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HETEROSIS AND INBREEDING DEPRESSION IN WHEAT GENOTYPES FOR YIELD-RELATED TRAITS UNDER WATER STRESS CONDITIONS

S. KHANZADA[1*], Z.A. SOOMRO[1], S.N. MARI[1], and M.A. SIAL[2]

[1]Department of Plant Breeding and Genetics, Sindh Agriculture University, Tandojam, Pakistan
[2]Nuclear Institute of Agriculture, Tandojam, Sindh, Pakistan
*Corresponding author's email: samreenkhanzada@gmail.com
Email addresses of co-authors: zasoomro@sau.edu.pk, snmari@sau.edu.pk, mahboobali.sial@gmail.com

SUMMARY

Twenty-one crosses and seven parental lines' assessment and their F_{1s} and F_{2s} used for enhanced grain yield under water stress imposed at the tillering stage was this study's major focus. The research layout had a randomized complete block design with three replications. The traits in focus in this study were productive tillers plant^{-1}, spike length, the number of grains spike^{-1}, seed index (weight of 1000 grains in g), and grain yield plant^{-1}. Results revealed that genotypes were highly significant for all the studied traits in both generations, whereas treatments and their interaction were highly significant in the F_2 generation. The recorded higher mean values for all assessed traits occurred in non-stressed environments under both generations. As for the heterosis in grain yield plant^{-1}, the cross Bhittai x Inqilab showed the highest mid-parent heterosis, while NIA-Sunder x Khirman displayed much better parent heterosis, with the minimum reduction % produced by the TD-1 x Inqilab. For the inbreeding depression, NIA-Sunder and Khirman exhibited it. The F_2 generation produced a higher grain yield plant^{-1}. Such hybrids should serve for hybrid crop development in wheat.

Keywords: Heterosis, inbreeding depression, water stress, wheat genotypes, yield traits

Key findings: The varieties TD-1, Marvi-2000, and NIA-Sunder showed better performances, and the crosses, such as Bhittai x TD-1, Inqilab x Khirman, Bhittai x Marvi-2000, Bhittai x Khirman, NIA-Sarang x NIA-Sunder, and Bhittai x TD-1, displayed high heterosis and low inbreeding depression; thus, they should be effective to use for higher yield in wheat.

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INTRODUCTION

More than 70% of the world's food supply comes from cereals, and among them, wheat (*Triticum aestivum* L.) is a rich source of essential human diet, having 70% carbohydrates, 12% protein, 22% crude fibers, 2% fat, 12% water, and 1.8% minerals (Hedieh *et al.*, 2017). Wheat is a self-pollinated crop; it belongs to the family Poaceae. Bread wheat is a hexaploid, as per ploidy level (2n=6x=42); it is an example of naturally occurring polyploidy, resulting from intergeneric hybridization and polyploidization (Shoran *et al.*, 2003). Grain quality standards of the wheat varieties are necessary during export and import as a commodity, as well as a prerequisite for the baking industries and during the evolution of new commercial wheat varieties. Ascertaining the potential grain yield of cereal crops could be better when grown under natural fields with optimum conditions, with its evaluation through yield and yield-associated agro-morphological traits (Mahboob *et al.*, 2012).

Water stress is a worldwide issue that predicts sustainable agricultural production (Jaleel *et al.*, 2007). Drought leads to stomata closure and reduction of water content, and turgor loss leads to death of plants by disturbing metabolism (Jaleel *et al.*, 2008). Water stress both affects morphological and physiological traits. Drought causes leaf senescence in various wheat genotypes, thus causing chlorophyll degradation. Proline is an amino acid that accumulates during various stresses as an osmoregulatory protein. Genotypes amassing more proline show tolerance against stress by maintaining the plant's water potential.

Heterosis is, presumably, the superiority of hybrids in comparison to either of their parents. It is the allelic or non-allelic interaction of genes under the influence of a specific environment. Heterosis estimation has progressed in a range of cultivated crops and has been considerably important to study as a means of increasing productivity of crop plants. In improving drought tolerance, the utilization of heterosis is an essential strategy, with the potential to overcome the yield problem in wheat (Rauf *et al.*, 2012). The choice of potential parents for crossing and identification of superior hybrid combinations is an indispensable issue in hybrid breeding. This made operation of heterosis one of the exceptional achievements in wheat because of the prospect of obtaining higher yields than pure lines. In self-pollinated crops, such as wheat, the management of heterosis depends primarily on its extent (Singh *et al.*, 2004). Heterosis breeding helps take a quantum jump in the production and productivity of crop plants under various agro-climatic conditions (Devi *et al.*, 2013). F_1 hybrids carrying heterotic effects, as featured in all crop species, detail that the yield gains are limited to the F_1 generation. The F_2 and succeeding generations obtained through selfing are useless due to reduced yields and developmental characters (Wang *et al.*, 2015). Formerly, utilization of heterotic effects for grain yield mainly referred to cross-pollinated crops. However, later, a report stated wheat was predominantly self-pollinated for the first time, coming from Freeman in 1919. Both positive and negative heterosis are useful depending on the breeding objectives. The development of wheat cultivars with high production capacity and excellent quality, which meet market requirements, is the goal of each breeding program (Williams *et al.*, 2008). Parental selection represents the major step in the development of new high-yielding cultivars, and the efficient identification of superior hybrid combinations is a fundamental issue in wheat breeding programs.

MATERIALS AND METHODS

The seeds of F_1 and F_2 progenies developed from half diallel of parents using the Griffing (1956) method (Table 1) underwent sowing in a randomized complete block design with two treatments (non-stress and stress at tillering stage) and three replications. The experiment transpired at the Botanical Garden, Department of Plant Breeding and Genetics, Sindh Agriculture University, Tandojam,

Table 1. The scheme of 7 × 7 half diallel mating crosses in wheat crops.

Parents (♀/♂)	Bhittai (P1)	Marvi-2000 (P2)	NIA-Saarang (P3)	TD-1 (P4)	NIA-Sundar (P5)	Inqilab (P6)	Khirman (P7)
Bhittai (P1)	-	P1 ×P2	P1 ×P3	P1 ×P4	P1 ×P5	P1 ×P6	P1 ×P7
Marvi-2000 (P2)		-	P2 ×P3	P2 ×P4	P2 ×P5	P2 ×P6	P2 ×P7
NIA-Saarang (P3)	-	-	-	P4 ×P4	P4 ×P5	P4 ×P6	P4 ×P7
TD-1 (P4)	-	-	-	-	P4 ×P5	P4 ×P6	P4 ×P7
NIA-Sundar (P5)	-	-	-	-	-	P5 ×P6	P5 ×P7
Inqilab (P6)	-	-	-	-	-	-	P6 ×P7
Khirman (P7)	-	-	-	-	-	-	-

Table 2. Soil analysis report before conducting the experiment.

No.	Bore/ Location	Depth (cm)	EC (1:2) dSm^{-1}	pH (1:2)	OM (%)	Texture Class	SM C %	SW H C %
1		0-15	1.95	8.5		Silty Clay Loam		
2	T-1	15-30	1.77	8.4	0.38	Silty Clay Loam	17.31	1.68
3		30-45	0.56	8.5		Silty Clay Loam		
4		0-15	2.00	8.5		Silty Clay Loam		
5	T-2	15-30	1.43	8.4	0.42	Silty Clay Loam	16.42	1.77
6		30-45	1.26	8.5		Silty Clay Loam		

EC = Electrical conductivity, OM = Organic matter, Texture, SMC -= Soil moisture content, and SWHC = Soil water holding capacity.

Table 3. Agro-meteorological data of wheat crop grown during 2019–2020 to 2020–2021.

Year	Month	Total Rain fall	Temperature			Relative humidity
		(mm)	Min. °C	Max. °C	Avg.	(%)
2019–2020	November	0.00	14.90	31.60	23.25	57.00
	December	0.00	9.30	25.90	17.6	59.00
	January	0.00	8.30	24.20	16.25	61.00
	February	0.00	9.30	25.90	17.6	41.00
	March	0.00	14.60	31.70	23.15	50.00
	April	0.10	20.90	40.00	30.45	43.00
2020–2021	November	0.05	14.00	30.50	22.25	56.00
	December	0.03	9.50	24.60	17.05	58.00
	January	0.00	8.70	23.70	16.13	60.00
	February	0.00	10.00	24.20	17.10	40.00
	March	0.00	13.20	30.45	21.83	49.00
	April	0.00	19.30	39.90	29.60	42.00

Source: Regional Agro-Meteorological Center Tandojam.

Pakistan. The study adopted all the recommended cultural practices, except irrigation. Soil analysis ensued before sowing and after harvesting, with the meteorological data recorded throughout the cropping seasons of both years (Tables 2 and 3). The data analysis helps estimate heterotic effects of F_{1s} and inbreeding depression in F_2 for yield traits. The traits under study were productive tillers plant^{-1}, spike length, the number of grains spike^{-1}, seed index (weight of 1000 grains in g), and grain yield plant^{-1}.

Statistical analysis

The analysis of variances proceeded using the statistical package Statix 8.1 and following the method by Gomez and Gomez (1984) to observe the significant differences among the genotypes, treatments, and treatments x genotypes. Calculating heterosis and inbreeding depression of hybrids employed the approach according to Fehr (1987).

RESULTS AND DISCUSSION

Productive tillers plant^{-1}

Genotypes and treatments were highly significant in the F_1 generation, whereas the treatments were highly significant in the F_2 generation (Tables 4 and 5). The average mean of the genotypes was higher in the non-stressed than in the stressed condition (Tables 4 and 5). According to the estimation of heterotic effects among F_1 hybrids evaluated under non-stress (Table 6), the study found that TD-1 x Khirman (26.71 and 13.59) recorded the highest relative and better parent heterosis, respectively. When noting the heterosis for the trait number of tillers per plant under drought stress imposed during the tillering stage, it was prominent that the uppermost heterosis and heterobeltiosis appeared in NIA-Sarang x Khirman (31.69 and 17.22, respectively). Meanwhile, the minimum inbreeding depression among F_2s under non-stress for the number of tillers per plant resulted in the cross NIA-Sarang x Khirman (0.13). The minimum inbreeding depression among F_{2s} under stress surfaced in the cross TD-1 x Khirman (4.52) for the number of tillers per plant (Table 5). The number of tillers per plant in wheat has a strong connection with the grain yield, and it was also a choice of study of Muhammad *et al.* (2016). A similar experiment by Patel (2018) revealed they estimated the nature and magnitude of heterosis for grain yield, its components, and quality traits in a diallel cross of eight genetically diverse wheat genotypes, excluding reciprocals. Highly significant differences were notable among the genotypes for all the studied traits. Moreover, they observed substantial heterobeltiosis, average heterosis, and standard heterosis in the cross HI 1588 x MP 4080, with values of 39.64, 54.59, and 54.30, respectively, over the check variety, cross HD 2392 x GW 273. It exhibited significant positive standard heterosis for the number of tillers per plant and spikelets per spike over the check. The cross UP 2669 x GW 273 displayed the ultimate and most remarkable positive heterosis over the better parent and midparent for the grains' protein content. According to them, these crosses can be effective in developing high-yielding cultivars with good-quality traits.

Spike length

Extremely significant results emerged for genotypes and considerable in interaction with treatment in the F_1 generation, whereas genotypes, treatments, and their interaction were highly noteworthy in the F_2 generation (Tables 4 and 5). The average mean of the genotypes was higher in the non-stressed than in the stressed condition (Tables 4 and 5). On the estimation of heterotic effects (Table 6) among F_1 hybrids evaluated under non-stressed conditions, the response of F_1 hybrids from data for the said trait revealed that Bhittai x TD-1 (24.08 and 34.59) recorded the highest relative and better parent heterosis. When taking note of heterosis for the trait of spike length under drought stress imposed during the tillering stage, the researchers found the highest mid-parent/relative and better parent heterosis in Bhittai x TD-1 (46.23 and 30.62, respectively). The minimum inbreeding depression (Table 7) among F_{2s} under non-stressed conditions for the spike length, as observed, resulted in the cross TD-1 x Inqilab (11.50). The minimum inbreeding depression among F_{2s} under stress for spike lengths, as observed, was in the cross NIA-Sarang x NIA-Sunder (14.16). Aamir *et al.* (2019) used six parent half diallel in bread wheat and found Sunco x Janbaz manifesting positive heterosis for the trait, including spike length, which ultimately increased grain yield. Furthermore, Kumar *et al.* (2020) and Satnam

Table 4. Mean performance for yield and its associated traits of bread wheat under normal and water stress in F_1 generations.

Parents and F_1 hybrids		Tillers plant^{-1}		R.D.*	Spike length		R.D.*	Grains spike^{-1}		R.D.*	Seed index		R.D.*	Grain yield plant^{-1}(g)		R.D.*
		Non - stress	Water stress		Non - stress	Water Stress		Non - stress	Water stress		Non - stress	Water stress		Non - stress	Water stress	
Bhittai		12.90	10.70	-2.20	12.54	11.96	-0.58	85.91	75.93	-9.98	44.45	41.23	-3.22	30.85	22.45	-8.40
Marvi-2000		9.90	10.30	0.40	15.89	13.90	-1.75	65.53	60.5	-5.03	43.30	35.48	-7.82	34.18	26.50	-7.68
NIA-Saarang		10.90	9.40	-1.50	13.98	14.00	0.02	70.32	68.32	-2.00	43.67	39.3	-4.37	35.82	29.60	-6.22
TD-1		11.00	9.50	-1.50	15.87	13.87	-2.00	57.42	49.47	-7.95	45.68	39.77	-5.91	31.59	28.59	-3.00
NIA-Sunder		11.80	10.80	-1.00	13.67	11.67	-2.00	54.77	50.77	-4.00	41.34	37.47	-3.87	38.22	32.46	-5.76
Inqilab		10.00	9.70	-0.30	15.65	13.92	-1.73	67.55	65.57	-1.98	45.41	38.55	-6.86	36.38	25.58	-10.80
Khirman		10.30	10.60	0.30	13.08	11.74	-1.34	62.07	58.73	-3.34	40.41	37.89	-2.52	39.21	33.40	-5.81
Bhittai x Marvi-2000		12.60	11.80	-0.80	15.90	13.20	-2.70	60.91	54.24	-6.66	45.44	41.57	-3.87	37.63	32.34	-5.29
Bhittai x NIA-Saarang		10.60	9.80	-0.80	15.18	13.35	-1.83	71.17	49.18	-21.99	45.10	40.78	-4.32	40.34	33.01	-7.33
Bhattai x TD1		11.50	10.60	-0.90	15.73	16.39	0.66	77.27	68.10	-9.17	42.19	40.26	-1.93	37.23	34.44	-2.79
Bhittai x NIA-Sundar		12.20	10.20	-2.00	13.29	13.83	0.54	77.43	62.59	-14.84	40.00	41.84	1.84	39.42	28.81	-10.61
Bhattai x Inqilab		13.10	11.10	-2.00	13.20	13.05	-0.15	49.96	72.63	22.68	45.48	39.85	-5.63	43.21	36.47	-6.74
Bhattai x Khirman		9.00	7.10	-1.90	13.19	12.19	-1.00	81.34	70.30	-11.04	43.10	40.64	-2.46	37.71	34.80	-2.91
Marvi-2000 x NIA-Saarang		10.20	9.30	-0.90	17.02	14.28	0.26	87.74	72.89	-14.85	44.56	42.55	-2.01	38.30	33.26	-5.04
Marvi-2000x TD-1		13.00	11.30	-1.70	13.04	13.12	0.08	67.48	47.03	-20.44	47.50	39.33	-8.17	39.95	33.00	-6.95
Marvi-2000 x NIA-Sundar		12.40	10.90	-1.50	10.57	10.04	-0.53	53.49	49.56	-3.92	43.44	41.15	-2.29	36.30	33.98	-2.32
Marvi-2000 x Inqilab		11.30	10.70	-0.60	12.97	12.71	-0.26	77.88	61.27	-16.60	45.68	40.38	-5.3	38.91	28.55	-10.36
Marvi-2000 x Khirman		13.60	11.80	-1.80	12.93	13.52	0.59	68.01	54.28	-13.72	37.67	35.6	-2.07	37.36	32.81	-4.55
NIA-Saarang x TD-1		10.20	9.00	-1.20	16.00	12.61	-3.39	49.12	59.44	10.33	43.47	38.5	-4.97	39.40	33.42	-5.98
NIA-Saarang x NIA-Sundar		10.90	9.60	-1.30	13.70	12.70	-1.00	61.18	51.21	-9.97	45.24	43.08	-2.16	40.17	35.96	-4.21
NIA-Saarang x Inqilab		9.80	7.80	-2.00	12.87	14.02	1.15	63.95	52.90	-11.05	39.18	37.19	-1.99	30.35	21.11	-9.24
NIA-Saarang x Khirman		9.20	7.90	-1.30	12.27	11.62	-0.65	69.02	49.81	-19.20	38.18	35.54	-2.64	36.04	25.57	-10.47
TD-1 x NIA-Sunder		9.00	10.80	1.80	13.22	11.26	-1.96	65.14	54.41	-10.72	42.43	40.33	-2.1	33.50	27.02	-6.48
TD-1 x Inqilab		9.30	8.70	-0.60	12.81	13.03	0.22	61.96	48.64	-13.32	42.56	45.02	2.46	37.56	43.88	6.32
TD1x Khirman		9.70	7.90	-1.80	12.73	10.37	-2.36	69.83	56.64	-13.18	42.16	39.28	-2.88	26.00	18.65	-7.35
NIA-Sunder x Inqilab		10.40	9.40	-1.00	12.46	11.08	-1.38	67.33	51.33	-16.00	46.19	37	-9.19	38.07	29.17	-8.90
NIA-Sunder x Khirman		11.90	10.90	-1.00	13.10	11.03	-2.07	70.28	50.28	-20.00	45.89	41.37	-4.52	35.99	25.14	-10.85
Inqilab x Khirman		9.00	8.50	-0.50	13.67	11.67	-2.00	54.58	63.52	8.93	39.49	33.54	-5.95	39.74	20.617	-9.12
Mean		10.92	9.86	-1.02	13.69	12.72	-0.97	66.74	58.20	-8.54	43.19	39.45	-3.74	36.77	30.02	-6.74
LSD (5%) (T)		0.31			0.31			3.58			8.69			2.78		
LSD (5%) (G)		1.17			0.38			0.95			2.32			0.74		
LSD (5%) (T x G)		1.66			1.64			5.06			12.29			3.93		
Replications	2	0.57			6.23			87.80			92.60			45.11		
Genotypes	27	15.67 **			8.60**			140.20**			227.10**			181.74**		
Treatment	1	6.54 **			0.14NS			906.7**			8.98NS			1.197NS		
Genotypes x Treatments	27	0.87 NS			1.630*			105.80**			16.70NS			9.04*		
Error	110	1.05			1.03			9.80			57.70			5.90		

Table 5. Mean performance for yield and its associated traits of bread wheat under normal and water stress in F_2 generations.

Parents and F_2 hybrids		Tillers plant^{-1}			Spike length			Grains spike^{-1}			Seed index			Grain yield plant^{-1} (g)		
		Non - stress	Water stress	R.D.*	Non - stress	Water stress	R.D.*	Non - stress	Water stress	R.D.*	Non - stress	Water stress	R.D.*	Non - stress	Water stress	R.D.*
Bhittai		10.70	8.90	-1.80	12.54	11.96	-0.58	85.93	56.4	-29.53	41.23	38.42	-2.81	23.85	17.80	-6.05
Marvi-2000		10.32	9.03	-1.29	15.89	13.90	-1.75	60.5	58.56	-1.94	43.48	40.21	-3.27	34.18	15.27	-18.91
NIA-Saarang		10.41	9.13	-1.28	13.98	14.00	0.02	72.32	56.26	-16.06	40.30	33.90	-6.40	43.99	32.99	-11.00
TD-1		11.18	9.33	-1.85	15.87	13.87	-2.00	61.47	49.4	-12.07	45.77	37.66	-8.11	31.59	18.75	-12.84
NIA-Sunder		11.84	8.73	-3.11	13.67	11.67	-2.00	58.77	51.36	-7.41	43.47	37.34	-6.13	31.22	15.42	-15.80
Inqilab		10.73	8.96	-1.77	15.65	13.92	-1.73	65.57	56.9	-8.67	45.55	35.45	-10.10	26.38	23.49	-2.89
Khirman		10.64	8.83	-1.81	13.08	11.74	-1.34	60.73	57.3	-3.43	42.89	38.22	-4.67	33.21	12.67	-20.54
Bhittai x Marvi-2000		11.75	8.63	-3.12	15.90	13.20	-2.70	54.25	47.66	-6.59	45.57	39.90	-5.67	32.63	21.60	-11.03
Bhittai x NIA-Saarang		10.11	8.43	-1.68	15.18	13.35	-1.83	71.18	63.86	-7.32	44.78	40.50	-4.28	32.22	22.15	-10.07
Bhattai x TD1		11.47	8.66	-2.81	15.73	16.39	0.66	68.10	45.71	-22.39	46.26	42.89	-3.37	33.23	20.14	-13.09
Bhittai x NIA-Sundar		10.19	8.7	-1.49	13.29	13.83	0.54	72.59	47.00	-25.59	45.84	37.90	-7.94	29.42	22.44	-6.98
Bhattai x Inqilab		13.08	10.06	-3.02	13.20	13.05	-0.15	72.64	48.90	-23.74	44.45	35.31	-9.14	43.21	21.19	-22.02
Bhattai x Khirman		8.97	7.40	-1.57	13.19	12.19	-1.00	81.30	56.33	-24.97	45.64	41.76	-3.88	31.71	19.15	-12.56
Marvi-2000 x NIA-Saarang		9.25	10.06	0.81	17.02	14.28	0.26	81.89	61.66	-20.23	48.55	42.51	-6.04	34.30	16.40	-17.90
Marvi-2000x TD-1		13.31	9.53	-3.78	13.04	13.12	0.08	67.04	42.76	-24.28	36.33	44.59	8.26	35.95	21.86	-14.09
Marvi-2000 x NIA-Sundar		12.86	9.86	-3.00	10.57	10.04	-0.53	49.57	47.91	-1.66	46.15	40.76	-5.39	33.30	19.44	-13.86
Marvi-2000 x Inqilab		12.74	9.43	-3.31	12.97	12.71	-0.26	61.28	52.46	-8.82	44.38	39.68	-4.70	28.91	18.61	-10.30
Marvi-2000 x Khirman		11.75	9.16	-2.59	12.93	13.52	0.59	66.29	44.90	-21.39	40.60	35.24	-5.36	30.36	20.07	-10.29
NIA-Saarang x TD-1		11.80	10.03	-1.77	16.00	12.61	-3.39	59.45	48.97	-10.48	38.50	31.10	-7.40	32.40	21.84	-10.56
NIA-Saarang x NIA-Sundar		9.64	10.93	1.29	13.70	12.70	-1.00	67.21	53.48	-13.73	46.08	43.21	-2.87	34.17	19.46	-14.71
NIA-Saarang x Inqilab		8.84	10.20	1.36	12.87	14.02	1.15	62.09	71.53	9.44	42.19	38.20	-3.99	20.35	16.00	-4.35
NIA-Saarang x Khirman		9.89	10.83	0.94	12.27	11.62	-0.65	62.82	44.32	-18.50	40.54	36.82	-3.72	26.04	15.48	-10.56
TD-1 x NIA-Sunder		10.84	8.46	-2.38	13.22	11.26	-1.96	63.42	49.84	-13.58	43.33	40.87	-2.46	23.50	18.87	-4.63
TD-1 x Inqilab		9.70	8.76	-0.94	12.81	13.03	0.22	61.64	46.63	-15.01	45.02	46.94	1.92	23.56	19.62	-3.94
TD1x Khirman		10.00	9.70	-0.30	12.73	10.37	-2.36	59.65	49.02	-10.63	39.28	42.79	3.51	21.78	16.87	-4.91
NIA-Sunder x Inqilab		11.41	9.76	-1.65	12.46	11.08	-1.38	69.34	55.66	-13.68	37.00	35.03	-1.97	28.07	21.01	-7.06
NIA-Sunder x Khirman		10.86	8.36	-2.50	13.10	11.03	-2.07	67.10	43.06	-24.04	45.37	41.97	-3.40	32.99	23.31	-9.68
Inqilab x Khirman		10.51	8.73	-1.78	13.67	11.67	-2.00	56.52	49.50	-7.02	43.54	39.45	-4.09	29.74	21.15	-8.59
Mean		10.89	9.24	-1.65	13.69	12.72	-0.97	65.74	52.05	-13.69	43.29	39.24		30.79	19.75	-11.04
LSD (5%) (T)		0.671			0.31			4.77			3.31			3.09		
LSD (5%) (G)		0.179			0.38			1.27			2.03			0.82		
SD (5%) (T x G)		1.664			1.64			6.01			4.56			4.37		
Replications	2	0.33			0.85			51.79			337.62			124.15		
Genotypes	27	0.85			16.79**			207.39**			128.51**			281.77**		
Treatment	1	18.44**			113.78**			1608.97**			133.69**			6250.43**		
Genotypes x Treatments	27	1.924*			17.08**			284.12**			1436.44**			284.12**		
Error	110	0.34			1.12			17.39			763.13			7.31		

Table 6. Heterotic effect of F_1 hybrids for tillers plant^{-1} and spike length of wheat grown under non-stress and water stress conditions.

F_1 hybrids	Tillers plant^{-1}				Spike length				Grains spike^{-1}			
	Non-stress		Water stress		Non-stress		Water stress		Non-stress		Water stress	
	M.P. (%)	B.P. (%)	M.P. (%)	B.P. (%)	M.P. (%)	B.P. (%)	M.P. (%)	B.P. (%)	M.P. (%)	B.P. (%)	M.P. (%)	B.P. (%)
Bhittai x Marvi-2000	7.09	5.73	13.91	6.77	-6.71	-4.78	10.72	8.69	8.68	5.69	-26.07	-35.68
Bhittai x NIA-Sarang	14.62	10.41	-8.09	-17.32	14.33	8.18	13.98	12.39	-13.8	-7.22	6.56	4.44
Bhittai x TD-1	10.82	6.12	-27.05	-24.49	24.08	21.95	46.23	30.62	-17.17	-20.73	-18.4	-15.7
Bhittai x NIA-Sundar	-6.65	-2.35	15.33	14.73	16.78	12.37	11.7	8.65	8.49	3.47	-6.69	-13.78
Bhittai x Inqilab	16.25	9.21	22.93	13.97	19.98	13.58	11.94	10.72	7.48	4.6	-16.97	-9.44
Bhittai x Khirman	-9.44	-7.48	27.1	10.88	23.53	11.4	11.58	6.46	-9.57	-5.57	11.18	9.17
Marvi-2000 x NIA-Sarang	-25.57	-35.96	22.24	16.8	-7.52	-10.53	10.22	9.89	-8.09	1.52	-10.91	-7.05
Marvi-2000x TD-1	14.66	10.29	11.21	7.01	10.65	3.77	6.39	2.6	2.08	0.63	-11.32	-8.42
Marvi-2000 x NIA-Sundar	-10.46	-17.97	15.67	8.07	17.22	12.18	-8.33	-6.52	6.53	3.23	-13.39	-11.8
Marvi-2000 x Inqilab	15.34	8.79	17.71	15.96	-0.36	9.75	9.67	8.84	2.92	1.54	5.17	3.73
Marvi-2000 x Khirman	20.61	14.24	-9.51	-6.73	-11.91	-4.86	24.22	11.97	11.37	7.38	-8.41	-12.17
NIA-Sarang x TD-1	17.06	11.68	-5.66	-13	-9.09	-1.96	5.57	3.5	-9.79	-12.86	6.7	3.28
NIA-Sarang x NIA-Sundar	-14.96	-17.09	23.84	12.84	6.92	4	9.72	8.21	-5.74	-2.6	8.5	5.79
NIA-Sarang x Inqilab	8.48	3.38	-10.55	-18.54	11.4	7.06	24.37	20.05	10.11	6.38	-6.27	-3.67
NIA-Sarang x Khirman	19.41	12	31.69	17.22	14.64	6.96	11.35	10.32	-0.73	-4.42	4.44	2.44
TD-1 x NIA-Sunder	-25.8	-12.09	16.15	5.58	12.68	8.93	27.41	14.54	9.03	6.44	46.31	39.43
TD-1 x Inqilab	23.14	14.47	12.17	4.87	-9.34	-12.58	23.04	19	7.21	4.04	15.49	11.01
TD1x Khirman	26.71	13.59	16.32	5.06	21.35	12.99	-6.66	-7.09	-20.15	-17.44	-14.86	-18.6
NIA-Sunder x Inqilab	-16.71	-7.16	-4.98-	-11.31	16.04	6.78	40.09	25.42	11.7	9.05	13.87	10.25
NIA-Sunder x Khirman	-18.37	-13.78	15.77	7.69	-16.03	-19.73	7.35	10.59	6.74	3.6	15.39	11.72
Inqilab x Khirman	21.21	12.34	-14.69	-9.33	18.22	12.62	19.22	15.29	-5.25	-13.75	-10.44	-14.62

Table 7. Inbreeding depression of F_2 progenies for yield traits of wheat genotypes grown under water stress conditions.

F_2 hybrids	Tillers plant^{-1}		Spike length		Grains spike^{-1}		Seed index		Grain yield plant^{-1}	
	NS	WS	NS	WS	NS	WS	NS	WS	NS	WS
Bhittai x Marvi-2000	-17.16	-18.42	17.48	30.87	2.91	-26.42	42.41	8.80	-0.63	-34.57
Bhittai x NIA-Sarang	-2.07	-26.49	34.42	29.68	-10.5	-30.11	52.56	15.31	9.78	-35.70
Bhittai x TD1	-18.35	-14.97	-1.20	41.88	-32.87	-42.02	50.54	37.81	14.43	-30.11
Bhittai x NIA-Sundar	-5.81	-33.48	32.56	51.48	51.78	-28.18	57.67	12.63	21.95	-45.88
Bhittai x Inqilab	-16.66	12.23	27.17	41.99	-38.17	6.40	52.57	70.32	19.01	-39.11
Bhittai x Khirman	18.17	-17.38	36.17	28.36	-30.71	-47.94	34.32	35.40	3.65	-42.42
Marvi-2000 x NIA-Sarang	6.30	9.18	-1.05	42.35	-19.81	-49.43	51.14	36.01	-0.31	-35.87
Marvi-2000x TD-1	-26.91	5.80	14.05	24.99	-13.97	-31.88	43.49	-0.23	-8.68	-19.11
Marvi-2000 x NIA-Sundar	-23.01	6.01	58.03	18.59	-15.26	-22.73	53.23	3.66	0.70	-11.17
Marvi-2000 x Inqilab	-26.47	14.71	26.90	43.46	-21.80	5.48	6.50	49.20	2.42	14.26
Marvi-2000 x Khirman	-18.29	-2.65	25.67	55.59	-21.55	-35.41	16.72	12.94	11.66	-31.19
NIA-Sarang x TD-1	-16.15	-10.60	29.52	42.27	-24.46	-37.56	40.88	52.95	-5.73	-33.43
NIA-Sarang x NIA-Sundar	1.31	7.53	32.28	14.16	-27.23	-46.45	23.65	30.55	9.82	-41.79
NIA-Sarang x Inqilab	9.64	14.00	-8.03	55.90	-14.64	16.07	48.28	78.34	2.82	-55.49
NIA-Sarang x Khirman	0.13	49.97	23.89	31.57	15.39	-11.56	51.77	11.00	35.03	-26.65
TD-1 x NIA-Sunder	-12.98	-41.60	16.83	25.69	-27.82	-53.39	42.01	4.71	4.26	-42.82
TD-1 x Inqilab	16.41	-29.07	11.50	75.92	-19.13	-27.08	14.49	-1.35	10.94	-42.25
TD1x Khirman	-7.00	4.52	12.63	44.95	-21.81	-37.29	6.38	28.00	14.48	-43.69
NIA-Sunder x Inqilab	15.74	-1.51	15.89	40.45	-29.29	6.53	11.02	61.61	-5.63	-16.41
NIA-Sunder x Khirman	-2.39	-7.41	20.84	48.38	-17.04	-10.06	26.91	-5.08	4.98	42.16
Inqilab x Khirman	3.39	-30.43	14.70	63.93	-23.80	13.47	25.47	12.97	9.64	31.53

et al. (2023) obtained similar results, reporting that some genotypes showed lesser inbreeding depression and developed transgressive segregants in advanced generations.

Grains per spike

Genotypes, treatments, and their interaction proved highly significant in both the F_1 and F_2 generations (Tables 4 and 5). The average mean of the genotypes was higher in the non-stressed than in the stressed conditions (Tables 4 and 5). Regarding the estimation of heterotic effects among F_1 hybrids evaluated under non-stressed settings (Table 6), the response of F_1 hybrids as per data collected for the said trait indicated that NIA-Sunder x Inqilab recorded the highest relative and better parent heterosis (11.70 and 9.05, respectively). The study found that the topmost mid-parent or relative and better parent heterosis was in TD-1 x NIA-Sunder (46.31 and 39.34, respectively) upon noting heterosis for the trait number of grains spike^{-1} under drought stress imposed during the tillering stage. The minimum inbreeding depression among F_{2s} under non-stressed settings for the number of grains per spike, as observed, resulted in the cross Bhittai x Marvi 2000 (2.91). The minimum inbreeding depression among F_{2s} under stressed conditions for the said quality was evident in the cross Marvi-2000 x Inqilab (15.48) (Table 7). Previous researchers like Jaydev *et al.* (2017) found heterosis in 50% of the crosses in their research for the trait grain spike^{-1}. Furthermore, they reported that an increase in grain spike^{-1} would be due to the rise in the spike length. However, Aditi *et al.* (2022) conducted inbreeding depression research in advanced generations like F_2 and F_3 and found significant depression in the populations.

Seed index

In F_1 generations, only genotypes showed highly significant results, whereas in F_2 generations, genotypes, treatments, and their interaction displayed highly noteworthy outcomes (Tables 4 and 5). The average mean of the genotypes was higher in non-stressed conditions than in the stressed conditions (Tables 4 and 5). According to the estimation of heterotic effects among F_1 hybrids evaluated under non-stressed settings (Table 8), the response of F_1 hybrids from data collected for the said trait implied that Bhittai x Inqilab recorded the highest relative and better parent heterosis (16.73 and 12.07, respectively). When recording heterosis for the trait seed index under drought stress imposed during the tillering stage, it displayed that the mid- and better parent heterosis was in Inqilab x Khirman (17.56 and 12.90, respectively). Table 5 shows the minimum inbreeding depression among F_{2s} under non-stressed conditions for seed index, which was evident in the cross TD-1 x Khirman (6.38). The minimum inbreeding depression among F_{2s} under stressed settings for seed index, as observed, resulted in the cross Marvi-2000 x NIA-Sunder (5.48). Ranjana *et al.* (2018) obtained significant heterosis over the midparent and commercial checks for all traits, including seed index in the desired direction. However, Anita *et al.* (2023) reported notable differences in the mean performance for the yield-associated traits and found desirable heterobeltiosis, selected as better transgressive segregants in succeeding generations.

Grain yield per plant

In the F_1 generation, the genotypes provided highly significant results, and interaction with treatment showed significance. Likewise, in the F_2 generation, genotypes, treatments, and their interaction were immensely remarkable (Tables 4 and 5). The average mean of the genotypes was better in the non-stressed conditions than in the stressed conditions (Tables 4 and 5). According to the estimation of heterotic effects (Table 8) among F_1 hybrids evaluated under non-stressed settings, the response of F_1 hybrids, as per data collected for the said trait, signified that NIA-Sarang x NIA-Sunder recorded the highest relative and better parent heterosis (24.11 and 15.74, respectively). When gathering heterosis for the trait of grain yield plant^{-1} under drought stress, the researchers found that the maximum mid-parent or relative heterosis and better parent

Table 8. Heterotic effect of F_1 hybrids for grains spike^{-1} and seed index of wheat grown under non-stress and water stress conditions.

F_1 hybrids	Seed index				Grain yield plant^{-1}			
	Non-stress		Water stress		Non-stress		Water stress	
	M.P. (%)	B.P. (%)	M.P. (%)	B.P. (%)	M.P. (%)	B.P. (%)	M.P. (%)	B.P. (%)
Bhittai x Marvi-2000	5.07	3.9	-4.22	-1.18	8.52	3.28	-6.91	-10.18
Bhittai x NIA-Sarang	-1.09	-0.45	-4.66	-1.96	6.96	4.29	26.52	17.64
Bhittai x TD-1	-1.96	-2.83	-9.48	-12.54	7.46	4.51	25.51	22.97
Bhittai x NIA-Sundar	5.32	3.06	-14.59	-21.88	9.24	7.12	-7.85	-3.78
Bhittai x Inqilab	16.73	12.07	10.54	8.88	-2.13	-8.13	5.88	7.29
Bhittai x Khirman	-1.31	-0.15	3.5	1.99	22.74	10.94	7.51	2.5
Marvi-2000 x NIA-Sarang	6.76	4.02	-5.02	-2.41	-29.87	-37.29	-4.68	-11.5
Marvi-2000x TD-1	-1.47	-0.31	-9.82	-14.72	-7.54	-3.25	-21.74	-21.74
Marvi-2000 x NIA-Sundar	-5.52	-7.07	4.61	3.42	-20.62	-12.32	16.31	7.09
Marvi-2000 x Inqilab	3.94	1.68	-6.38	-10.72	17.38	13.81	-12.03	-8.27
Marvi-2000 x Khirman	15.18	11.86	6.23	4.57	15.61	9.63	16.6	8.63
NIA-Sarang x TD-1	-9.85	-5.25	-11.92	-6.65	-5.52	-2.72	19.92	10.98
NIA-Sarang x NIA-Sundar	-6.76	-10.25	7.7	5.21	24.11	15.74	14.32	16.59
NIA-Sarang x Inqilab	3.73	1.13	-3.45	2.2	-2.2	-4.48	28.59	19.78
NIA-Sarang x Khirman	-3.74	-5.63	-8.83	-13.24	14.89	10.09	8.49	3.92
TD-1 x NIA-Sunder	-2.49	-4.53	-5.36	-4.73	11.4	7.12	6.32	4.32
TD-1 x Inqilab	4.5	2.98	5.56	3.93	19.33	16.3	-11.2	-16.58
TD1x Khirman	3.11	1.86	9.45	3.8	21.5	14.68	14.02	10.37
NIA-Sunder x Inqilab	11.5	8.39	7.14	4.78	-18.42	-18.42	-11.28	-4.44
NIA-Sunder x Khirman	2.98	0.46	3.84	2.01	23.32	11.78	6.94	3.92
Inqilab x Khirman	6.97	4.94	17.56	12.9	20.49	12.02	-11.37	-19.73

heterosis was in NIA-Sarang x Inqilab (28.59 and 19.78, respectively). The minimum inbreeding depression among F_{2s} under non-stressed settings for grain yield, as observed, resulted in the cross Marvi-2000 x NIA-Sunder (0.70). The observed minimum inbreeding depression (Table 5) among F_{2s} under stressed conditions for grain yield per plant was evident in the cross Marvi x Inqilab (14.26). Previous scientists like Panhwar *et al.* (2021) and Satnam *et al.* (2023) shared results that all the parents and hybrids were highly significant for all the parameters studied at the < 0.01 level. The F_1 hybrids Benazir 2013 x TD-1, TD-1 x Benazir -2013, TD-1 x Hamal, and Kiran-95 x Benazir-2013 showed better response in mid-parent heterosis and heterobeltiosis for most traits, except plant height. Based on current findings, one can conclude that these cross combinations may be favorable in the improvement of bread wheat for yield enhancement. Research with the same objectives also came from Fareed *et al.* (2024), as per their study findings.

CONCLUSIONS

Results revealed that genotypes were highly significant for all the studied traits in both generations, whereas treatments and their interaction were vastly substantial in the F_2 generation. Higher mean values were noteworthy for all the scrutinized qualities in non-stressed environments under both generations. As for the heterosis in grain yield plant^{-1}, the cross Bhittai x Inqilab gave the highest mid-parent heterosis, while NIA-Sunder x Khirman displayed the utmost better parent heterosis. For the inbreeding depression, NIA-Sunder and Khirman showed superiority in the F_2 generation and produced higher grain yield plant^{-1}. The varieties like TD-1, Marvi-2000, and NIA-Sunder exhibited better performance. Meanwhile, the crosses, such as Bhittai x TD-1, Inqilab x Khirman, Bhittai x Marvi-2000, Bhittai x Khirman, NIA-Sarang x NIA-Sunder, and Bhittai x TD-1 demonstrated high heterosis and low inbreeding depression; thus, they should be desirable for use for higher yield in wheat.

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