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Estimation of combining ability and heterosis under normal and heat stress environments in hybrids of bread wheat (*Triticum aestivum* L. em. Thell)

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Abstract
The frequency, duration, and severity of heat is aggravated by climate change. Under heat stress, the growth of the plant plays an important role in wheat. This study examines heterosis and combining ability under timely sown and heat stress of growth characters in wheat using line x tester mating design. Field experiments were conducted with eleven spring (8-line, 3-tester) wheat genotypes. The study unveiled diverse GCA effects for spike length, highlighting the positive impact of UP 262 in timely sown and UP 2572 in heat stress conditions. SCA effects varied across crosses, with VL 967 X QLD 91 showing strong positive SCA in timely sown environment and UP 2927 X QLD 91 in heat stress environment. For peduncle length, diverse GCA effects within parental lines were observed, including negative impacts of genotypes like PBW 725 in timely sown and VL 967 Under heat stress environment. Similarly, SCA effects across crosses varied, encompassing negative effects in cases like AGRA LOCAL X HS 490 Under timely sown and UP 3069 X HS 490 under heat stress. The study also unveiled significant positive relative heterosis and heterobeltiosis for cross UP 262 X QLD 91 under timely sown and heat stress, indicating potential for spike length improvement. Standard heterosis analyses highlighted the importance of AGRA LOCAL X DBW 222 in timely sown and UP 2572 X HS 490 in heat stress for enhancing spike length. Notably, significant negative relative heterosis, heterobeltiosis and standard heterosis was observed in in timely sown for cross PBW 725 X QLD 91 and for late sown highest relative heterosis and heterobeltiosis reported UP 2572 X QLD 91 and UP 2572 X DBW 222 for peduncle length. These findings contribute to our understanding of wheat enhancement and offer valuable guidance for future breeding endeavors.

Keywords: Combining ability, heat stress, wheat, heterosis, line x tester

1. Introduction

Wheat (*Triticum aestivum* L. em. Thell) is the most widely grown cereal crop throughout the world ranging over multitude of optimum and stressful conditions *viz.*, temperate irrigated and dry environments to high rain-fall areas (Acevedo *et al*. 2002) [27]. It is imperative to recognize that heat stress stands as one of the most prevalent environmental constraints impeding the growth and physiology of wheat. Instances of heat stress, either in isolation or in conjunction with other repercussions, are commonplace throughout various stages of plant development (Wardlaw, 2002) [26]. In field conditions, heat stress often coincides with drought stress. Some investigations have delved into the ramifications of the combined effects of drought and heat stress, postulating that such a fusion could yield a substantially greater detrimental impact on crop growth and productivity compared to the individual stressors being considered in isolation (Savin and Nicolas, 1996) [19]. Evidently, heat stress leads to a 10 - 15% decline in yield owing to the reduction in single kernel weight (Wardlaw and Wrigley, 1994) [25]. The mere reliance on mean performance, adaptation, and genetic diversity for parent selection does not necessarily yield favourable outcomes. This is attributed to the distinct capabilities of parents, which are influenced by intricate gene interactions. Judging parental potential solely based on mean performance is inadequate (Allard, 1960) [1]. In the context of the wheat breeding program, parents excelling in hybrid performance hold significant importance and can be used in breeding programs for selecting good progenies in segregating generations. Vital insights into combining ability and the relative extent of genetic variance for economically vital traits are essential to unlock the potential of existing gene interactions within the population. Wheat breeders actively seek the most fitting breeding materials and effective ways to transparently convey findings from experimental scientific investigations. Notably, the general (GCA) and specific (SCA) combining abilities play a pivotal role in genotype evaluation and population enhancement.

GCA signifies the average performance of a genotype in hybrid combinations, encompassing multiple genotypes. Conversely, SCA represents the average performance of a specific cross combination, manifesting as a deviation from the population mean. The estimation of combining abilities proves instrumental in assessing the utility of parents in hybrid combinations and in crafting superior hybrids adaptable to diverse environments (Sprague and Tatum, 1942) [23].

Table 1: List of genotypes (with codes) and crosses used for evaluation.

Sl.	code	Genotype	Sl.	Genotype	Sl.	Genotype	Sl.	Genotype
1	L1	UP 262	12	UP 262 X DBW 222	23	UP 3069 X QLD 91	34	Agra Local X HS 490
2	L2	UP 2572	13	UP 2572 X DBW 222	24	PBW 725 X QLD 91	35	PBW 813 X HS 490
3	L3	UP 2927	14	UP 2927 X DBW 222	25	VL 967 X QLD 91		
4	L4	UP 3069	15	UP 3069 X DBW 222	26	Agra Local X QLD 91		
5	L5	PBW 725	16	PBW 725 X DBW 222	27	PBW 813 X QLD 91		
6	L6	VL 967	17	VL 967 X DBW 222	28	UP 262 X HS 490		
7	L7	Agra Local	18	Agra Local X DBW 222	29	UP 2572 X HS 490		
8	L8	PBW 813	19	PBW 813 X DBW 222	30	UP 2927 X HS 490		
9	T1	DBW 222	20	UP 262 X QLD 91	31	UP 3069 X HS 490		
10	T2	QLD91	21	UP 2572 X QLD 91	32	PBW 725 X HS 490		
11	T3	HS490	22	UP 2927 X QLD 91	33	VL 967 X HS 490		

2. Materials and Methods

Eight varieties of bread wheat (*Triticum aestivum* L. em. Thell.), namely, UP 262, UP 2572, UP 2927, UP 3069, PBW 725, VL 967, Agra Local, PBW 813, was used as line which were then crossed with 3 testers namely DBW 222, QLD 91, HS 490 in Line x Tester fashion. The 11 parents and their resulting 24 F_1's were grown in randomized block design with three replications under normal (timely sown–11th November) and heat stress (heat stress –30th December, delayed sowing was practiced to expose the crop to terminal heat stress) conditions at Norman E. Borlaug Crop Research Centre, G. B. Pant University of Agriculture and Technology, Pantnagar, India during the *Rabi* season of 2022-23. The list of parents and crosses evaluated using randomised complete block design is given in Table 1. Plots of parents and F_1 have consisted of two rows of one-meter length. 10 plants in parents and F_1's were selected randomly for recording observations under each environment separately. The mean of each plot was used for statistical analysis to draw conclusive inferences from data.

Analysis of variance for all the characters in each environment was done as suggested by Panse and Sukhatme (1967) [16]. The relative heterosis, heterobeltiosis and standard heterosis were estimated as deviation of F_1 value from the mid-parent and the better-parent values as suggested by Matzinger *et al.* (1962) [14] and Fonseca and Patterson (1968) [6], respectively. The following formulae were used for the estimation of heterosis and heterobeltiosis in each environment for all the characters.

(a) Relative heterosis = $\frac{\overline{F_1}-\overline{MP}}{\overline{MP}} \times 100$

(b) Heterobeltiosis = $\frac{\overline{F_1}-\overline{BP}}{\overline{BP}} \times 100$

(c) Standard heterosis = $\frac{\overline{F_1}-\overline{CP}}{\overline{CP}} \times 100$

Where,

$\bar{F}_1$ = Mean performance of F_1 hybrid, $\bar{P}_1$ = Mean performance of parent one, $\bar{P}_2$ = Mean performance of parent two, $\overline{BP}$ = Mean performance of better parent, $\overline{CP}$ = Mean performance of check parent, $\overline{MP}$ = Mean mid-parental value *i.e.* $(P_1+P_2)/2$

Table 2: Analysis of Variance for Spike length and Peduncle length of genotypes under study across the site

Source of variation		Spike Length	Peduncle Length
	Df	Mean sum of square	
Site	1	48.56**	1830.69**
Replication(site)	4	0.24	1.46
Genotypes	23	1.58**	31.38**
Line	7	3.88**	54.88**
Tester	2	1.20**	126.26**
Line:tester	14	0.49**	6.07**
Site:genotypes	23	1.79**	12.08**
Site:line	7	1.91**	15.03**
Site:tester	2	4.4**	25.95**
Site:line:tester	14	1.36**	8.62**
Error	92	0.15	0.89
*,** Significance at 5% and 1% probability levels			

The differences in the magnitudes of relative heterosis, heterosis over male parents, and heterosis over female parents were tested using the method proposed by Panse and Sukhatme (1961) [15]. Further 't' value is calculated to test the significance of deviation of F1 from better parent and Standard Check as proposed by Arunachalam (1974) [2]. The calculated 't' value compared with the table't' value at error degrees of freedom.

2.1 ANOVA for combining ability analysis

The variation among the hybrids further partitioned into genetic components attributable to general combining ability (GCA) and specific combining ability (SCA) following the method suggested by Kempthorne (1957) [9]. For this purpose, pooled data over replications for crosses was compiled in the form of a Two-way table for each character. From this table, Sum of squares due to lines, Sum of squares due to testers, and Sum of squares due to line × tester computed.

3. Results and Discussion

3.1 Analysis of variance

All genotypes that were used in the research showed significant differences with respect to the traits under study (Table 2 and 3) which reflected significance among lines, testers and Line: tester, hence calculation of general and specific combining abilities of genotypes in the population is very advantageous.

Table 3: Analysis of variance for spike and peduncle length of genotypes under study in timely sown and heat stress environments

Source of variation	Character	Peduncle length		Spike length	
	Df	Timely sown	Heat stress	Timely sown	Heat stress
Replication	2	1.904	1.03	0.063	0.43
Genotypes	23	24.76**	18.70**	1.95**	1.42**
Line	7	29.09*	40.83**	3.50*	2.28**
Tester	2	127.21**	25.01**	3.93*	1.68**
Line:tester	14	7.96**	6.73**	0.896**	0.95**
Error	46	0.63	1.14	0.15	0.15
*,** Significance at 5% and 1% probability levels					

Table 4: Estimated genetic components

	Spike Length		Peduncle Length	
	Timely sown	Heat stress	Timely sown	Heat stress
Mean	12.6	11.44	38.37	31.28
Range	10.66-14.33	9.66-13	31.67-43.33	27-40
CV	3.11	3.48	2.08	3.43
GCV	6.148	5.678	7.39	7.742
PCV	6.887	6.661	7.677	8.466
Genetic Advance value % means	11.305	9.97	14.654	14.583
Heritability	79.684	72.654	92.665	83.616
σ^2 GCA	0.216	0.1106	4.6979	1.9255
σ^2 SCA	0.2476	0.2668	2.4434	1.8616
σ^2 GCA/σ^2 SCA	0.87	0.41	1.92	1.03

It can be seen that all testers and lines that used in the research had significant differences in terms of the studied traits (Table 2 and 3). A box plot representing line mean for spike length and peduncle length based on F1's performance across site is presented in figure 1. Maximum spike length was under timely sown 13.83 cm of AGRA LOCAL X DBW 222 and 12.50 cm of UP 2572 and HS 490 under heat stress, while minimum value for spike length obtained under timely sown was 11.00 cm for VL 967 X HS 490 and 11.17 cm for PBW 813 X HS 490 under heat stress. Maximum Peduncle length obtained from UP 3069 X HS 490 under timely sown (42.19 cm) and from AGRA LOCAL X HS 490 under heat stress (39.33 cm), while minimum values was obtained from the combination of PBW 725 X QLD 91 (31.83 cm) under timely sown and from PBW 813 X DBW 222 (28.00 cm) under heat stress.

3.2 Estimation of combining ability

3.2.1 Spike length

The GCA effect among parental lines was ranged from -0.88 to 0.893 and -0.89 to 0.72 in timely sown and heat stress respectively (Table 5). Significant positive GCA effect was shown by five parents in timely sown and by 3 parents in heat stress conditions. In timely sown highest significant GCA effect was exhibited by UP 262 (0.893) while highest negative GCA effect showed by parent PBW 813 (-0.88) (Table 5). While in heat stress condition, UP 2572 (0.72) exhibited highest significant positive GCA effect while highest negative significant GCA effect was observed for UP 3069 (-0.89).

The SCA effect among crosses varied from -1.05 to 0.745 and -0.99 to 1.01 in timely sown and heat stress respectively (Table 6). Significant positive SCA effect exhibited by seven crosses in timely sown and eight crosses in heat stress. In timely sown condition highest significant positive SCA effect was exhibited by crosses VL 967 X QLD 91 (0.745) followed by UP 2927 X HS 490 (0.673) whereas highest SCA effect but in negative direction showed by crosses VL 967 X HS 490 (-1.05) followed by UP 3069 X QLD 91 (-0.59). In Heat stress condition highest positive SCA effect exhibited by crosses UP 2927 X QLD 91 (1.01) followed by AGRA LOCAL X HS 490 (0.66) whereas highest SCA effect in negative direction showed by crosses AGRA LOCAL X QLD 91 (-0.99) followed by UP 3069 X HS 490 and UP 2927 X HS 490 jointly (-0.51).

Lines UP 262 in timely sown and UP 2572 in heat stress heat stress identified as good general combiners with high GCA effect in positive direction for long spike length (Table 5). Whereas for increasing length of spike, crosses VL 967 X QLD 91 in timely sown and UP 2927 X QLD 91 in heat stress identified as good specific combiners. Similar significant results for spike length have been reported by Parveen *et al*. (2018) [17]; Soughi *et al*. (2019) [22] Tomar *et al*. (2020) [24].

Our investigation delved into the genetic potential of parental lines and their crosses under different conditions. The study uncovered a spectrum of general combining ability (GCA) effects among parental lines, with varying positive and negative effects observed in different settings. Specifically, UP 262 emerged as a noteworthy contributor to positive GCA effects, particularly in timely sown and UP 2572 in heat stress conditions. Conversely, PBW 813 exhibited the most pronounced negative GCA effects in timely sown and UP 3069 under heat stress environment. Additionally, specific combining ability (SCA) effects manifested diversely among crosses, with a multitude of positive and negative effects detected. The cross VL 967 X QLD 91 exhibited the highest positive SCA effect in timely sown conditions, while UP 2927 X QLD 91 showcased strong positive SCA effects in heat stress environment.

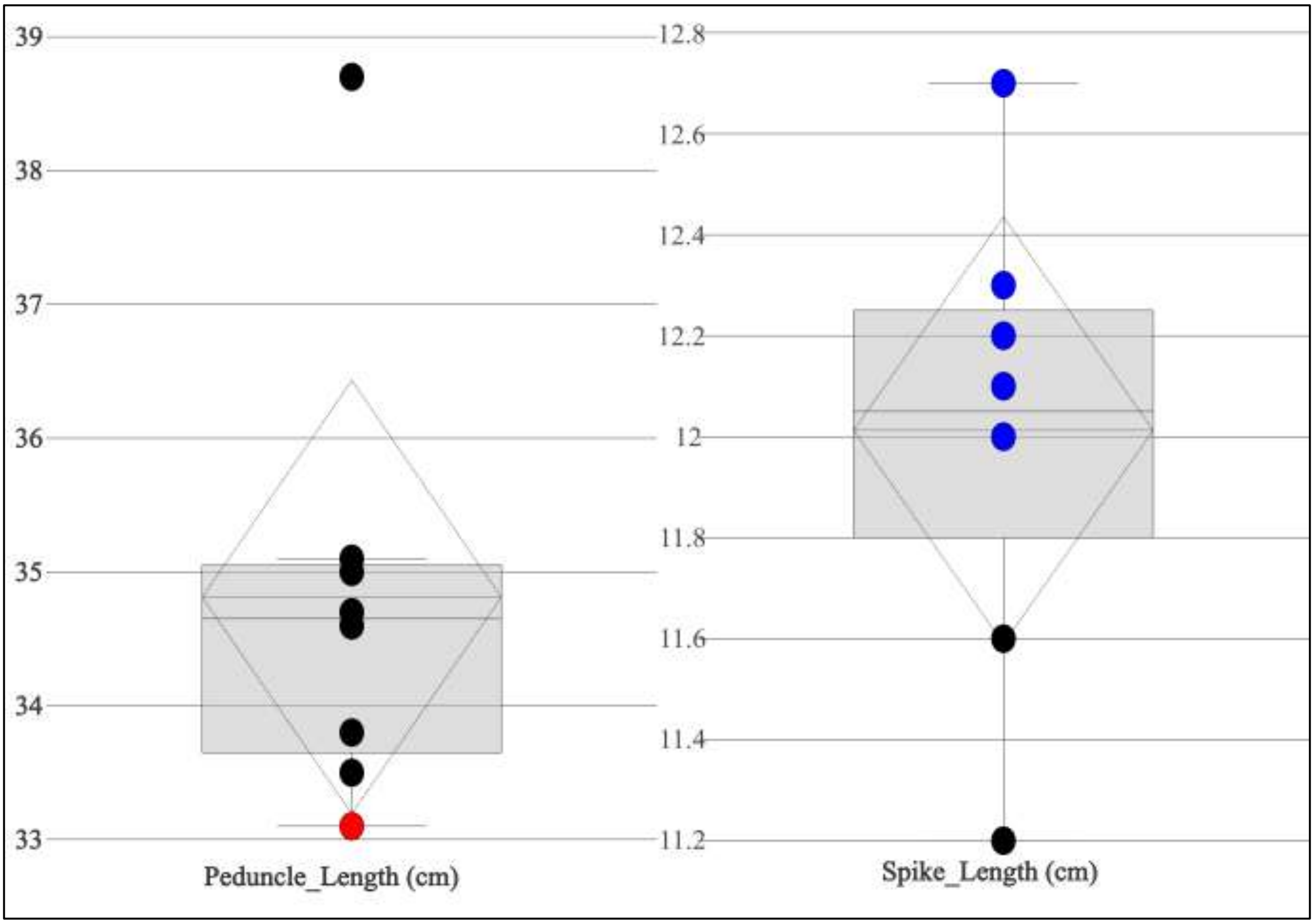

Fig 1: Box plot of lines used in experiment for Spike length and Peduncle length.

Table 5: General combining ability (GCA) effects of Lines and testers for the traits under study.

	GCA Spike Length		**GCA peduncle length**	
Lines	**Timely sown**	**Heat stress**	**Timely sown**	**Heat stress**
1	0.893**	0.53**	0.827**	-1.22**
2	-0.155	0.72**	0.538*	-0.09
3	0.454**	-0.06	-1.220**	0.93*
4	-0.824**	-0.89**	1.424**	-0.94*
5	0.324*	-0.33*	-2.772**	-0.69
6	-0.155	0.11	-1.005**	-1.54**
7	0.343*	-0.23	2.976**	4.88**
8	-0.880**	0.11	-0.767**	-1.36**
S.E.	0.1304	0.13	0.266	0.35
Testers	**Timely sown**	**Heat stress**	**Timely sown**	**Heat stress**
9	0.413**	-0.06	-0.709**	-0.80**
10	-0.017	-0.24**	-1.864**	-0.351
11	-0.396**	0.28**	2.573**	1.15**
S.E.	0.0799	0.081	0.1629	0.21
*,** Significance at 5% and 1% probability levels				

3.2.2 Peduncle length

The GCA effects among parental lines for peduncle length ranged from -2.77 to 2.97 and -1.54 to 4.88 in timely sown and heat stress environments respectively (Table 5). Five out of twelve parents showed significant positive GCA effect in timely sown and three parent in heat stress. In timely sown highest significant positive GCA effect exhibited by AGRA LOCAL (2.97) followed by UP 3069 (1.42) while highest significant negative GCA effect showed by parent PBW 725 (-2.77) followed by UP 2927 (-1.22). In heat stress condition parent AGRA LOCAL (4.88) followed by UP 2927 (0.93) showed highest positive GCA effect while, highest negative GCA effect was shown by parent VL 967 (-1.54) followed by PBW 813 (-1.36).

The SCA effect among crosses varied from -3.06 to 2.33 and -2.36 to 2.06 in timely sown and heat stress respectively (Table 6). Significant positive SCA effect exhibited by five crosses in timely sown and four in heat stress. Under timely sown environment significant positive SCA effect found in crosses PBW 725 X HS 490 (2.33) followed by AGRA LOCAL X QLD 91 (1.89). Whereas highest significant SCA effect in negative direction showed by crosses AGRA LOCAL X HS 490 (-3.06) followed by VL 967 X DBW 222 (-2.16). In Heat stress condition (heat stress) highest positive significant SCA effect was exhibited by crosses AGRA LOCAL X HS 490 (2.06) followed jointly by VL 967 X DBW 222 (1.54) and UP 3069 QLD 91 (1.54) however highest negative significant SCA effect showed by UP 3069 X HS 490 (-2.36) followed by AGRA LOCAL X DBW 222 (-2.28). Short peduncles are involved in better stem reserve remobilization which has been considered as an adaptive trait in wheat for heat stress condition and are also responsible for shorter plants that are lodging resistant. Lines, PBW 725 in timely sown and heat stress is identified as good general combiners for short peduncle length (Table 5) while in heat stress good general combiner is VL 967. Crosses UP 3069 X HS 490 in heat stress environment and AGRA LOCAL X HS 490 in timely sown identified as best specific combinations for short peduncle length with highest SCA effect in negative direction (Table 6). These findings are in accordance with the earlier observation of Farshadfar and Hasheminasab (2013) [5], Desale *et al*. (2014) [3], Tabassum *et al*. (2017) [28].

Table 6: Specific combining abilities (SCA) effects for the characters under study

	SCA Spike Length		**SCA Peduncle Length**	
Crosses	**Timely sown**	**Heat stress**	**Timely sown**	**Heat stress**
L1 X T1	-0.408	0.502*	0.68	-0.31
L1 X T2	0.19	-0.41	-0.341	0.32
L1 X T3	0.218	-0.1	-0.339	-0.02
L2 X T1	0.148	0.22	0.793	0.63
L2 X T2	-0.097	-0.27	-0.304	0.35
L2 X T3	-0.052	0.04	-0.489	-0.99
L3 X T1	-0.302	-0.501*	-0.561	0.61
L3 X T2	-0.371	1.01**	0.182	-1
L3 X T3	0.673**	-0.513*	0.379	0.38
L4 X T1	-0.024	0.16	1.073*	0.81
L4 X T2	-0.594*	0.34	-0.884	1.54*
L4 X T3	0.618**	-0.513*	-0.189	-2.36**
L5 X T1	-0.228	-0.06	-0.425	0.07
L5 X T2	-0.075	0.12	-1.90**	-1.04
L5 X T3	0.303	-0.07	2.334**	0.97
L6 X T1	0.307	-0.498*	-2.16**	1.54*
L6 X T2	0.745**	0.17	1.78**	-0.02
L6 X T3	-1.051**	0.32	0.387	-1.52*
L7 X T1	0.475*	0.32	1.172*	-2.28**
L7 X T2	0.074	-0.99**	1.892**	0.22
L7 X T3	-0.549*	0.66**	-3.06**	2.06**
L8 X T1	0.031	-0.17	-0.568	-1.09
L8 X T2	0.128	0.009	-0.414	-0.38
L8 X T3	-0.16	0.15	0.982*	1.46*
S.E.	0.2259	0.23	0.4607	0.61
*,** Significance at 5% and 1% probability levels				

Our study explored the genetic impacts of crosses on peduncle length under diverse growth conditions. The results unveiled a wide range of general combining ability (GCA) effects within parental lines, manifesting uniquely in various scenarios including timely sown and heat stress environments.

3.3 Estimation of heterosis

3.3.1 Spike length

Relative heterosis for spike length (Table 7) ranged from -10.07 to 22.42 in timely sown and -10.14 to 24.17 in heat stress environments. eighteen and seventeen out of twenty-four crosses showed significant heterosis over mid parental value for this trait in timely sown and heat stress environments respectively. Highest significant mid parental positive heterosis was found in crosses UP 262 X DBW 222 (22.42) followed by UP 262 X QLD 91 (18.84) in timely sown and in cross UP 262 X DBW 222 (24.17) followed by UP 262 X HS 490 (18.70) in heat stress environment. Highest significant mid parental negative heterosis was found in crosses UP 3069 X QLD 91 (-10.07) followed by PBW 813 X HS 490 (-5.63) in timely sown, and in cross UP 3069 X HS 490 (-10.14) followed by UP 3069 X DBW 222 (-6.98) in heat stress. Heterobeltiosis for spike length (Table 7) ranged from -10.67 to 18.54 and -11.43 to 14.62 in timely sown and heat stress environments respectively. Thirteen and sixteen out of twenty-four crosses showed significant heterobeltiosis in timely sown and heat stress environment respectively. The cross UP 262 X DBW 222 (18.54) showed highest significant positive heterosis followed by AGRA LOCAL X DBW 222 (16.90) in timely sown and cross UP 262 X DBW 222 (14.62) followed by UP 2572 X DBW 222 (12.12) in heat stress environments. Highest significant negative heterosis was found in crosses UP 3069 X QLD 91 (-10.67) followed by VL 967 X HS 490 (-8.33) in timely sown and in cross UP 3069 X HS 490 (-11.43) followed by UP 2927 X DBW 222 (-10.99) in heat stress. Standard heterosis over check PBW 725 (Table 7) for spike length ranged from -8.33 to 15.28 and -7.69 to 15.38 in timely sown and in heat stress environment respectively. Seventeen and eleven out of twenty-four crosses showed significant heterosis in timely sown and heat stress environment respectively. Highest significant positive heterosis was shown by the cross AGRA LOCAL X DBW 222 (15.28) followed by UP 262 X QLD 91 (13.89) in timely sown condition and the cross UP 2572 X HS 490 (15.38) followed by UP 262 X DBW 222 (14.62) in heat stress condition. Highest significant negative heterosis was shown by the cross VL 967 X HS 490 (-8.33) followed by UP 3069 X QLD 91 (-6.94) in timely sown condition and the cross AGRA LOCAL X QLD 91 (-7.69) followed by UP 3069 X HS 490 (-4.62) in heat stress condition. Similarly, significant and desirable heterosis for spike length was found by Singh *et al*., (2020), Kumar *et al*., (2020) and Kumar *et al*., (2021). The study reveals diverse relative heterosis and heterobeltiosis effects on spike length under various growth conditions. Notably, several crosses exhibit significant positive heterosis, such as UP 2572 X DBW 222 and PBW 813 X HS 490, indicating potential for improved spike length. Conversely, negative heterosis is observed in certain crosses like UP 3069 X QLD 91 and VL 967 X QLD 91. Standard heterosis analyses over checks PBW 725 further highlight the significance of specific crosses, particularly PBW 813 X HS 490 and UP 2572 X DBW 222, in enhancing spike length. Our study demonstrates varying levels of relative, heterobeltiosis and standard heterosis effects on spike length across timely sown and heat stress conditions. For relative heterosis crosses UP 262 X DBW 222 (timely sown) and UP 262 X DBW 222 (heat stress) exhibited positive heterosis, for heterobeltiosis crosses UP 262 X DBW 222 (timely sown) and UP 262 X DBW 222 (heat stress) exhibited positive heterosis, and for standard heterosis crosses AGRA LOCAL X DBW 222 (timely sown) and UP 2572 X HS 490 (heat stress) exhibited positive heterosis indicating potential for longer spike length. These findings provide insights for increasing spike length traits in wheat breeding across different environments.

Table 7: Estimation of heterosis for spike length (cm) in heat stress and timely sown environments

	Relative Heterosis		**Heterobeltiosis**		**Standard heterosis PBW725**	
Crosses	**Timely sown**	**Heat stress**	**Timely sown**	**Heat stress**	**Timely sown**	**Heat stress**
L1 X T1	22.42**	24.17**	18.54**	14.62**	12.50**	14.62**
L1 X T2	18.84**	14.29**	10.81**	6.25*	13.89**	4.62
L1 X T3	17.50**	18.70**	10.97**	7.35*	10.97**	12.31**
L2 X T1	21.60**	12.98**	14.22**	12.12**	8.41**	13.85**
L2 X T2	10.41**	7.69**	0	6.06*	2.78	7.69*
L2 X T3	9.06**	11.94**	0	10.29**	0	15.38**
L3 X T1	8.72**	-5.83*	2.6	-10.99**	9.72**	-0.03
L3 X T2	0.67	6.60*	-1.29	0.03	5.56*	12.34**
L3 X T3	7.38**	-4.99*	3.9	-8.25**	11.11**	3.05
L4 X T1	1.86	-5.16*	-2.67	-8.54**	1.39	-1.51
L4 X T2	-10.07**	-4.48	-10.67**	-8.57**	-6.94*	-1.54
L4 X T3	-2.04	-10.14**	-4	-11.43**	0	-4.62
L5 X T1	12.11**	1.54	9.26**	1.54	9.26**	1.54
L5 X T2	5.48*	2.33	4.05	1.54	6.94*	1.54
L5 X T3	6.94**	2.26	6.94*	0	6.94*	4.62
L6 X T1	18.50**	3.94	15.61**	1.54	9.72**	1.54
L6 X T2	13.74**	9.52**	6.82*	7.81*	9.79**	6.15*
L6 X T3	-3.65	12.31**	-8.33**	7.35*	-8.33**	12.31**
L7 X T1	19.14**	6.03*	16.90**	6.03	15.28**	6.03
L7 X T2	7.60**	-6.98*	5.41*	-7.69*	8.34**	-7.69*
L7 X T3	0.7	9.80**	0	7.38*	0	12.34**
L8 X T1	5.54*	4.03	4.29	3.49	1.39	4.58
L8 X T2	-1.39	4.87	-4.05	3.52	-1.39	4.62
L8 X T3	-5.63*	7.71**	-6.94*	5.88*	-6.94*	10.77**

*,** Significance at 5% and 1% probability levels

3.3.2 Peduncle length (cm)

Relative heterosis for peduncle length ranged from -15.11 to 23.60 in timely sown, and -12.20 to 38.42 in heat stress. Twenty and eighteen out of twenty-four crosses showed significant heterosis over mid parental value for this trait in timely sown, and heat stress environments respectively. Highest significant positive heterosis was found in crosses AGRA LOCAL X DBW 222 (23.60) followed by UP 262 X HS 490 (23.39) in timely sown whereas, in cross AGRA LOCAL X HS 490 (38.42) followed by AGRA LOCAL X QLD 91 (22.38) in heat stress. Highest significant negative heterosis was found in crosses PBW 725 X QLD 91 (-15.11) followed by PBW 813 X QLD 91 (-7.83) in timely sown whereas, in cross UP 2572 X QLD 91 (-12.20) followed by VL 967 X QLD 91 (-9.29) in heat stress. Heterobeltiosis for peduncle length (Table 8) ranged from -20.42 to 21.29 and -22.82 to 36.42 in timely sown and heat stress environments respectively. Twenty and seventeen, out of twenty-four crosses showed significant heterosis over better parental value for this trait in timely sown and heat stress environments respectively. Highest significant positive heterosis was shown by the crosses UP 262 X HS 490 (21.29) followed by AGRA LOCAL X DBW 222 (20.05) in timely sown, cross AGRA LOCAL X HS 490 (36.42) followed by AGRA LOCAL X DBW 222 (18.05) in heat stress. Highest significant negative heterosis was found in crosses PBW 725 X QLD 91 (-20.42) followed by UP 3069 X QLD 91 (-12.47) in timely sown whereas, in cross UP 2572 X DBW 222 (-22.82) followed by UP 2572 X QLD 91 (-22.40) in heat stress environment. Standard heterosis over check PBW 725 (Table 8) for peduncle length ranged from -9.05 to 20.53 and -2.89 to 36.42 in timely sown and heat stress environment respectively. eighteen and thirteen out of twenty-four crosses showed highest significant heterosis in timely sown and heat stress environment respectively. Highest significant positive heterosis was shown by the cross UP 3069 X HS 490 (20.43) followed by AGRA LOCAL X DBW 222 (19.48) in timely sown, cross AGRA LOCAL X HS 490 (36.42) followed by AGRA LOCAL X QLD 91 (24.86) in heat stress environments. Highest negative significant heterosis was found in cross PBW 725 X QLD 91 (-9.05) in timely sown environment. Similar findings on significant and desirable heterosis for this character have been reported by Farooq *et al*., (2005), Kumar *et al*., (2020) and Kaur *et al*., (2020). Our study demonstrates varying levels of relative, heterobeltiosis and standard heterosis effects on peduncle length across timely sown and heat stress conditions. For relative heterosis crosses PBW 725 X QLD 91 (timely sown) and UP 2572 X QLD 91 (heat stress) exhibited significant negative heterosis, for heterobeltiosis crosses PBW 725 X QLD 91 (timely sown) and UP 2572 X DBW 222 (heat stress) exhibited significant negative heterosis, and for standard heterosis crosses PBW 725 X QLD 91 (timely sown) exhibited significant negative heterosis indicating potential for reduced peduncle length. These findings underscore the importance of specific crosses in reducing peduncle length trait, contributing to our understanding of potential improvements in wheat breeding programs under varying growth conditions.

Table 8: Estimation of heterosis for peduncle length (cm) in heat stress, timely sown and across both environments.

	Relative Heterosis		Heterobeltiosis		Standard heterosis PBW725	
Crosses	**Timely sown**	**Heat stress**	**Timely sown**	**Heat stress**	**Timely sown**	**Heat stress**
L1 X T1	19.01**	6.59*	18.71**	4.14	11.93	0.32
L1 X T2	1.37	4.65	-7.50**	-2.7	5.71**	4.05
L1 X T3	23.39**	12.65**	21.29**	8.09*	18.40**	8.09*
L2 X T1	14.05**	-8.75**	9.67**	-22.82**	11.43**	7.51*
L2 X T2	-2.73	-12.20**	-8.13**	-22.40**	4.99*	8.10*
L2 X T3	17.60**	-9.18**	15.30**	-21.99**	17.14**	8.67**
L3 X T1	4.53**	5.59*	0.15	-2.54	2.54	10.98**
L3 X T2	-6.44**	-3.14	-11.31**	-6.09*	1.36	6.94*
L3 X T3	14.60**	9.36**	11.94**	2.7	14.60**	16.95**
L4 X T1	6.87**	-1.81	-5.12**	-10.79**	14.76**	5.19
L4 X T2	-9.99**	-2.83	-12.47**	-7.35**	5.87**	9.25**
L4 X T3	10.29**	-7.34**	-0.35	-14.38**	20.53**	0.96
L5 X T1	1.64	5.40*	-1.51	3.47	-1.51	3.47
L5 X T2	-15.11**	-2.22	-20.42**	-5.39	-9.05**	1.17
L5 X T3	17.15**	13.34**	15.75**	13.34**	15.75**	13.34**
L6 X T1	-2.82	-1.18	-9.61**	-10.02**	-1.43	5.58
L6 X T2	-4.60**	-9.29**	-6.78**	-13.31**	6.53**	1.72
L6 X T3	11.52**	-6.38*	5.68**	-13.30**	15.24**	1.73
L7 X T1	23.60**	18.51**	20.05**	18.04**	19.48**	14.62**
L7 X T2	10.60**	22.38**	3.46*	16.76**	18.23**	24.86**
L7 X T3	18.44**	38.42**	17.31**	36.42**	16.75**	36.42**
L8 X T1	4.56**	-6.76*	-0.91	-13.26**	3.81*	-2.89
L8 X T2	-7.83**	-7.57**	-11.67**	-9.64**	0.95	1.17
L8 X T3	16.24**	6.36*	12.27**	0.68	17.62**	12.72**

*,** Significance at 5% and 1% probability levels

4. Conclusion

The research unveiled a variety of general combining ability (GCA) effects for spike length, notably the positive impact of UP 262 in timely sown and UP 2572 in heat stress conditions. Specific combining ability (SCA) effects displayed variation among different crosses, with VL 967 X HS 490 exhibiting a robust positive SCA in timely sown conditions, and UP 2927 X QLD 91 shows significant positive SCA effects in heat stress scenarios. The genetic influence on peduncle length in parental lines and crosses across diverse growth conditions demonstrated a wide spectrum of GCA effects within parental lines, including notable negative effects in specific genotypes like PBW 725 in timely sown and VL 967 in late sown. SCA effects across crosses also varied, featuring significant negative combining ability effects in crosses like AGRA LOCAL X HS 490 in timely sown and UP 3069 X HS 490 in late sown. The study also uncovered a diverse range of relative heterosis and heterobeltiosis effects on spike length across various conditions. Significant positive relative heterosis and heterobeltiosis found in UP 262 X DBW 222 in both timely sown and heat stress environment, cross UP 262 X DBW 222, and UP 2572 X HS 490 showed maximum positive standard heterosis in timely sown and heat stress environmets for spike length respectively, suggesting potential for enhancing spike length. These findings provide valuable insights for increasing spike length traits in wheat breeding across diverse environments. Regarding peduncle length, significant negative relative heterosis was found in crosses PBW 725 X QLD 91 and UP 2572 X QLD 91 under timely sown and heat stress environment, and cross PBW 725 X QLD 91 in timely sown, UP 2572 X DBW 222 in late sown exhibited maximum positive heterobeltiosis, similarly PBW 725 X QLD 91 outperformed the check PBW 725 and showed maximum positive standard heterosis.

These findings underscore complex genetic interactions and the potential of specific crosses to increase spike length and decrease peduncle length timely sown and heat stress environment. These findings highlight the complex interplay of genetic interactions and underscore the potential of specific lines and crosses as effective combiners for enhancing spike length in varying environmental conditions. The insights gleaned from this study contribute to a deeper understanding of the genetic mechanisms at play in wheat improvement strategies and offer valuable guidance for future breeding efforts.

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