cross $P_4 \times P_3$ recorded the highest positive effects for the number of total tillers per plant at all salinity levels, spike length and the number of grains per spike under Sm and Ss conditions, and 100-grain weight and grain yield per plant under severe salinity stress. The cross $P_4 \times P_2$ recorded maximum negative effect value heading date under different salinity levels, grain weight at Sm, 100-grain weight at non-stress salinity, and grain yield/plant at severe salinity stress (Fig. 2). Griffing 1956, suggested employing reciprocal effects to distinguish between variability caused by sex-linked genes and that resulting from maternal influences.

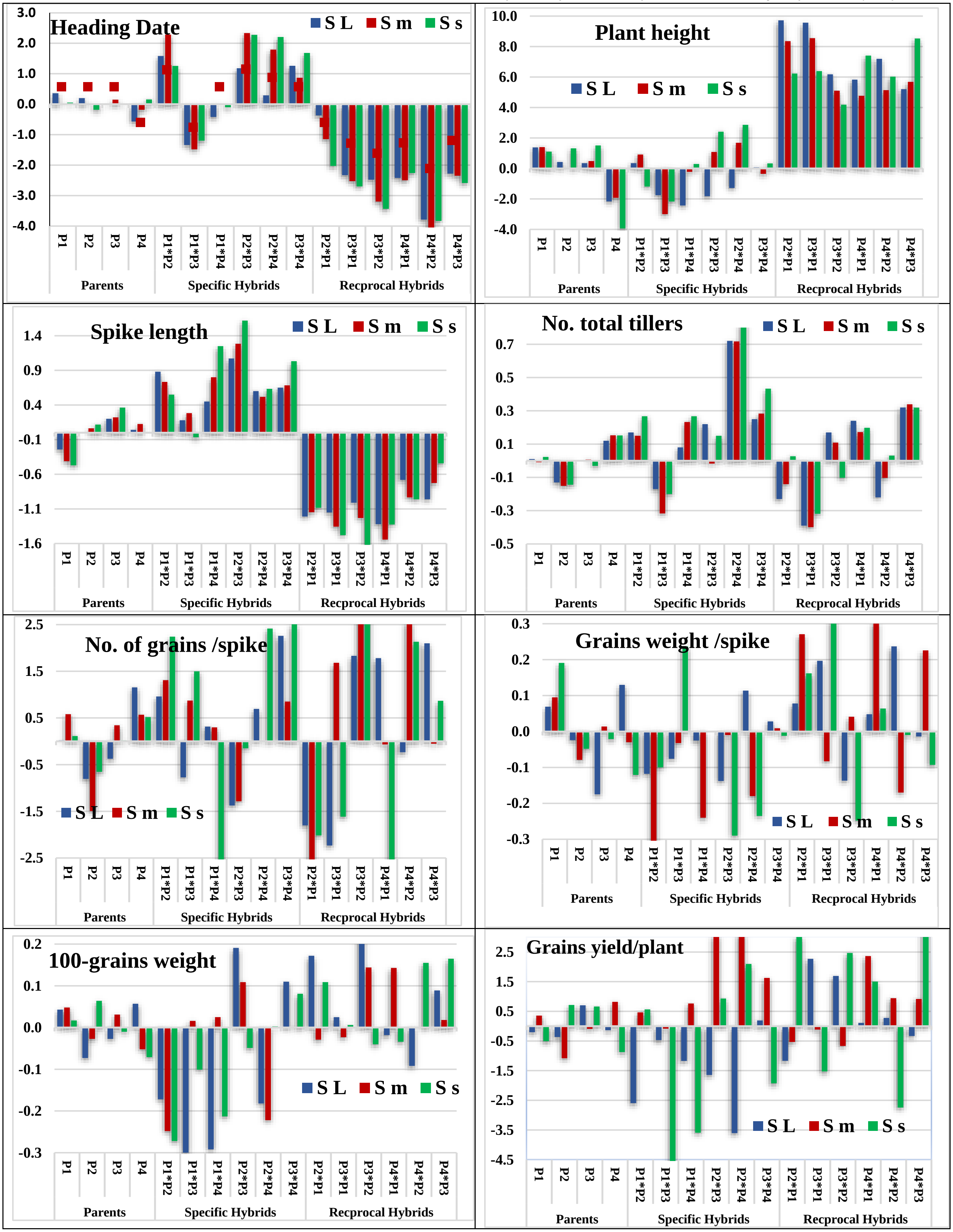
3.4. *The estimates of heterosis relative to mid- parent and better parent*

The estimates of heterosis relative to mid- parent and better parent for heading date, plant height, and spike length, total tillers/pant grain number and grain weight/spike, 100 weight and grain yield/ plant of four parent full diallel crosses are presented in (Table 4). Under low salinity condition cross P_{1x4} showed the best values and highly significant of heading date, plant height and spike length, while P_{4x3} for number of tillers/plant and grain numbers/spike and P_{2x3} for grain yield/plant heterosis and heterobeltiosis, respectively, under low salinity condition. Similarly, P_{4x2} cross exhibited best values and highly significant heterosis relative to mid- parent and better parent for heading date, plant height, spike length, total tillers/pant and grain yield/ plant, whereas P_{1x4} and P_{3x2} crosses showed the beast values and highly significant heterosis relative to mid- parent and better parent for grain weight /spike and 100-grain weight, respectively, under moderate stress. On the other hand, under severe stress the P_{2x4} gave the best values and highly significant for heading date and spike length, P_{4x2} showed the best values and highly significant for total number of tillers/plant and grain number/ spike and P_{3x4} and P_{1x4} crosses showed the best values and highly significant for grain yield /plant traits in heterosis and heterobeltiosis.

The data in the Table 4 presents the estimates of heterosis relative to mid- parent and better parent for heading date, plant height, spike length, total tillers per plant, grain number per spike, grain weight per spike, 100 weight, and grain yield per plant of four parent complete diallel crosses.

Under low salinity conditions, cross P_{1x4} exhibited the best values and was highly significant for heading date, plant height, and spike length. Cross P_{4x3} showed the highest values for the number of tillers per plant and grain numbers per spike, while P_{2x3} displayed the best values for grain yield per plant in terms of heterosis relative to mid- parent and better parent.

Under moderate stress conditions., crosses P_{4x2} demonstrated the best values and significant heterosis relative to mid- parent and better parent for heading date, plant height, spike length, total tillers per plant, and grain yield per plant. whereas, crosses P_{1x4} and P_{3x2} displayed the best values and significant heterosis relative to mid- parent and better parent for grain weight per spike and 100-grain weight traits, respectively, On the other hand, under severe stress, P_{2x4} gave the best values and was highly significant for heading date and spike length; P_{4x2} showed the best values and was highly significant for total number of tillers/plant and grain number/spike; and P_{3x4} and P_{1x4} crosses showed the best values and were highly significant for grain yield/plant traits in heterosis relative to mid- parent and better parent.



Fi;g. 1. Estimates of effects the general combining ability, specific combining ability, and reciprocal effect for four parent lines and their hybrids in a complete diallel cross under three salinity levels (SL, Sm and Ss) conditions.

Table (4): Shows estimates of heterosis relative to mid- parent (MP) and better parent (BP,%) for yield and its components in a 4x4 full diallel cross of wheat under three levels stress conditions

Gen.	Heading date		Plant height		Spike length		No. of total tillers		No. of grains /spike		Grains weight/spike		100 grains weight		Grain yield/ plant	
	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP
Under low salinity condition (N)																
P1*P2	-9.81**	-9.12**	-28.11**	-27.56**	5.03**	1.45**	-6.99**	-7.88**	4.75**	3.63**	13.72**	13.03**	12.42**	8.32**	11.63**	11.40**
P1*P3	-8.89**	-8.15**	-27.67**	-27.47**	-0.20	-7.56**	-1.70**	-1.70**	2.59**	2.30**	14.24**	10.61**	12.34**	8.92**	25.04**	23.23**
P1*P4	-11.03**	-10.17**	-2.39**	-1.72**	-4.74**	-10.98**	1.88**	-1.59**	0.66	0.27	10.91**	8.05**	7.04**	4.65**	8.90**	5.74**
P2*P3	-13.09**	-13.05**	-3.00**	-2.53**	-8.19**	-12.10**	-2.17**	-3.10**	-4.52**	-5.27**	3.62**	0.92**	7.83**	7.13**	26.89**	24.80**
P2*P4	-14.48**	-14.32**	-3.74**	-2.33**	24.93**	20.71**	-16.28**	-18.37**	4.05**	3.34**	10.39**	6.90**	4.83**	-1.16**	19.96**	16.71**
P3*P4	-14.08**	-13.95**	-6.11**	-5.19**	-8.40**	-9.26**	0.47**	-2.95**	2.79**	2.69**	3.50**	-2.30**	2.76**	-2.52**	6.23**	1.69**
P2*P1	-5.86**	-5.14**	-26.40**	-25.84**	2.67**	-0.83**	-2.17**	-3.10**	-0.65	-1.71**	6.40**	5.76**	5.05**	1.22**	-13.10**	-13.29**
P3*P1	-12.26**	-11.54**	-27.93**	-27.73**	2.86**	-4.73**	-6.57**	-6.57**	-4.00**	-4.28**	9.55**	6.06**	-0.21**	-3.25**	20.48**	18.73**
P3*P2	-10.16**	-10.12**	-5.95**	-5.50**	20.83**	15.69**	4.10**	3.10**	0.96	0.17	-5.20**	-7.67**	16.09**	15.33**	10.98**	9.14**
P4*P1	-12.07**	-11.23**	-6.41**	-5.78**	27.22**	18.88**	4.23**	0.68**	5.97**	5.56**	9.44**	6.61**	-4.66**	-6.78**	-1.97**	-4.82**
P4*P2	-13.75**	-13.59**	-5.84**	-4.47**	21.24**	17.15**	3.72**	1.13**	3.40**	2.69**	16.91**	13.22**	-2.77**	-8.33**	-13.39**	-15.74**
P4*P3	-10.95**	-10.82**	-5.97**	-5.05**	-0.76**	-1.70**	7.51**	3.85**	9.03**	8.93**	5.33**	-0.57**	7.25**	1.74**	8.03**	3.42**
Under Moderately Stress (Sm)																
P1*P2	-13.85**	-12.52**	-25.75**	-24.27**	3.30**	0.00	-4.94**	-5.43**	8.82**	7.38**	31.46**	31.46**	6.78**	4.92**	-1.37**	-3.62**
P1*P3	-10.50**	-9.24**	-24.58**	-23.98**	-0.54**	-8.17**	-0.26**	-0.77**	0.98	-0.25	9.21**	6.62**	1.65**	0.82**	4.44**	2.69**
P1*P4	-12.99**	-11.59**	-3.24**	-2.63**	-10.80**	-17.56**	-0.62**	-3.86**	3.38**	2.34**	32.77**	30.13**	5.16**	2.25**	23.97**	19.02**
P2*P3	-17.53**	-17.42**	-6.41**	-5.31**	-11.09**	-15.34**	1.29**	0.26**	-7.20**	-9.53**	6.95**	4.42**	3.47**	2.50**	-19.32**	-22.45**
P2*P4	-18.67**	-18.62**	-7.65**	-5.20**	26.60**	20.66**	-13.68**	-16.91**	-3.04**	-5.27**	8.78**	6.62**	7.73**	6.58**	-1.15**	-2.92**
P3*P4	-14.90**	-14.74**	-3.90**	-2.51**	-8.28**	-8.37**	0.87**	-1.93**	2.60**	2.38**	15.98**	11.04**	3.51**	1.46**	7.57**	1.62**
P2*P1	-7.99**	-6.57**	-25.33**	-23.83**	-0.57**	-3.74**	-0.26**	-0.78**	-0.61	-1.92**	7.62**	7.62**	-3.65**	-5.33**	3.41**	1.05**
P3*P1	-14.32**	-13.11**	-25.37**	-24.77**	1.19**	-6.57**	-10.03**	-10.49**	6.16**	4.87**	7.27**	4.73**	2.27**	1.43**	3.59**	1.85**
P3*P2	-11.61**	-11.50**	-4.57**	-3.44**	24.58**	18.63**	0.78**	-0.26**	3.95**	1.34*	6.30**	3.79**	8.10**	7.08**	11.95**	7.61**
P4*P1	-12.94**	-11.54**	-3.62**	-3.01**	27.11**	17.47**	6.37**	2.90**	3.15**	2.11**	16.55**	14.24**	6.22**	3.28**	32.00**	26.73**
P4*P2	-14.14**	-14.09**	-4.75**	-2.21**	24.61**	18.76**	7.90**	3.86**	4.99**	2.57**	-3.38**	-5.30**	-1.72**	-2.76**	32.65**	30.28**
P4*P3	-12.70**	-12.54**	-4.51**	-3.13**	-3.29**	-3.39**	9.32**	6.28**	2.45**	2.23**	16.64**	11.67**	3.72**	1.67**	24.35**	17.48**
Under Severe stress (Ss)																
P1*P2	-14.99**	-13.96**	-25.80**	-25.34**	0.61**	-1.20**	-1.98**	-1.98**	11.48**	6.83**	15.53**	12.62**	11.37**	10.78**	34.42**	23.09**
P1*P3	-12.29**	-11.37**	-20.81**	-19.93**	1.37**	-6.54**	-0.41**	-2.70**	8.87**	6.06**	10.53**	7.91**	4.60**	3.38**	47.54**	43.22**
P1*P4	-13.11**	-12.01**	-3.78**	-2.42**	-17.12**	-24.59**	2.61**	-0.53**	2.59**	2.31**	10.37**	9.63**	7.93**	3.59**	54.18**	53.08**
P2*P3	-19.11**	-18.98**	-4.34**	-2.68**	-15.19**	-20.46**	-5.39**	-7.57**	1.14	-0.56	-0.79**	-0.95**	4.09**	3.42**	32.23**	24.50**
P2*P4	-19.47**	-19.44**	-7.82**	-5.93**	30.12**	20.39**	-12.21**	-14.89**	5.87**	1.71*	4.89**	1.58**	8.97**	5.13**	-14.61**	-21.29**
P3*P4	-16.83**	-16.66**	-1.30	-1.00	-11.43**	-12.70**	-1.34**	-2.13**	7.47**	4.97**	-3.75**	-6.65**	6.58**	3.46**	61.16**	57.55**
P2*P1	-11.69**	-10.62**	-24.22**	-23.76**	1.60**	-0.24	7.08**	7.08**	4.80**	0.43	9.06**	6.31**	-0.32**	-0.85**	41.58**	29.64**
P3*P1	-15.45**	-14.56**	-35.65**	-34.94**	-0.92**	-8.65**	-7.05**	-9.19**	3.55**	0.88	26.09**	23.10**	0.32**	-0.85**	-14.92**	-17.41**
P3*P2	-13.21**	-13.07**	0.11	1.84**	21.71**	14.14**	-0.41**	-2.70**	12.63**	10.73**	-19.12**	-19.24**	1.94**	1.28**	43.69**	35.29**
P4*P1	-13.37**	-12.28**	-3.22**	-1.85**	23.42**	12.30**	11.39**	7.98**	-7.73**	-7.97**	10.37**	9.63**	-1.54**	-5.50**	4.51**	3.76**
P4*P2	-13.75**	-13.71**	-2.52**	-0.53	27.69**	18.14**	15.23**	11.71**	12.99**	8.55**	-10.42**	-13.25**	9.19**	5.34**	11.71**	2.97**
P4*P3	-12.47**	-12.29**	-0.67	-0.38	-5.82**	-7.17**	12.60**	11.70**	10.31**	7.75**	-4.73**	-7.59**	10.14**	6.93**	35.30**	32.27**

*Signifcant at P < 0.05; **P < 0.01,

4. DISCUSSION

4.1. *Evaluation of mean performances of parents and their F1 crosses*

The results indicate that salinity stress negatively impacts various growth and yield traits in both parents and F1 hybrids, with more severe stress leading to more pronounced reductions [27]. Under salinity stress, heading date decreased, suggesting an accelerated development process as a stress response [27], [28]. Plant height was also reduced, indicating inhibited growth due to the stress. Spike length and the number of tillers per plant both showed reductions, impacting reproductive structures and overall productivity [27], [29]. Grains per spike, grain weight per spike, and 100-grain weight all decreased under salinity stress, directly affecting yield [27], [28], [29]. Grain yield per plant dropped significantly, highlighting the detrimental effects of salinity on overall productivity [27], [29]. [30], reported inherited additive and non-additive gene effects in control of wheat salinity tolerance at the seedling stage.

Among the parents, some showed better performance under salinity stress [8], [27], [31]. Parent P4 consistently demonstrated greater resilience, maintaining relatively higher values for heading date, plant height, spike length, and grain yield per plant under severe salinity conditions. Similarly, hybrid combinations involving P4, particularly P4 × P3 and P4 × P2, exhibited better tolerance to salinity stress, maintaining higher values across several traits. These hybrids showed relatively less reduction in plant height, spike length, grain weight per spike, and grain yield per plant under severe salinity conditions compared to other hybrids [8], [27], [31], [32].

The variability in responses among different hybrids suggests that certain genetic combinations confer better tolerance to salinity stress [33], [34]. This genetic variability is crucial for breeding programs aimed at developing salinity-tolerant crop varieties [32], [33], [34]. By selecting and crossing parents like P4, which exhibit better performance under salinity stress, and creating hybrids such as P4 × P3 and P4 × P2, it is possible to enhance the resilience of crops, ensuring stable yields in saline-prone areas. Overall, the results emphasize the importance of breeding for salinity tolerance and the potential of hybrid vigor to mitigate the adverse effects of salinity on crop productivity [32], [33], [34].

Estimates of general and specific combining ability as well as reciprocal effects

The results indicate that salinity stress negatively impacts various growth and yield traits in both parents and F1 hybrids, with more severe stress leading to more pronounced reductions. General Combining Ability (GCA) for parents, Specific Combining Ability (SCA) for diallel crosses, and Reciprocal Combining Ability (RCA) for reciprocal crosses were estimated and represented in Fig. 1. P4 showed the maximum positive and significant GCA effect values for the number of tillers per plant and the number of grains per spike at different salinity levels (N, Sm, and Ss), and under moderate salinity for grain weight, 100-grain weight, and grain yield per plant. P4 also had the highest negative GCA effect value for heading date under low and moderate salinity and plant height under different salinity levels, making it the best combiner for these traits. P3 recorded the highest positive GCA values for plant weight under severe salinity (Ss), spike length at all salinity levels (N, Sm, and Ss), and 100-grain weight and grain yield per plant under normal salinity (N). In contrast, P1 recorded the highest negative GCA effect values for spike length, grain per spike, grain weight per spike, grain yield per plant, and plant under moderate salinity. These results are supported with the findings of [35].

Among the crosses, the cross P2×P3 exhibited the highest positive SCA effect values for spike length under N, Sm, and Ss conditions, 100-grain weight under N and Sm conditions, and grain yield per plant under both Sm and Ss conditions. The cross P2×P4 showed the highest positive SCA effect values for the number of total tillers per plant under N, Sm, and Ss conditions, plant height, grain yield per plant under both Sm and Ss conditions, and grain weight per spike under non-stress salinity. On the other hand, the cross P1×P3 exhibited the maximum negative effects for heading date, spike length, the number of total tillers under all salinity stresses, plant height, and grain yield per plant under Sm and Ss conditions. The reciprocal cross P4×P3 recorded the highest positive effects for the number of total tillers per plant at all salinity levels, spike length, and the number of grains per spike under Sm and Ss conditions, and 100-grain weight and grain yield per plant under severe salinity stress. In contrast, the cross P4×P2 recorded the maximum negative effect values for heading date under different salinity levels, grain weight under Sm, 100-grain weight under non-stress salinity, and grain yield per plant under severe salinity stress [36], [35].

These findings underscore the importance of selecting the best combiners and hybrids for breeding programs aimed at improving salinity tolerance. P4 emerged as a superior parent due to its positive GCA effects on key yield traits and its negative effects on growth traits like heading date and plant height under stress conditions. Hybrids such as P2×P3 and P2×P4 showed remarkable SCA effects, indicating their potential for maintaining higher yields and better growth traits under salinity stress. These superior combinations can be utilized to develop new varieties with enhanced resilience to salinity, ensuring stable yields in saline-prone areas. Overall, the results highlight the significance of combining ability in selecting parents and hybrids for breeding programs aimed at salinity tolerance, leveraging genetic variability to mitigate adverse effects on wheat productivity.

4.2. *The estimates of heterosis relative to mid- parent and better parent*

In the study of wheat crosses under varying stress conditions, several notable findings emerged. Cross P1×P4 exhibited significant heterosis relative to mid and heterobeltiosis for heading date, plant height, and spike length under non-saline stress conditions [37]. Under moderate stress, cross P4×P2 demonstrated significant values for heading date, plant height, spike length, total tillers per plant, and grain yield per plant [37], [38]. Additionally, P3×P2 displayed significant heterosis relative to mid and heterobeltiosis for grain weight per spike, while P1×P4 showed the best values for 100-grain weight traits [37], [38]. Under severe stress, P2×P4 was highly significant for heading date and spike length, P4×P2 for total tillers per plant and grain number per spike, and P3×P4 and P1×P4 for grain yield per plant traits in heterosis relative to mid- and heterobeltiosis [37], [38]. These findings highlight the diverse performance of different crosses under varying stress levels, providing valuable insights for wheat breeding programs.

In terms of heterosis relative to mid- and heterobeltiosis, under non-saline stress conditions, cross P1×P4 exhibited the best values and was highly significant for heading date, plant height, and spike length. Cross P4×P3 showed the highest values for the number of tillers per plant and grain numbers per spike, while P2×P3 displayed the best values for grain yield per plant. Under moderate stress conditions, cross P4×P2 demonstrated the best values and significant heterosis relative to mid and heterobeltiosis for heading date, plant height, spike length, total tillers per plant, and grain yield per plant. Crosses P1×P4 and P3×P2 displayed the best values and significant heterosis relative to mid- and heterobeltiosis for grain weight per spike and 100-grain weight traits, respectively. Under severe stress, cross P2×P4 gave the best values and was highly significant for heading date and spike length; P4×P2 showed the best values and was highly significant for the total number of tillers per plant and grain number per spike; and crosses P3×P4 and P1×P4 showed the best values and were highly significant for grain yield per plant traits in heterosis relative to mid- and heterobeltiosis. These results are supported with the findings of [39], [27], [40].

5. Conclusions

The study reveals that salinity stress adversely affects growth and yield traits in both parents and their crosses, with increased stress leading to more significant reductions. Parent P4 demonstrated superior resilience, maintaining better performance in key traits under severe salinity. Hybrid combinations involving P4, such as P4 × P3 and P4 × P2, also exhibited more tolerant. The analysis of combining abilities and heterosis highlights P4 as the best parent and crosses like P2×P3 and P2×P4 as promising genotypes for breeding programs. These findings emphasize the importance of selecting and developing salinity-tolerant varieties to ensure stable yields in saline environments.

Acknowledgment

The authors would like to thank Fayoum University for supporting the publication of this work.

Author Contributions

All authors contributed significantly to this work. Mohamed G. Aboud prepared the samples and conducted the experimental measurements. Ahmed A. M. Yassin and Ahmed E. Kalaf collaborated on drafting the manuscript and monitored the experimental performance. Ahmed A. M. Yassin also assisted the first author in completing the sample preparation. Kamal H. Ghallab, together with Mohamed G. Aboud, contributed to the data analysis, validation, and completion of the manuscript. Additionally Kamal H. Ghallab oversaw the revision process and managed the submission of the manuscript for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] J. Datta, S. Nag, A. Banerjee, N. Mondai, Impact of salt stress on five varieties of wheat (*Triticum aestivum* L.) cultivars under laboratory condition. J. Appl. Sci. Environ. Manag. 13 (2009) 93–97.
[2] A. Raza, S. S. Mehmood, J.T. abassum, R. Batool, Targeting plant hormones to develop abiotic stress resistance in wheat. In Wheat Production in Changing Environments; Springer: Berlin/Heidelberg, Germany; (2019) 557–577.
[3] FAO (Food and Agriculture Organization of the United Nations). "FAOSTAT - Food and Agriculture Data." Accessed June (2024). Available at: http://www.fao.org/faostat/en/#data/QC
[4] P. Alexander, C. Brown, A. Arneth, J. Finnigan, M. D. A. Rounsevell, Human appropriation of land for food: the role of diet. Glob. Environ. Chang. 41 (2016) 88–98.
[5] USDA & FAS. World Agricultural Production. Circular Series, United States Department of Agriculture and Foreign Agricultural Service. [cited (2022) August 26]. Available from https://apps.fas.usda.gov/psdonline/circulars/production
[6] A. E. H. Zohry, S. Ouda, Wheat insufficiency and deficit irrigation. Springer, Cham. In Deficit Irrigation, (2020) 109-138.
[7] B. C. Oyiga, R. C. Sharma, J. Shen, M. Baum, Identification and characterization of salt tolerance of wheat germplasm using multivariable screening. J. Agron. Crop Sci., 202(6) (2016) 472-485.
[8] M. T. El Ameen, G. A. K. Abdelsabour, F. O. E. Ibrahim, Genetic analysis of eight parents and their 28 hybrids under salinity tolerance in bread wheat. Asian J. of Res. in Bio., 2(1) (2020) 37-48.
[9] M. V. Mickelbart, P. M. Hasegawa, J. Bailey-Serres, Genetic mechanisms of abiotic stress tolerance that translate to crop yield stability. National Review, Genet, 16(4) (2015) 237–251.
[10] E. G. oyal, S. K. Amit, R. S. Singh, Transcriptome profiling of thesalt-stress response in *Triticum aestivum* cv. Kharchia Local. Sci. Report, 6(1) (2016) 1-14.
[11] N. Dholariya, V. Akabari, J. Patel, V. Chovatia, Combining ability and gene action study for grain yield and its attributing traits in bread wheat. Electronic J. of Plant Breeding, 5(3) (2014) 402–407.
[12] S. A. Masood, S. Ahmad, M. Kashif, Q. Ali, Role of combining ability to develop higher yielding wheat (*Triticum aestivum* L.) genotypes: An overview. Natural Sci., 12 (2014) 155–161.
[13] R. J. Baker, Issues in diallel analysis. Crop Sci., 18(4) (1978) 533-536.
[14] M. A. EL-Maghraby, M. E. Moussa, N. S. Hana, H. A. Agrama, Combining ability under drought stress relative to SSR diversity in common wheat. Euphytica. 141(3) (2005) 301-308.
[15] M. Iqbal, A. Navabi, D. F. Salmon, R. C. Yang, B. M. Murdoch, S. S. Moore, D. Spaner, Genetic analysis of flowering and maturity time in high latitude spring wheat. Euphytica, 154(1) (2007) 207-218.
[16] S. A. Afiah, A. A. Elgammaal, A. A. EL- Hosary, Selecting diverse bread wheat genotypes under saline stress conditions using ISSR marker and tolerance indices. Egypt. J. Plant Breed. 23 (1) (2019) 77 –92.
[17] A. El-Fahdawy, A. A. El-Hosary, M. El. M. El-Badawy, S. A. S. Mehasen, A. A. A. El-Hosary, Utilization of diallel crosses to determine combining ability and heterosis in wheat grown under drought and normal irrigation treatments. Egypt. J. Plant Breed, 23(3) (2019) 219 -229.
[18] J. H. Lonnquit, C. D. Gardner, Heterosis in intervarietal crosses in maize and its implications in breeding procedures. Crop Sci., 1(3) (1961) 179-183.
[19] M. A. Chowdhry, M. Rafiq, K. Alam, Genetic architecture of grain yield and certain other traits in bread wheat. Pakistan J. Agric. Res., 13(3) (1992) 216-220.
[20] A. Topal, C. Aydin, N. Akgiin, M. Babaoglu, Diallel cross analysis in durum wheat (*Triticum durum* Desf.): identification of best parents for some kernel physical features. Field Crop Res., 87(1) (2004) 1-12.
[21] A. A. El-Hosary, M. El. M. El-Badawy, S. A. S. Mehasen, A. A. A. El-Hosary, T. A. ElAkkad, A. El-Fahdawy, Genetic diversity among wheat genotypes using RAPD markers and its implication on genetic variability of diallel crosses. Bioscience Res., 16(2) (2019) 1258- 1266.
[22] K. H. Ghallab, Gene action and combining ability effects in F1 and F2 diallel crosses of some wheat varieties under the conditions of newly reclaimed salt affected soil. 2nd Conf. on Farm Integrated Pest Mamag., Fac. Agric. Fayoum Univ. 16-18 January (2006) 54-66.
[23] W.C. Dahnke, D. A. Whitney, Measurement of soil salinity. in recommended chemical soil test procedures for the north central region; Dahnke, W.C., Ed.; North Dakota Dep. of Agric.: Bismarck, ND, USA.; (1988) 32–34.
[24] K. A. Gomez, A. A. Gomez, Statistical procedures for agricultural research. John wiley & sons (1984).
[25] B. Griffing, Concept of general and specific combining ability in relation to diallel crossing system. Australian J. Bio. Sci., 9(4) (1956) 463-493.
[26] G. M. Bhatt, Heterotic performance and combining ability in a diallel cross among spring wheat (*T. aestivum* L.) Aust. J. Agr. Res., 22(3) (1971) 359 - 369.
[27] I. A. Khatab, A. B. A. El-Mouhamady, S. A. Mariey, Comprehensive selection criteria for high-yielding bread wheat (*Triticum aestivum* L.) hybrids under salinity stress. Egyptian J. of botany, 61(3) (2021) 709-730.
[28] S. Omrani, A. Arzani, M. Esmaeilzadeh Moghaddam, M. Mahlooji, Genetic analysis of salinity tolerance in wheat (*Triticum aestivum* L.). Plos one, 17(3) (2022) e0265520.
[29] R. K. Rathore, Inheritance of important metric traits of wheat in salt stress environments. Inter. J. of Phytology Res., 3(2) (2023) 20-23.

[30] S. Muralia, E. D. Sastry, Combining ability for germination and seedling establishment characters in bread wheat (*Triticum aestivum* L.) under normal and saline environments. Indian J. of Genetics and Plant Breeding, 61(01) (2001) 69-70.

[31] O. K. Hammam, A. E. Zaher, M. H. Haridy, K. A. Al-Aref, Estimate of combining ability and correlation for yield and its components in bread wheat (*Triticum aestivum* L.). Archives of Agric. Sci. J., 3(3) (2020) 1-12.

[32] M. A. Darwish, E. Zeinab, M. A. Iqbal, I. B. R. A. H. I. M. M. Al-Ashkar, S. Islam, A. Y. M. A. N. El Sabagh, Determining the gene action and combining ability of F2 bread wheat by diallel analysis. Pak. J. Bot, 56(4) (2024) 1407-1417.

[33] P. Tomar, S. K. Singh, S. Singh, J. P. Chaurasiya, M. S. Singh, Combing ability and heterosis analysis for yield and its related traits in bread wheat (*Triticum Aestivum* L.). J. of Pharmacognosy and Phytochemistry, 2020, 9(6), 2184-2188.

[34] A. Kumari, H. Sharma, A. Dashora, Combining ability analysis in bread wheat (*Triticum aestivum* L.) for grain yield with heat tolerance traits under different environmental conditions. The Pharma Innovation J. 11(2) (2022) 515-518.

[35] B. N. Bekmurodovich, J. D. Turdikulovich, D. S. Dilmurodovich, N. I. Xolbekovich, B. B. Elmurodovich, K. A. Abdullayevich, Diallel analysis of the bread wheat (*Triticum aestivum* L.) in the southern regions of the republic of Uzbekistan. Asian J. of Agric. and Horticultural Res., 10(4) (2023) 205-213.

[36] T. N. Hama Amin, S. Towfiq, inheritance of grain yield and its related characters for 5× 5 diallel cross of f1 bread wheat. Ecology and Environ. Res., 17(2) (2019) 3013-3032.

[37] S. Choudhary, B. S. Rajpurohit, V. Khandelwal, U. Singh, S. Kumawat, Heterosis for grain yield and quality characters in pearl millet (*Pennisetum glaucum* (L.) Br.). Annals of Plant and Soil Res., 25(1) (2023) 157-162.

[38] D. Chaudhary, S. Prashant, J. P. Jaiswal, R. Rohit, S. Joshi, Comparative study of standard heterosis for yield and its attributes in bread wheat under two different water regimes. Plant Genetic Resources, 21(1) (2023) 50-57.

[39] Y. M. Feltaous, Inheritance of yield and its components in two bread wheat crosses under normal and water stress conditions. Assiut J. Agric. Sci, 51(2) (2020) 74-90.

[40] M. M. Mohamed, S. T. Eissa, Genetic parameters estimation for yield and its components in two bread wheat crosses by using six populations model. J. of Plant Production, 13(8) (2022) 549-553.