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Determination of Potence Ratio, Inbreeding Depression, and Heterobeltiosis in Wheat Yield Components Under Salinity Stress

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.

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ABSTRACT

Salinity stress is one of the most devastating abiotic stresses that greatly affect crop productivity; wheat is susceptible to it. The estimation of heterobeltiosis, potence ratio, and inbreeding depression were done through four generations: P_1, P_2, F_1, and F_2. A full diallel among four genotypes was conducted relative to yield components assessed under three levels of salinity. The analysis of variance revealed that salinity stress significantly affected yield components across generations. The variability's for heading date, plant height, and spike length appeared under the stress conditions. Regarding salinity stress, the mean performance of the parents and their progeny revealed the superior performance of some hybrids in the F_1 generation. The heading date, plant height, and spike length showed variation between the F_1 and F_2 generations under the influence of stress. Partial dominance of some traits and overdominance in most of the phenotypes under the study were identified in F_1 hybrids. Therefore, partial dominance was identified, while the majority of the traits under study showed overdominance in the identified F_1 hybrids. Confirmation of trait stability and further validation from the results observed in the F_2 generation were done with the evaluation of inbreeding depression and heterobeltiosis. Features affected by inbreeding depression, such as heading date and yield of grains/plant, varied among crosses and levels of stress. Heterobeltiosis analysis over the F_2 generation showed significant variability in the performance of hybrids under salt stress. The hybrids $P_4 \times P_1$, $P_2 \times P_4$, and $P_4 \times P_2$ performed very well across the different levels of salinity, with high robustness and good output considering some main characteristics: heading date and grain production per plant. This study highlights the multiple interactions among genetic variation, salinity stress, and breeding strategy in wheat improvement.

1. Introduction

Wheat is the second most important crop in the world, playing a vital role in food security and the global food supply. One-third of the population of the world is dependent upon wheat as a staple food [1,2]. Global wheat production in 2023/2024 is forecast at 787.36 million metric tons down fractionally from 789.34 million metric tons in 2022/2023 [3]. It is the major staple food of all Egyptians and is grown on an area of approximately 3.24 million fed with a production of 8.87 million tons with an average productivity of 2,750 kg per fed. The national requirement is over 18 million tons; thus, there is a huge gap between supply and consumption [4].

Soil salinity is one of the major stumbling blocks in wheat cultivation due to osmotic stress, ion toxicity, and nutritional imbalance. It has become very prevalent in most arid and semi-arid countries where agricultural productivity and economic viability are at their all-time lowest. Since salinity already affects about 7% of the world's land area, engineering salt tolerance in crops is important for long-term agriculture and food security globally. Under extreme circumstances, wheat yields can be reduced by 50% or more due to salinity. This gives reason for the emphasis on producing salt-tolerant varieties [5-10].

Heterosis the improved performance of offspring compared with that of the average of their parents-depends on differences in allelic states at many loci interacting nonadditive through dominance and epistasis. The magnitude of heterosis depends on genetic distance between parents and also environmental stressors. Hybrids tend to give superior yield under salinity conditions through better control of osmotic stress. This is brought about by the complex nature of these interactions and the poor understanding of genotype combining ability, hence prediction of Heterobeltiosis remains complex and dependent on finding allelic differences between parents. In cereals, the magnitude of Heterobeltiosis ranges from 10% to 25% [11], while for wheat, economic Heterobeltiosis has been recorded to range between 7% and 42% [12]. The potence ratio (PR) of wheat is the gold standard of

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

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measurement for gene dominance in F1 hybrids and is one of the important parameters in estimating hybrid vigor. A high PR means strong positive Heterobeltiosis, where F1 hybrids surpass the mid-parent value. Both genetic background and environmental conditions make a difference in this ratio; hence, selection for superior hybrids should be considered within wheat breeding programs. However, the consequence of continuous self-pollination is a resultant inbreeding depression (ID) that diminishes vigor and fertility but is necessarily required to select the valuable segregates in wheat breeding [13]. Therefore, two apparent opposites must be combined into crop improvement strategies: ID and Heterosis. This study aimed to evaluate Heterobeltiosis, ID, and PR in bread wheat to identify superior parents and crosses for use in future breeding programs for salt tolerance.

2. Material and Methods

Plant materials for the field experiment was four promising wheat genotypes, designated as P1, P2, P3 and P4 (Table 1), which were developed through a continuous breeding program [14].

Table 1: Code number, wheat genotypes and pedigree were 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

Tolerance to abiotic stresses, including salinity and drought, has been shown by these genotypes, and evaluation was conducted under three salinity levels (Table 2): low (3.21 dS/m), moderate (7.78 dS/m), and severe (10.62 dS/m) [15]. The experiments were conducted at Demo Research Farm, the Faculty of Agriculture, Fayoum University, Egypt, where planting of the genotypes was done in a full diallel mating design during the 2019-20 seasons by which 12 F_1 hybrids were produced. These F_1 hybrids were subsequently advanced to F_2 generation through nursery cultivation at the same farm in the following season (2020-21).

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)
Texture class		Sandy loam	Sandy loam	Sandy loam
Ph		7.71	7.81	7.73
Ece	(dS m^{-1})	3.21	7.78	10.62
CEC	($cmol_e$ kg^{-1})	11.75	11.86	11.93
$CaCO_3$	(%)	6.48	11.91	14.50
N		0.07	0.05	0.03
P	(mg kg^{-1} soil)	4.39	4.38	4.33
K		48.70	47.60	46.89

The genotypes were planted in a Randomized Complete Block Design (RCBD) with three replications. The experimental plot consisted of five rows for each genotype. Each row was 3m in length and 50cm width. Seeds were spaced at 10cm within rows and one plant was left per hill. The experimental unit area = 5 * 3* 0.5= 7.5 m^2. Agronomic practices were followed throughout the growing seasons for plant establishment and maintenance. During the 2020-21 season, four parents and their 12 F_1s were assessed under three different salinity levels. In the subsequent 2021-22 season, these four parents, along with the 12 F_1s and their resulting 12 F_2s, were evaluated under the same three stress conditions.

Data of the agronomical traits were collected randomly from ten competitive plants within the parental lines, F_1s, and F_2s progenies for the following traits: heading date (HD), plant height (PH), No. of tillers (NTT), spike length (SL), grains weight per spike (GWS), 100-grain weight (HSW), and Grain yield/plant (GYP). Additionally, proline content was measured during the heading stage to assess plant stress tolerance [16]. PR was computed to assess the degree of dominance using the formula [17]: $PR = \frac{F_1 - MP}{0.5*(P_2 - P_1)}$. Inbreeding depression (I.D, %) was calculated when both F_1 and F_2 populations of the same cross were available and estimated using the method suggested [18]. It was measured using the formula:

$$I.D\ (\%) = \frac{F_1 - F_2}{F_1}\ \%$$

The relative better-parent heterobeltiosis (HB) for F_2 was estimated using the following equations [19]:

$$HB = \frac{F_2 - BP}{BP} * 100$$

The data were analyzed to assess the variations among treatments, parental lines, F_1s, and F_2s using analysis of variance (ANOVA) [20].

3. Results

3.1. Agronomic traits

According to the ANOVA results in Table 3, salinity stress had a highly significant effect on all yield component traits for four generations (P1, P2, F1, and F2) among two seasons. This is evident from the high mean squares for salinity, reflecting the substantial influence of salinity on wheat growth and yield performance. Proline content was significantly increased under salinity conditions, with values of 28.7 in the first season and 135.5 in the second season. This suggests that wheat plants actively responded to salinity stress by producing more proline, a protective compound against salt-induced damage. The genetic differences between generations had a significant impact on all studied traits in both seasons. This indicates the presence of substantial genetic variation among the generations in terms of salinity tolerance. There were significant differences in spike length, grain weight per spike, and No. of tillers, demonstrating the role of genetic variation in influencing yield performance under stress conditions (Table 3). Error values were relatively low in both years, indicating precision of the experimental design and the limited variation between replications. This enhances the reliability of ANOVA results and minimizes the influence of random factors.

Table 3: Analysis of variance for yield components in wheat across four generations (P1, P2, F1, and F2) under three levels of stress conditions.

Source of variance	df	Heading date	Plant height	Spike length	No. of tillers	Grains weight/ spike	100 grain weight	Grain yield/ plant	Proline content
1st year									
Replication	2	1.70	19.36	0.43	0.07	0.003	0.02	2.26	0.00
salinity	2	511.6**	2232.8**	139.6**	12.05**	3.190**	6.20**	575.1**	28.7**
genotypes	15	154.9**	1512.2**	6.56**	1.60**	0.910**	0.20**	28.25**	1.56**
Error	124	1.59	10.18	0.42	0.14	0.040	0.02	1.90	0.01
2nd year									
Replication	2	4.31	8.62	0.88	1.07	0.06	0.05	4.20	0.002
Salinity	2	73.42**	1408.4**	139.1**	5.76**	11.29**	4.65**	845.1**	135.5**
Genotypes	27	231.68**	725.5**	77.00**	1.76**	0.48**	0.18**	55.67**	0.270**
Error	220	5.94	15.05	0.40	0.37	0.02	0.02	2.04	0.050

* and ** denote significant differences at 0.05 and 0.01 levels, respectively.

3.2. Analysis of mean performances of parent and their subsequent generations (F_1, F_2)

Mean performances for the four populations (P1, P2, F1 and F2) for all traits studied under salinity stress are illustrated in Fig. 1. The evaluation of mean performance revealed a general decrease in trait values as salinity stress increased.

A heading date, plant height, spike length, number of tillers, grain weight per spike, 100 grains weight, grain yield per plant, and proline content were determined for parents, F1 and F2 generations, under both low and stress conditions. The findings revealed significant differences in all characteristics within and between generations as well as at varying stress levels. The heading date values varied from 63.45 to 80.24 days where for parents the P4 parent was recorded the lowest heading date of (71.50, 70.26 and 68.90 days) under low, moderate and high salinity conditions, respectively. With respect to F1 hybrids, P3×P1, P1×P3 and P3×P1 crosses had better heading date under three conditions with 65.95, 65.10 and 63.45 days, respectively; while in the F2 hybrid P2×P4 cross had advantage with fewer values of 72.53, 70.40 and 68.30, respectively. Plant height showed varied between 94.79 and 127.50 cm with P3 exhibiting the highest plant height under low and moderate conditions, while P4 displayed the lowest under severe stress. The hybrid P3×P2 in the F1 generation showed superior and stable plant height across stress levels, also in F2 P3×P2 hybrid showed relatively stable plant height across conditions with values of 108.00, 113.30 and 108.67 cm under low, moderate and severe stress, respectively. Spike length values ranged from 8.76 to 18.17 cm, with P3 achieving the highest spike length (17.42 and 16.64 cm) under low and moderate conditions, while P4 had the lowest spike length under severe stress (8.76 cm). The hybrid P2×P4 in the F1 was demonstrating favorable spike length across all conditions.

In the F2 generation the cross P2×P4 favorable over other hybrids exhibited high spike length values of 17.80, 16.83 and 15.93 cm, respectively under low, moderate, and severe stress conditions. Number of tillers values range from 3.07-8.00 tillers, with P4 presenting the highest number of tillers under low conditions, but showing a drastic drop under severe stress conditions. The hybrid P2×P4 in the F1 an F2 generations were maintained the highest number of tillers across all conditions achieving values of 7.53, 7.27 and 6.83 under low, moderate and severe stress, respectively. Values of grain weight per spike ranged from 1.80 to 3.79 g with P4 achieving the highest grain weight per spike under low conditions but showing a substantial decrease under severe stress whereas hybrid P2×P4 exhibited notable stability across stress levels. In F2 hybrid, the cross P2×P4 exhibited notable grain weight per spike stability recording 3.51, 3.29 and 3.07 g under low, moderate and severe stress, respectively. Values for 100 grains weight values ranged from 2.57 to 5.52 g and P4 exhibited the highest weight under low conditions (5.12 g) with showed a marked decline under severe stress (2.57 g) while, in the F1 cross P2×P4 showing superior performance and stress tolerance. In F2 the crosses P3×P4 and P1×P3 displayed resilience maintaining weights close to their low values even under severe stress with P3×P4 showing a weight of 5.07 g under severe stress. Grain yield per plant displayed significant variation with values ranged from 10.54 - 29.14 g with P4 showing high sensitivity to stress while F1 cross P2×P4 demonstrated remarkable stress tolerance maintaining the highest yield under severe stress. In F2 generation, results indicated that the crosses P2×P4 and P4×P1 displayed resilience, while P2×P4 maintaining the highest yield under severe stress (18.85 g). Concerning proline content. Results recorded increase under stress indicating adaptive responses with P2 and P4 showing the highest accumulation among parents while F1 and F2 crosses including P4×P2 and P4×P1 exhibited enhanced proline levels under severe stress.

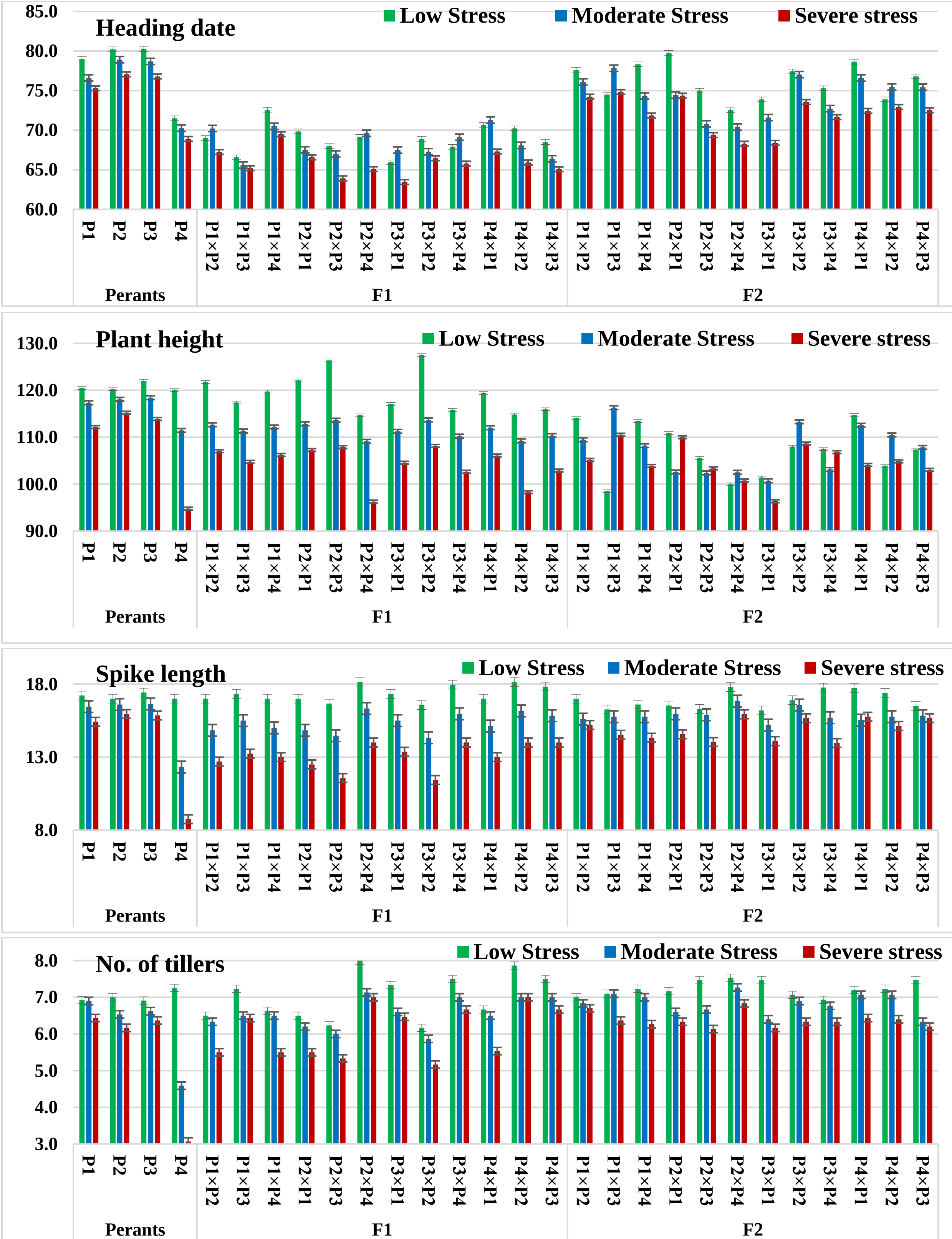
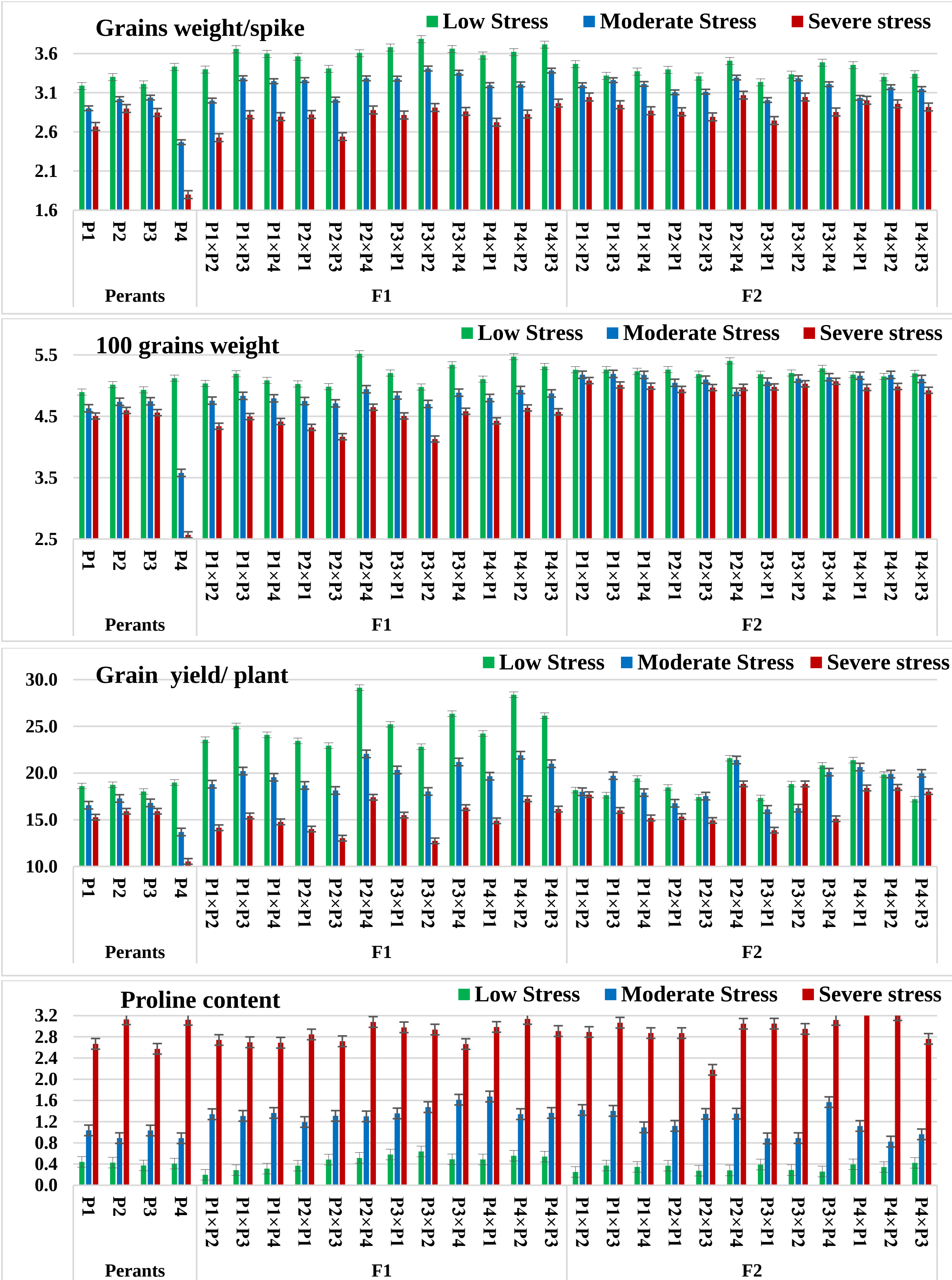


Fig.1: illustrates the mean performance of four parent and their subsequent generations (F1 and F2) under three levels stress.


Grains weight/spike
Low Stress
Moderate Stress
Severe stress
3.6
3.1
2.6
2.1
1.6
100 grains weight
5.5
4.5
3.5
2.5
Grain yield/ plant
30.0
25.0
20.0
15.0
10.0
Proline content
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
P1
P2
P3
P4
P1×P2
P1×P3
P1×P4
P2×P1
P2×P3
P2×P4
P3×P1
P3×P2
P3×P4
P4×P1
P4×P2
P4×P3
Perants
F1
F2

Cont. Fig 1

3.3. Estimation of potence ratio in wheat generations under salinity stress

The estimated PR across various salinity levels revealed significant variability in all studied traits (Fig. 2). The PR for F1 hybrids traits indicated the presence of dominance effects were controls inheritance all studied traits. All of hybrids had negative values for heading date under different salinity conditions, indicated partial and overdominance (Fig. 2) while PR varied in the rest of traits (plant height, spike length, No. of tillers, grains weight per spike, 100-grain weight, grain yield/plant and proline content) under different salinity conditions as follows:

Under low saline conditions, the highest negative PR was observed for HD in (P2×P3), plant height in (P3×P2) hybrid, spike length in (P3×P2) hybrid, No. of tillers in (P3×P1) hybrid, grain yield/plant in (P2×P4) hybrid and proline in (P3×P1) hybrid. Conversely, the least negative PR values were noted for heading date in (P1×P4), plant height in (P2×P3), spike length in (P1×P4) hybrid, No. of tillers in (P4×P2) hybrid, grains weight per spike in (P3×P2) hybrid, grain yield/plant in (P2×P3) hybrid and proline in (P4×P1) hybrid. Under moderate salinity stress, the highest negative PR values were for heading date, plant height and spike length in (P2×P3) hybrid while the least negative PR values were recorded for heading date in (P4×P1) hybrid, plant height in (P1×P4) hybrid, spike length in (P2×P4) hybrid and grain yield/plant in (P3×P1) hybrid. Under severe salinity stress, the highest negative PR values were for heading date, plant height , spike length, No. of tillers , grains weight per spike and grain yield/plant in (P2×P3) hybrid with the least negative PR observed for heading date in (P1×P4) hybrid, plant height in (P1×P4) hybrid, spike length in (P3×P4) hybrid and (P4×P3) hybrid and grain yield/plant in (P2×P4) hybrid.

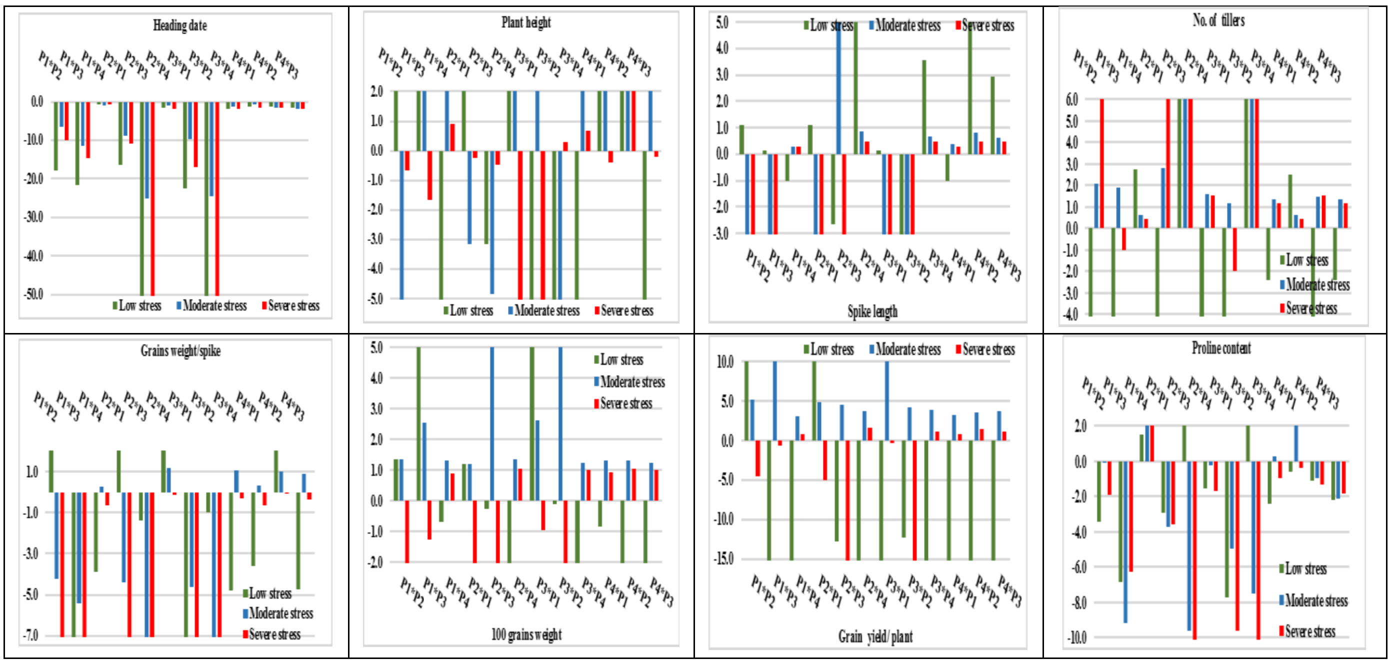


Figure 2: Potence ratio (PR) in wheat hybrids under salinity levels.

3.4. Estimation of inbreeding depression in wheat generations under salinity stress

Inbreeding depression (ID) across different salinity levels revealed notable variability in all evaluated traits (Fig. 3). The most significant negative values for ID under low conditions was were observed for traits, i.e. such as heading date (HD) in the (P2×P4) cross at -4.87%, plant height (PH) in (P1×P4) cross at 8.65%, spike length (SL) in (P2×P3) cross at 16.46%, No. of tillers (NTT) in (P4×P2) at 8.05%, grains weight per spike (GWS) in (P3×P1) cross at 12.09%, 100-grain weight (HGW) in (P1×P3) cross at 36.63%, grain yield per plant (GY) in (P4×P3) cross at 34.18%, and proline content in (P3×P2) cross at 54.91%. On the other hand, the least negative ID was found in HD for the (P2×P1) cross at -14.20%, PH in (P1×P3) cross at -3.48%, SL in (P4×P1) cross at 3.91%, NTT in (P2×P3) cross at -19.79%, GWS in (P1×P2) cross at -2.03%, HGW in (P4×P1) cross at 3.27%, GY in (P4×P1) cross at 11.75%, and proline content in (P1×P3) cross at -30.27%.

Under moderate stress, the highest negative ID values were observed in HD for (P2×P4) hybrid at -1.13%, PH in (P2×P4) hybrid at 11.83%, SL in (P2×P3) hybrid at 9.89%, NTT in (P4 × P3) hybrid at 9.52%, GWS in (P3×P1) hybrid at 8.34%, HGW in (P3×P1) hybrid at 26.51%, GY in (P3×P1) hybrid at 20.76%, and proline content in (P3×P2) hybrid at 39.65%. Conversely, the lowest negative values for ID was were recorded in HD for (P1×P3) hybrid at -18.65%, PH in (P2×P1) hybrid at -1.66%, SL in (P1×P3) hybrid at -4.46%, NTT in (P3×P2) hybrid at -17.61%, GWS in (P1×P2) hybrid at -6.53%, HGW in (P4×P2) hybrid at -1.10%, GY in (P4×P1) hybrid at -5.02%, and proline in (P1×P3) hybrid at -7.21%.

Under severe stress conditions, the most significant negative values for ID was were observed in HD for (P1×P4) hybrid at -3.41%, PH in (P2×P4) hybrid at 9.44%, SL in (P3×P1) hybrid at 7.84%, NTT in (P4×P2) hybrid at 8.57%, GWS in (P3×P1) hybrid at 2.52%, HGW in (P3×P1) hybrid at 25.23%, GY in (P3×P1) hybrid at 10.43%, and proline content in (P2×P3) hybrid at 19.82%. The least negative values for ID under severe stress was were found in HD for (P1×P3) hybrid at -14.78%, PH in (P2×P1) hybrid at 2.73%, SL in (P4×P2) hybrid at -6.68%, NTT in (P3×P2) hybrid at -22.58%, GWS in (P1×P2) hybrid at -20.51%, HGW in (P3×P2) hybrid at -31.66%, GY in (P3×P2) hybrid at -47.79%, and proline content in (P3×P4) hybrid at -17.03%.

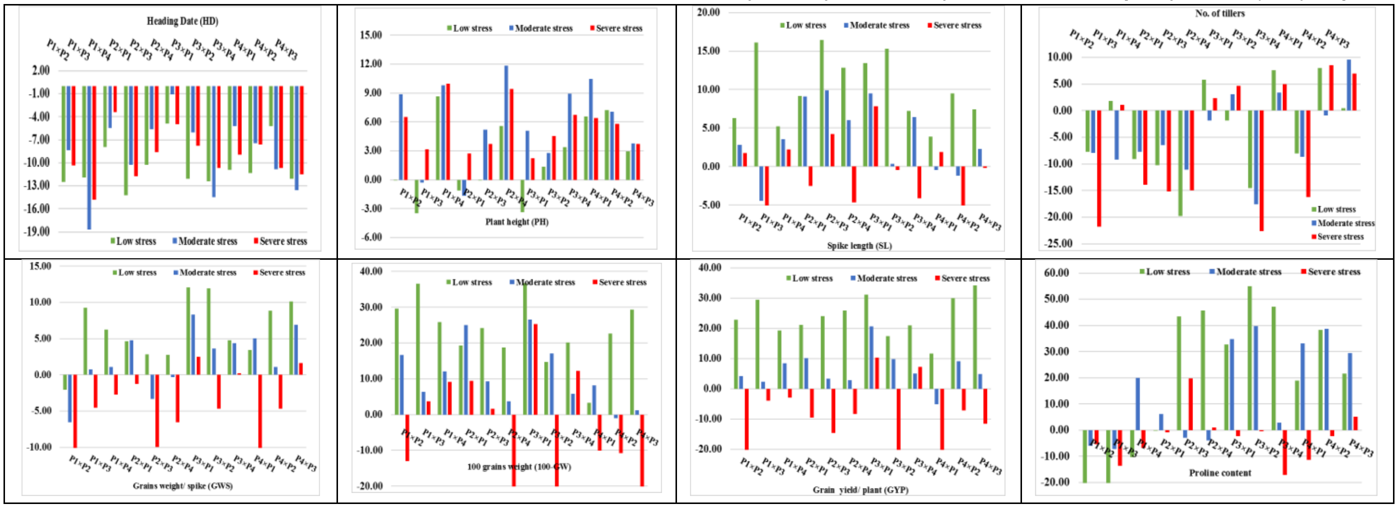


Figure 3: illustrates the analysis of inbreeding depression (ID) in the F_2 generation of wheat hybrids under three salinity stress levels.

3.5. Estimation of Heterobeltiosis in wheat generations under salinity stress

The findings showed that there was a great difference in heading date (HD), plant height (PH), spike length (SL), number of tillers (NTT), weight of grains per spike (GWS), weight of 100 grains (HGW), grain yield per plant (GY) and proline content of estimated heterobeltiosis at different salinity levels, indicating the stress responses and tolerance of the wheat crosses (Fig. 4).

Crosses demonstrated varying HB values for different traits under low, moderate and severe stress in Fig. 4. Heterobeltiosis were observed in For HD for, P4×P1 hybrid (10.02%), P1×P4 hybrid (9.56%) and P4×P3 hybrid (7.41%) showed high positive HB, whereas P2×P3 hybrid exhibited the lowest values (-6.51 to -10.03%) across stress levels. Regarding PH, P1×P4 hybrid showed value of 9.61% under severe stress, while P4×P1 exhibited 9.82% under severe saline and 1.00% under moderate conditions. In contrast, crosses P1×P3 and P2×P3 had significant negative HB, particularly under low and moderate stress (-18.26 to -14.16%).

For spike lengthSL, cross P2×P4 showed positive HB (4.71%) under low saline conditions but declined under saline stress. Positive values were also observed in P4×P1 hybrid (2.97%) and P3×P1 hybrid (1.98%) under low saline conditions, while P1×P3, P2×P3 and P3×P1 hybrids displayed notable negative HB which ranged from (-8.34 to -12.05%) across stress salinity levels. In NTT, P2×P4 hybrid consistently showed high positive HB (3.83% to 11.22%), while P3×P1 and P3×P4 hybrids exhibited negative HB in several conditions in Fig. 4.

Grain weight /spike recorded that the P4×P1 hybrid gave the highest positive values for HB (12.53%) and exhibited consistent performance in GWS P4 × P1 moderate saline (10.70%), while P4×P2 and P4×P3 crosses showed negative HB in the control condition but improved under saline stress. Hundred grain weight showed positive HB for all the studied crosses with P1×P4 cross (11.74%) performing better in moderate saline while P3×P4 cross (11.18%) performed better in severe saline. In GYP, P4×P1 cross had the highest HB under severe saline (20.49%) and maintained strong performance under moderate saline (24.66%), while P2×P4 cross also performed well across all conditions. Conversely, P3×P1 and P2×P3 crosses exhibited negative HB in most scenarios in Fig. 4.

Proline content showed negative HB under low saline conditions for most crosses except P4×P3 cross (3.64%). Under moderate stress crosses P2×P4 and P4×P2 crosses showed high positive HB (51.80% and 51.85%), while severe stress led to negative HB, especially in P2×P3 crosses (-30.40%).

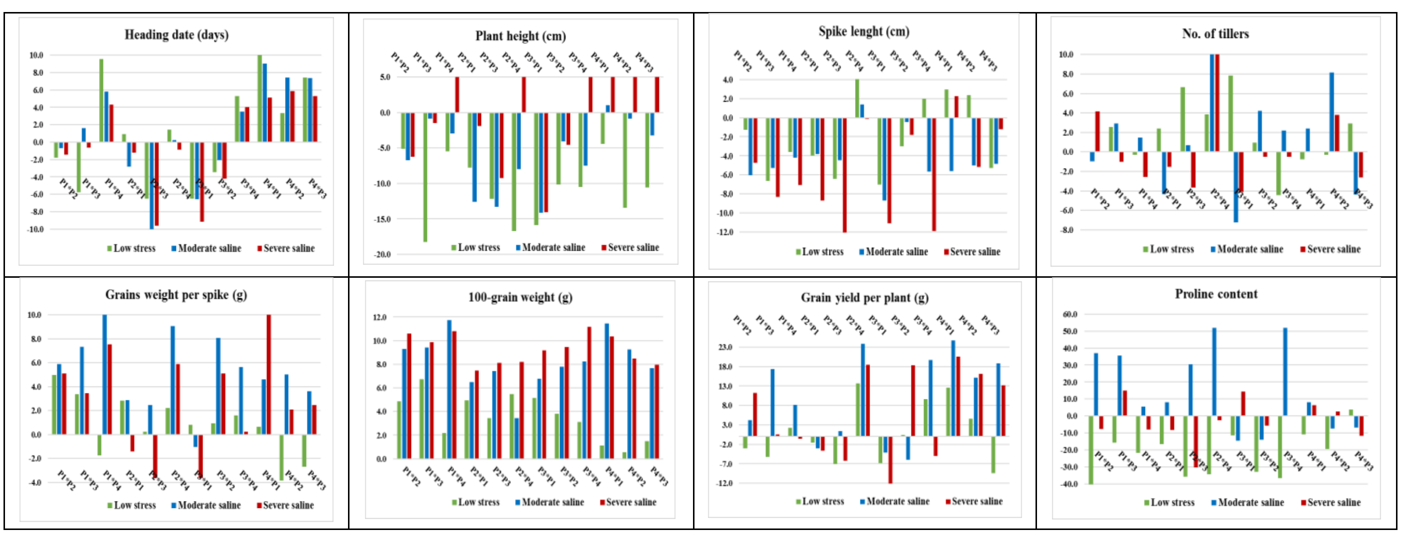


Figure 4: Analysis of heterobeltiosis (HB) in the F_2 generation of wheat hybrids under three levels of salinity stress.

4. DISCUSSION

Salinity stress affects all traits and yielding components in wheat as revealed by the analysis of variance along the lines of genetic tolerance to salinity of the generations studied [21, 22]. To improve wheat salinity tolerance depends on genetic variability and also on improving other traits such as increased proline content and developing genotypes that are high yielding under salinity stress [22].

4.1. Evaluation of mean performances of parents and their hybrids

Environmental stress such as salinity stress has a greatly detrimental effect on some of the growth and yield parameters in general and among the parental lines and their F1 and F2 hybrids in particular and with increasing salinity levels, the effects become more pronounced. For example, the heading date (HD) is reduced under stress, which means these genotypes may be responding by hastening their development [22, 23]. Moreover, parameters such as plant height (PH), spike length (SL), and number of tillers (NTT) all show a decrease, which influences the reproductive organs and the quantity of yield produced as a whole. In addition, the grain weight per spike (GWS) and also the hundred grain weight (HGW) were decrease with higher salinity levels and this leads lead to a reduction in the grain yield per plant (GY). At the same time, proline content increases, which indicates a metabolic process due to the adverse effect of salinity on high productivity of plants [22-24].

Hybrids involving parent P4, such as P2×P4, P4×P2, P4×P3, and P3×P4 in the F1 generation, and P2×P4, P4×P1, and P4×P2 in the F2 generation, consistently enhanced performance across traits under low, moderate and severe saline conditions [22, 25, 26]. These hybrids inherited the high-yield potential from parent P4, along with stress tolerance traits from the other parents. Additionally, increased proline content improved stress tolerance, suggesting that these hybrids are less affected than other combinations under saline stress [22, 23, 27-30]. Various hybrids, including P2×P4, P4×P2, P3×P4, P3×P1, and P4×P3 in the F1 generation, and P3×P1, P4×P2, P2×P3, P4×P2, and P4×P3 in the F2 generation also showed lack of important traits like HD and PH which resulted in reduced yield under stress conditions [23, 29, 30]. Based on the results of mean performance, we recommend prioritizing the use of hybrids involving parent P4, for breeding programs aimed at improving salinity tolerance.

4.2. Potence ratios (PR)

PR indicate the dominance of inherited traits. Values over ±1, indicate overdominance, whereas values between -1 and +1 reflect partial dominance, whereas value of +1 indicates complete dominance, and value of 0 suggests an absence of dominance. Figure 2 represents PR values among 12 F1 wheat hybrids across three salinity stress levels, illustrating how these values shift with increasing stress, similar results were mentioned in previous studies [26, 29]. Confirming that overdominance gave a key role of traits under salinity stress.

The PR values for HD being assessed over twelve hybrids have shown different degrees of dominance, with a recurring trend of overdominance appearing in the stress related studied traits. This was similar in the case of PH and GY where over-dominance was also exhibited in all twelve crosses under both low and moderate salinity stresses. However, the number of crosses exhibiting over-dominance decreased to ten for proline content under moderate salinity stress, reflecting a weakening dominance effect as stress levels rose [24]. Under severe stress, overdominance in traits PH, NTT and GY was limited to eight crosses, while only six crosses showed over-dominance for SL [26, 29]. An additional decrease was observed for SL and HGW under control treatment except for four crosses which only show over dominance. Partial dominance was observed in the rest of the hybrids for all studied traits and non-dominance was not observed. These results are in line with those reported [26, 29] supporting that over dominance is a key factor for the expression of important traits especially under salinity stress conditions.

The ability of PR to change with salinity levels is a predictor of the degree of stress maintenance expression as seen in the stress-related traits. For instance, some hybrids like P4×P3, P2×P4, P4×P2 and P1×P4 recorded positive values of PR for the traits of salinity level, GWS, HGW and GY indicating the existence and dominance of favorable alleles contributing to enhanced stress rights [26, 29]. These positive values further suggest that certain genotypes are relatively better than others in tolerating salinity due to the existence of certain dominant alleles that mitigate stress. In particular, negative values of PR were found in some crosses suggesting less dominance or more of undesirable alleles where loss of traits such as growth and reproduction performance occurs such as it was with HD in the cross P2×P3 which indicates development that is shorter to stress imposition thus also less growth and reproduction season. However, the overdominance was less pronounced by stress for certain qualities such as SL, HGW or GWS while the high or moderate stressing did as these traits can positively respond to stress on a genetic basis [26, 29].

4.3. The inbreeding depression (ID)

Inbreeding depression (HD) exhibited variation concerning the traits assessed and levels of salinity. In the absence of stress, traits; HD, PH, SL, NTT, GWS, HGW and GY and proline content had a moderate level of ID [22, 23, 25, 30-32]. Under moderate salinity stress, the effects of ID became more pronounced for PH, GWS, and GY, with hybrids like P2×P4 and P3×P1 showing significant reduction in growth and yield [25, 26, 30, 31]. Severe salinity stress intensified these impacts, especially in key yield-related traits, GY, HGW, and GWS, with significant reductions in crosses particularly P3×P2 and P3×P1 Proline content increased in some hybrids, suggesting attempts to mitigate salinity effects biochemically, indicating this increase was insufficient to prevent substantial yield losses [21, 33]. Different crosses respond differently to salinity stress, affecting their performance and resilience. This highlights the challenges of inbreeding in breeding programs, especially in environments like salinity. Strategies must consider inbreeding effects for sustainable crop productivity.

4.4. The Heterobeltiosis (HB)

The Heterobeltiosis (HB) analysis across different salinity levels revealed critical insights into the performance of wheat hybrids and the influence of stress on key agronomic traits [25, 27, 28, 32]. In low saline conditions, positive heterosis for days to heading (HD) was seen in crosses such as P4×P1 and P1×P4, which indicated early maturity that could be beneficial for shorter growing periods. On the other hand, P2×P3 and P3×P1 crosses showed negative HB values and delayed maturation [27, 32]. For PH, most hybrids, showed negative HB, except P4×P1 hybrid, which showed less reduction mixed values were observed in SL and NTT, with some hybrids showing positive HB for tiller production and grain weight indicating enhanced performance compared to their parents, suggesting that these crosses possess strong genetic potential for grain production under non-stress conditions [25, 27, 28, 32]. Under moderate salinity stress, positive HB for HD was observed in crosses P4×P1 and P4×P2, indicating early maturity and resilience under stress, while others, such as P2×P3 cross had a negative HB and delayed development indicating stress sensitivity. Results observed for SL and NTT, hybrids P4×P1 and P2×P4 , P4×P1 and P2×P4, crosses performed well under moderate salinity [27]. This suggests that these hybrids exhibit moderate salinity tolerance and may thrive under slightly stressed conditions [25, 27]. However, P3×P1 and P3×P2 crosses, were more sensitive to even moderate salinity. Additionally, proline accumulation was enhanced in certain hybrids, contributing to their stress tolerance [21, 24, 33, 34].

Severe salinity stress, revealed substantial HB variability, with positive HB for HD and PH for hybrids P4×P1, P1×P4, and P4×P3, suggested early heading and better growth as a potential survival strategy under extreme conditions [27]. Whereas, crosses P2×P3 and P3×P1 displayed negative HB for PH and GWS indicated poor adaptation and delayed development, indicating susceptibility. For PH, positive HB was recorded in hybrids P3×P4, P4×P2, and P4×P1, under severe stress, while negative HB was found in cross P3×P1 [27]. Hybrids P2×P4, P4×P1, and P4×P2 retained relatively high GY, indicating superior tolerance to salinity [25, 27]. Proline content varied across the hybrids, with some maintaining positive HB, while others showed declines [21, 24, 33, 34]. These findings illustrated the potential of selecting wheat crosses with traits conducive to salinity tolerance for effective breeding programs aimed at improving crop performance under saline conditions.

5. Conclusions

This study evaluated the metrics of wheat performance in parent lines, F1 and F2 generations under different salinity levels such as heading days, plant height, spike length, No. of tillers, grain weight and yield. Mean performance, PR, inbreeding depression (ID) and heterobeltiosis (HB). Salinity was found to have an abating effect on the traits generally and a positive effect on the proline content due to stress. The variation observed in the F2 generation was higher than that of the F1 generation. Crosses made with the P4 parent such as P2×P4 and P4×P2 managed to exhibit resilience and good performance under saline conditions. PR analysis of certain traits shows a clear suggestion of tolerance enhancement by over-dominance. ID was high in stressful environments and particularly on heading date, spike length and Grain yield/plant in most hybrids. For hybrids P4×P1 and P2×P4, heterobeltiosis was present even in adverse conditions, which shows their significance in breeding programs.

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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.

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