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Research Article

Identification of Superior Combiners for Yield and Component Traits in Bread Wheat using Half-Diallel Analysis Across F_1 and F_2 generations

DM Vekaria*[1], AG Pansuriya[2], CJ Rajani[3] and Chandrakant Singh[4]

[1] *Wheat Research Station, Junagadh Agricultural University, Junagadh-362001, Gujarat, India*
[2] *Director of Research, Junagadh Agricultural University, Junagadh-362001, Gujarat, India*
[3] *Main Oilseeds Research Station, Junagadh Agricultural University, Junagadh, Gujarat, India*
[4] *ICAR - Directorate of Weed Research, Jabalpur, Madhya Pradesh-482004, India*

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****Corresponding author:***
E-mail: dmvekaria1991@jau.in

Abstract

In a diallel cross (excluding reciprocals) involving ten wheat (*Triticum aestivum* L.) parents, 45 F_1 and 45 F_2 genotypes were evaluated for combining ability in relation to grain yield and associated traits. The analysis of variance revealed significant differences for both general combining ability (GCA) and specific combining ability (SCA). The magnitude of SCA variance exceeded that of GCA, suggesting that non-additive gene action played a predominant role in the inheritance of most traits across both generations. Among the parents, UAS 3011 (F_1-1.409 and F_2-2.154), MACS 6222 (F_1-2.380 and F_2-0.944) and GW 513 F_1-1.722 and F_2-1.415) emerged as strong general combiners for grain yield and its key contributing attributes, making them valuable candidates for hybridization programs aimed at developing superior segregants. Notably, the crosses WR 544 × DBW 187, UAS 3011 × DBW 187, CG 1029 × HI 1544, and MACS 6222 × GW 513 consistently showed favorable SCA effects for grain yield per plant in both generations. The crosses involving good general combiners and showing high SCA effects may be utilized for further breeding purposes and bi-parental mating and diallel selective mating would be useful to exploit both type of gene action (additive and non-additive).

Keywords: General and specific combining ability, diallel crosses, bread wheat

1. Introduction

Wheat is one of the most important cereal crops globally, occupying a leading position in terms of acreage, production, and adaptability to diverse agro-climatic conditions (Sharma and Sharma, 2025). In India, wheat is the second most vital cereal after rice, and the country holds the position of the world's second-largest producer, following China. Wheat serves as a staple food for over a billion people in India and is also a dietary mainstay in more than 40 other countries (Anonymous, 2025).

The demand for wheat is increasing with the increase in population. In order to meet out the growing demand of wheat grains, wheat production and productivity must be enhanced (Nagar *et al.,* 2018). Consequently, the central aim of most wheat breeding programs is to develop varieties with enhanced yield potential. Yield, however, is a complex trait influenced by multiple contributing factors such as genetic makeup, sowing time, and environmental stresses. Grafius (1959) even questioned whether specific genes for yield exist, emphasizing the importance of focusing on yield components. Therefore, improving wheat productivity requires a component breeding approach. Although numerous studies have evaluated combining ability and gene action in wheat using F_1 populations, limited attention has been given to the comparative assessment of these genetic parameters across both F_1 and F_2 generations. The transition from F_1 to F_2 involves segregation and recombination, which may alter the relative importance of additive and non-additive gene effects. However, systematic studies addressing the consistency and shifts in combining ability across these generations are scarce. For this, plant breeders must select appropriate breeding strategies, which depend largely on combining ability, the type and magnitude of gene action, and the overall inheritance pattern of yield and its associated traits. Diallel mating design is widely used in plant breeding research to obtain information on genetic effects for a fixed set of parental lines or estimates of general combining ability, specific combining ability. The general combining ability (GCA) gives information about additive and additive x additive gene action, whereas specific combining ability (SCA) provides information about the non-allelic interaction and dominance gene action. In addition, diallel analysis gives an opportunity to the plant breeders for choosing the most efficient selection method by allowing them to estimate several genetic parameters by Singh and Chaudhary (1979). Diallel analysis provides a unique opportunity to test a number of lines in all possible combinations. Keeping the above facts under consideration, the present study was undertaken to identify the best general and specific combiners based on their general and specific combining ability for grain yield and its component traits in bread wheat (Nagar *et al.,* 2018).

2. Materials and methods

Ten genotypes of wheat (*Triticum aestivum* L. Em. Thell) namely WR 544 (P_1), HD 2967 (P_2), UAS 3011 (P_3), CG 1029 (P_4), HI 1544 (P_5), MACS 6222 (P_6), GW 451 (P_7), DBW 187 (P_8), GW 513 (P_9) and GW 533 (P_{10}) as basic material which had been taken on the basis of their differences in origin, adaptability and morphological characters. All these parents have genetic variability for yield level as well as for various good yield components. In the present investigation, all possible crosses among the selected parents were made in one direction only, *i.e.* direct crosses. Here, each parent was used either as male or as female in the mating. The number of single crosses attempted was equal to [n (n-1)/2], where n is the number of parents used. Half diallel design was used in the present study because reciprocal differences are not significant in wheat crops (Kumar *et al.,* 2017). A total of 45 crosses were made in half-diallel mating design during *Rabi* 2020-21 and their F_2 generation was made during *Rabi* 2021-22 and final evaluation trial comprised of ten parents along with F_1's, F_2's and one standard check (MACS 6478) was carried out during *Rabi* 2022-23 and progenies were evaluated using Randomized Block in 3 replications at Wheat Research Station, Junagadh Agricultural University, Junagadh. The experimental material was sown in each replication, parents and F_1s were sown in single row while F_2s were sown in two rows. The length of each row was 3.0m with inter and intra-row distance of 20 and 10cm respectively. Recommended doses of fertilizers @ 120 kg N + 60 kg P_2O_5 + 60 kg K_2O per hectare were applied in the experimental area along with four irrigations at all critical stages. Various observations were recorded on five competitive plants selected randomly from each single row plot of each parents and F_1's as wells as 20 competitive plants of F_2's were selected in each replication. The observations were recorded on sixteen characters *viz.,* days to heading, days to maturity, grain filling period, plant height, number of tillers per plant, length of main spike, number of spikelets per spike, number of grains per spike, 100 grain weight, grain yield per plant, biological yield per plant, harvest index, chlorophyll content-15 DAA, chlorophyll content-21 DAA, Canopy Temperature Depression at 15 Days After Anthesis (CTD-15 DAA) and CTD-21 DAA. Canopy Temperature Depression (CTD) reading was taking with the help of Infra-red thermometer and chlorophyll content was recorded with the help of SPAD-502 meter during sunny, clear, and calm days between 12:00 p.m. and 3:00 p.m. Mean values over selected plants were used for statistical analysis. The mean values of different parents, F_1s and F_2s for all characters were subjected for analysis of variance and the estimates of variance for general combining ability and specific combining ability and their effects were computed by Method 2 (Model I) as suggested by Griffing (1956b). The analysis was done using the WINDOSTAT 7.5 statistical package. The general mathematical model for analysis as given by Griffing (1956a).

Xijk = μ + gi + gj + Sij + eijk/b

Where,

Xijk = an observation of the phenotype of a cross between ith and jth parents in kth block

μ = General mean

gi = General combining ability (GCA) effect of jth parent

sij = Specific combining ability (SCA) effect for cross between ith and jth parent such that si = sj

eijk = Environmental effects associated with ijkth observation

b = Number of blocks

Table 1: List of Parents used for study and their key features

Sr. No.	Name of Parents	Key Feature
1	WR 544	Earliness
2	HD 2967	Grain yield, Tillers
3	UAS 3011	Grain yield, Tillers
4	CG 1029	Grain yield, Earliness
5	HI 1544	Grain yield, Grain appearance
6	MACS 6222	Grain yield, Tillers, spike length
7	GW 451	Grain yield, Tillers, Dwarfness, Earliness
8	DBW 187	Grain yield, Tillers, spike length
9	GW 513	Grain yield, Tillers, spike length
10	GW 533	Grain yield

3. Results and discussion

3.1. Combining ability analysis

The analysis of variance for combining ability in F_1 and F_2 generations (Table 2) revealed that both general combining ability (GCA) and specific combining ability (SCA) mean squares were highly significant for all the traits studied. This indicates the involvement of both additive and non-additive gene actions in governing the expression of these traits across generations. The simultaneous significance of GCA and SCA suggests that selection as well as hybridization-based approaches may be effective for genetic improvement. Significant GCA and SCA effects for traits such as days to maturity, plant height, number of tillers per plant, number of grains per spike, 100-grain weight, grain yield per plant, biological yield per plant, and harvest index have also been reported by Nagar *et al.* (2018). The present findings are in agreement with earlier reports by Choudhary *et al.* (2018), El-Gammaal and Yahya (2018), Kumar *et al.* (2019), Ali *et al.* (2020), Meghawal *et al.* (2021), Babar *et al.* (2022), Dragov (2022) and Darwish *et al.* (2024), who also documented the concurrent role of additive and non-additive gene effects in the inheritance of yield and its component traits in wheat.

The ratio of GCA to SCA variance was less than unity for most of the traits studied, indicating the predominance of non-additive gene action in their inheritance. However, exceptions were observed for days to heading and number of spikelets per spike in both F_1 and F_2 generations, where relatively higher GCA/SCA ratios suggested a greater role of additive gene effects. The overall predominance of non-additive gene action for the majority of traits implies that selection based on specific combining ability (SCA) effects would be more effective for identifying superior cross combinations and achieving substantial genetic improvement in wheat. These findings are in accordance with earlier reports by Choudhary *et al.* (2018), El-Gammaal and Yahya (2018), Ali *et al.* (2020) and Meghawal *et al.* (2021), who also documented the predominance of non-additive gene action for grain yield and its component traits in wheat.

3.2. General combining ability effects

The parents were categorized as good, average, and poor combiners for various traits based on the estimates of general combining ability effects for the F_1 and F_2 populations, as outlined in Table 3 and 4. It was evident from the Table 3 and 4 that one of parent UAS 3011 which was good general combiner for grain yield per plant in both the generations, was also good general combiner for some of yield contributing characters like grain filling period, number of tillers per plant, length of the main spike, number of spikelets per spike, number of grains per spike and biological yield per plant in both the generations and harvest index in F_1 generation as well as chlorophyll content-15 DAA, chlorophyll content-21 DAA, and CTD-21 DAA in F_2 generation. The second good general combiner MACS 6222 was also a good general combiner for days to maturity, grain filling period, number of spikelets per spike, 100 grain weight and

Table 2a: Analysis of variance for combining ability for different characters

			Mean squares							
Effect	**Generation**	**d. f.**	**Days to heading**	**Days to maturity**	**Grain filling period**	**Plant height**	**Number of tillers per plant**	**Length of main spike**	**Number of spikelets per spike**	**Number of grains per spike**
GCA	F_1	9	84.160**	41.889**	18.038**	41.000**	8.297**	2.933**	7.920**	84.741**
	F_2	9	70.336**	25.533**	24.317**	45.904**	11.083**	4.556**	8.566**	107.807**
SCA	F_1	45	6.894**	12.933**	6.570**	6.599**	2.916**	0.897**	0.804**	23.035**
	F_2	45	5.968**	5.604**	8.885**	11.335**	2.924**	0.592**	0.791**	20.154**
Error	F_1	108	0.305	0.249	0.323	2.591	0.520	0.184	0.180	7.516
	F_2	108	0.243	0.209	0.249	3.220	0.845	0.211	0.220	7.810
σ^2GCA	F_1		6.988	3.470	1.476	3.201	0.648	0.229	0.645	6.435
	F_2		5.841	2.110	2.006	3.557	0.853	0.362	0.696	8.333
σ^2SCA	F_1		6.589	12.685	6.246	4.008	2.396	0.713	0.624	15.519
	F_2		5.725	5.395	8.636	8.115	2.079	0.381	0.571	12.345
σ^2GCA / σ^2SCA	F_1		1.061	0.274	0.236	0.799	0.271	0.321	1.034	0.415
	F_2		1.020	0.391	0.232	0.438	0.410	0.951	1.219	0.675

Table 2b: Analysis of variance for combining ability for different characters

			Mean squares							
Effect	**Generation**	**d. f.**	**100 grain weight**	**Grain yield per plant**	**Biological yield per plant**	**Harvest index**	**Chlorophyll content-15 DAA**	**Chlorophyll content-21 DAA**	**CTD-15 DAA**	**CTD-21 DAA**
GCA	F_1	9	0.232**	48.339**	352.524**	15.128**	5.579**	7.171**	1.743**	0.633**
	F_2	9	0.349**	48.412**	570.783**	44.019**	5.481**	3.226**	0.418*	0.165**
SCA	F_1	45	0.160**	12.358**	111.133**	18.603**	1.368**	2.140**	1.275**	0.258**
	F_2	45	0.127**	15.056**	158.791**	13.684**	1.394**	2.593**	0.399**	0.316**
Error	F_1	108	0.020	1.553	14.679	2.911	0.298	0.588	0.070	0.044
	F_2	108	0.018	2.006	26.159	4.838	0.331	0.732	0.165	0.063
σ^2GCA	F_1		0.018	3.899	28.154	1.018	0.440	0.549	0.139	0.049
	F_2		0.028	3.867	45.385	3.265	0.429	0.208	0.021	0.009
σ^2SCA	F_1		0.140	10.806	96.454	15.692	1.070	1.553	1.025	0.214
	F_2		0.109	13.049	132.632	8.846	1.063	1.861	0.234	0.253
σ^2GCA /	F_1		0.126	0.361	0.292	0.065	0.411	0.353	0.116	0.230
σ^2SCA	F_2		0.254	0.296	0.342	0.369	0.404	0.112	0.090	0.034

Table 3a: Estimation of general combining ability (GCA) effect of parents

Parents	Days to heading		Days to maturity		Grain filling period		Plant height		Number of tillers per plant		Length of main spike	
	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
WR 544	-4.700**	-4.433**	-2.422**	-1.211**	1.544**	2.400**	-1.367**	-1.628**	-2.067**	-1.900**	-0.461**	-0.678**
HD 2967	2.078**	1.706**	1.300**	3.011**	-0.817**	1.261**	1.383**	1.650**	0.433*	-0.261	0.678**	0.489**
UAS 3011	5.078**	3.928**	3.689**	1.900**	-1.900**	-2.072**	3.300**	1.678**	0.739**	0.628*	0.372**	0.600**
CG 1029	-0.811**	-2.739**	0.633**	-1.350**	1.794**	1.400**	-2.644**	-3.239**	-0.761**	-0.400	-0.628**	-0.817**
HI 1544	-0.644**	-0.711**	-0.894**	-0.433**	-0.483**	0.067	-1.200**	-1.406**	0.350	-0.011	-0.072	-0.011
MACS 6222	-0.033	1.067**	-0.533**	-0.961**	-0.428**	-1.739**	1.189**	1.206*	0.322	-0.372	0.150	0.044
GW 451	-2.172**	-1.461**	-1.867**	-1.017**	0.406**	0.317*	-2.228**	-2.156**	0.461*	1.461**	-0.683**	-0.456**
DBW 187	2.022**	1.567**	0.272*	-0.294*	-1.094**	-1.156**	0.467	2.372**	-0.094	0.850**	0.539**	1.072**
GW 513	-1.006**	0.067	-1.700**	-0.489**	-0.344*	-0.406**	1.022*	1.428**	0.294	0.739**	0.372**	0.267*
GW 533	0.189	1.011**	1.522**	0.844**	1.322**	-0.072	0.078	0.094	0.322	-0.733**	-0.267*	-0.511**
S. E. (G_i) ±	0.151	0.135	0.137	0.125	0.156	0.137	0.441	0.492	0.198	0.252	0.118	0.126

Table 3b : Estimation of general combining ability (GCA) effect of parents

Parents	No. spikelets per spike		No. of grains per spike		100 grain weight		Grain yield per plant		Biological yield per plant	
	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
WR 544	-0.628**	-0.306*	-2.489**	-1.094	-0.092*	-0.029	-4.345**	-3.888**	-12.837**	-14.287**
HD 2967	1.122**	0.889**	4.733**	3.072**	-0.184**	-0.116**	0.627	0.415	1.806	-5.831**
UAS 3011	0.733**	0.806**	2.817**	2.378**	-0.214**	-0.316**	1.409**	2.154**	2.787**	7.767**
CG 1029	-1.044**	-1.278**	-2.933**	-5.011**	0.236**	0.323**	-2.238**	-1.993**	-3.307**	-5.081**
HI 1544	-0.350**	-0.639**	-0.989	-1.678*	0.063	-0.071*	-0.021	-0.703	-0.856	1.891
MACS 6222	0.289*	0.556**	0.844	2.572**	0.099**	0.168**	2.380**	0.944*	4.829**	1.824
GW 451	-1.211**	-0.972**	-3.794**	-3.817**	0.102**	-0.074*	0.586	0.976*	4.527**	5.273**
DBW 187	0.928**	1.194**	1.511*	3.822**	0.008	0.054	-0.768*	2.319**	-3.451**	6.125**
GW 513	0.317**	0.139	0.122	0.517	0.044	0.040	1.722**	1.415**	3.134**	4.961**
GW 533	-0.156	-0.389**	0.178	-0.761	-0.062	0.021	0.648	-1.639**	3.370**	-2.643
S. E. (G_i) ±	0.116	0.129	0.751	0.765	0.038	0.036	0.341	0.388	1.049	1.401

*, ** Significant at 5 % and 1 % levels, respectively

Table 3c: Estimation of general combining ability (GCA) effect of parents

Parents	Harvest index		Chlorophyll content-15 DAA		Chlorophyll content-21 DAA		CTD-15 DAA		CTD-21 DAA	
	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
WR 544	1.178*	2.378**	-0.363*	0.689**	0.512*	-0.045	-0.287**	-0.044	0.328**	-0.136*
HD 2967	0.150	4.128**	-0.485**	0.163	0.334	-0.183	0.369**	0.085	0.288**	0.066
UAS 3011	0.956*	-0.817	-0.108	0.712**	0.386	0.538*	0.135	-0.009	-0.271**	0.174*
CG 1029	-1.544**	-0.567	0.670**	0.022	-0.267	0.046	-0.775**	-0.399**	-0.287**	-0.253**
HI 1544	0.178	-2.400**	-0.785**	-1.140**	-1.968**	-0.915**	-0.204**	-0.112	0.016	-0.011
MACS 6222	0.539	0.211	1.042**	0.845**	0.952**	0.209	0.495**	0.154	-0.070	0.050
GW 451	-1.850**	-1.122	0.890**	0.298	-0.036	0.750**	0.366**	0.300**	-0.236**	0.042
DBW 187	0.706	0.239	-0.365*	-0.216	0.045	-0.619**	0.128	-0.094	-0.025	0.043
GW 513	0.928*	-0.789	-0.798**	-0.625**	0.041	-0.238	-0.055	0.023	0.258**	-0.001
GW 533	-1.239**	-1.261*	0.303*	-0.748**	0.001	0.456	-0.172*	0.097	-0.002	0.025
S. E. (G_i) ±	0.467	0.602	0.149	0.158	0.210	0.234	0.073	0.111	0.057	0.069

*, ** Significant at 5 % and 1 % levels, respectively

Table 4a: Classification of parents based on general combining ability effects for various traits

Sr. No.	Characters	Generations	Parents									
			WR 544	**HD 2967**	**UAS 3011**	**CG 1029**	**HI 1544**	**MACS 6222**	**GW 451**	**DBW 187**	**GW 513**	**GW 533**
1	Days to heading	F_1	G	P	P	G	G	A	G	P	G	A
		F_2	G	P	P	G	G	P	G	P	A	P
2	Days to maturity	F_1	G	P	P	P	G	G	G	P	G	P
		F_2	G	P	P	G	G	G	G	G	G	P
3	Grain filling period	F_1	P	G	G	P	G	G	P	G	G	P
		F_2	P	P	G	P	A	G	P	G	G	A
4	Plant height	F_1	G	P	P	G	G	P	G	A	P	A
		F_2	G	P	P	G	G	P	G	P	P	A
5	Number of tillers per plant	F_1	P	G	G	P	A	A	G	A	A	A
		F_2	P	A	G	A	A	A	G	G	G	P

6	Length of main spike	F_1	P	G	G	P	A	A	P	G	G	P
		F_2	P	G	G	P	A	A	P	G	G	P
7	Number of spikelets per spike	F_1	P	G	G	P	P	G	P	G	G	A
		F_2	P	G	G	P	P	G	P	G	A	P
8	Number of grains per spike	F_1	P	G	G	P	A	A	P	G	A	A
		F_2	A	G	G	P	P	G	P	G	A	A

Table 4b: Classification of parents based on general combining ability effects for various traits

Sr. No.	Characters	Generations	Parents									
			WR 544	HD 2967	UAS 3011	CG 1029	HI 1544	MACS 6222	GW 451	DBW 187	GW 513	GW 533
9	100 grain weight	F_1	P	P	P	G	A	G	G	A	A	A
		F_2	A	P	P	G	P	G	P	A	A	A
10	Grain yield per plant	F_1	P	A	G	P	A	G	A	P	G	A
		F_2	P	A	G	P	A	G	G	G	G	P
11	Biological yield per plant	F_1	P	A	G	P	A	G	G	P	G	G
		F_2	P	P	G	P	A	A	G	G	G	A
12	Harvest index	F_1	G	A	G	P	A	A	P	A	G	P
		F_2	G	G	A	A	P	A	A	A	A	P
13	Chlorophyll content -15 DAA	F_1	P	P	A	G	P	G	G	P	P	G
		F_2	G	A	G	A	P	G	A	A	P	P
14	Chlorophyll content -21 DAA	F_1	G	A	A	A	P	G	A	A	A	A
		F_2	A	A	G	A	P	A	G	P	A	A
15	CTD-15 DAA	F_1	P	G	A	P	P	G	G	A	A	P
		F_2	A	A	A	P	A	A	G	A	A	A
16	CTD-21 DAA	F_1	G	G	P	P	A	A	P	A	G	A
		F_2	P	A	G	P	A	A	A	A	A	A

G = Good combiner (Significant and desirable direction), A = Average combiner (non-significant), P = Poor combiner (Significant and undesirable direction) chlorophyll content-15 DAA in both the generations and biological yield per plant, chlorophyll content-21 DAA and CTD-15 DAA in F_1 generation and number of grains per spike in F_2 generation. Likewise, GW 513 was found to be good general combiner for grain yield per plant in both generations, also found to be good general combiner for days to maturity, grain filling period, length of the main spike, biological yield per plant in both the generations and days to heading, number of spikelets per spike, harvest index and CTD-21 DAA in F_1 generation and number of tillers per plant in F_2 generation. Similar finding of good GCA effects for different traits were reported by Desale and Mehta (2013), EL-Hosary and Nour El Deen (2015), Kutlu and Sirel (2019) and Darwish *et al.* (2024) in wheat.

Better performance of hybrids involving average × poor general combiners indicated dominance × dominance (epistasis) type of gene action. Such cross could be utilized in the production of high yielding homozygous lines. Crosses which were involved at least one good general combiner, indicating additive × dominance type of gene interaction, which could produce desirable transgressive segregants in subsequent generations (Vora *et al.,* 2025). Top of Form

High GCA effects are mostly due to additive gene effects and/or additive × additive interaction effects (Griffing, 1956). In view of this, breeders may utilize the good general combiners in specific breeding programme for improvement in grain yield. It is therefore recommended that the breeder should breed for superior combining ability for the component traits with an ultimate objective to improve the overall GCA for grain yield in bread wheat. In order to synthesize a dynamic population with most of the favorable genes accumulated, it will be pertinent to make use of these parents, which are good general combiner for several traits in multiple crossing programmes. In contrast to the conventional breeding methods which are relying mainly on additive or additive × additive types of gene action, population improvement appears to be a promise alternative. In general, the crosses involving parents with good x good GCA effects indicated additive x additive type of interaction; good x average or good x poor GCA effects showed additive x dominance type of gene action, while in rest of the cases (*i.e.* average x average, average x poor and poor x poor) of GCA effect revealed dominance x dominance type of gene interaction. It was further observed that crosses involving both poor combiners also resulted in high SCA effects for some of the traits. This may be because of the role of high magnitude of non-additive gene action. These crosses could be utilized through intermating in the segregating generations, followed by simultaneous selection for desirable plant type for grain yield per plant and its component traits. These findings are in agreement with the earlier findings of Choudhary *et al.* (2018), Dedaniya *et al.* (2019), Bajaniya *et al.* (2019), Shah *et al.* (2020) and Vora *et al.* (2025) in wheat.

The study revealed that parents with good general combining ability also displayed high *per se* performance across nearly all the traits studied. High general combining ability effects mostly contribute additive gene effects or additive x additive interaction effects (Griffing, 1956a and 1956b) and represent fixable portion of genetic variation. Accordingly, GW 513, UAS 3011 and MACS 6222 offer the best possibilities of exploitation for the development of improved pure lines with enhanced grain yielding ability. It is suggested that population involving these lines in a multiple crossing programme may be developed for isolating desirable recombinants. Further, the varieties or lines showing good general combining ability for particular components may be utilized in component breeding programme for improving a specific trait of interest.

3.3. Specific combining ability effects

The specific combining ability (SCA) effects play a crucial role in identifying superior cross combinations for developing promising hybrids. Crosses exhibiting high SCA effects, especially when involving parents with high general combining ability (GCA) effects, can lead to the emergence of desirable segregants in future generations. However, it is important to note that while SCA effects are estimates, *per se,* performance represents realized values. Therefore, both SCA effects and *per se* performance should be carefully considered when selecting the best cross combinations.

In the present study, among the 45 crosses, top ten crosses were selected based on significant and desirable SCA effects for higher grain yield and also for other yield component in both F_1 and F_2 generations (Table 5 and 6). With respect to days to heading, out of five crosses, one crosses *viz.*, WR 544 X GW 533 in F_1 generation displayed the high *per se* performance and significant SCA effects

(Table 5), while in F_2 generation, WR 544 X HD 2967, reported high *per se* performance and significant SCA effects in F_2 generation. Similar results have also been reported by Afridi *et al.* (2017), Bhardwaj *et al.* (2017) and Dawwam *et al.* (2022) in wheat.

With regard to days to maturity, one cross *viz*, WR 544 X CG 1029 in F_1 generation reported high *per se* with significant SCA effects. In F_2 generation, none of the crosses exhibited high *per se* performance with significant SCA effects. This result is in confirmation with the results of Bhardwaj *et al.* (2017) and Dawwam *et al.* (2022) in wheat.

For grain filling period, three crosses *viz*, HD 2967 X DBW 187, HD 2967 X UAS 3011 and HI 1544 X MACS 6222 in F_1 generation reported high *per se* with significant SCA effects. However, three cross combinations *viz*, UAS 3011 X DBW 187, HD 2967 X UAS 3011 and HD 2967 X DBW 187, reported high *per se* performance and significant SCA effects in F_2 generation. This result is in confirmation with the results of Bhardwaj *et al.* (2017), Dedaniya *et al.* (2019), Bajaniya *et al.* (2019) and Meghawal *et al.* (2021) in wheat.

Considering plant height, three crosses, namely (Table 5), GW 451 X DBW 187, CG 1029 X DBW 187 and HI 1544 X MACS 6222 exhibited high *per se* performance and significant SCA effects in F_1 generation. However, four cross combinations *viz*, UAS 3011 X DBW 187, CG 1029 X MACS 6222, UAS 3011 X GW 451 and WR 544 X HI 1544, reported high *per se* performance and significant SCA effects in F_2 generation. The results are akin to the results of El-Gammaal and Yahya (2018) in wheat.

In case of number of tillers per plant (Table 5), all the five crosses were common which reported high *per se* performance with significant SCA effects in F_1 *viz*, UAS 3011 X DBW 187, HD 2967 X GW 533, HD 2967 X HI 1544, UAS 3011X MACS 6222 and MACS 6222 X GW 513, whereas in F_2, four cross combinations *viz*, UAS 3011 X DBW 187, HI 1544 X MACS 6222, UAS 3011 X GW 451 and HD 2967 X GW 513 showed high *per se* performance with significant SCA effects. This finding is in confirmation with the findings of Verma *et al.* (2016), Nagar *et al.* (2018) and Shah *et al.* (2020) in wheat.

In case of length of main spike, four crosses were common, which reported high *per se* performance with significant SCA effects in F_1 *viz*, UAS 3011 X GW 513, HD 2967 X DBW 187, HD 2967 X HI 1544 and UAS 3011 X MACS 6222, whereas two crosses were common *viz*, HD 2967 X DBW 187 and DBW 187 X GW 513, which showed high *per se* performance with significant SCA effects in F_2 generation. This finding is in accordance with the findings of Verma *et al.* (2016), Afridi *et al.* (2017), Nagar *et al.* (2018) and Shah *et al.* (2020) in wheat.

Among top five crosses studied for number of spikelets per spike, three crosses *viz*, HD 2967 X DBW 187, UAS 3011 X DBW 187 and HD 2967 X HI 1544 revealed high *per se* performance with significant SCA effects (Table 5) in F_1 generation and HD 2967 X UAS 3011, WR 544 X DBW 187 and HD 2967 X MACS 6222 crosses in F_2 generation, reported high *per se* performance with significant SCA effects. For number of grains per spike, four crosses *viz.*, HD 2967 X DBW 187, HD 2967 X UAS 3011, UAS 3011 X GW 513 and UAS 3011 X DBW 187 in F_1 generation and three crosses *viz*, UAS 3011 X MACS 6222, DBW 187 X GW 513 and WR 544 X DBW 187 in F_2 generation exhibited high *per se* performance with significant SCA effects. Similar results were reported by Afridi *et al.* (2018), Kumar *et al.* (2019) and Nageshwar *et al.* (2021) in wheat.

For 100 grain weight, two crosses HI 1544 X GW 451 and WR 544 X GW 513 in F_1 generation, and four crosses *viz*, CG 1029 X DBW 187, MACS 6222 X GW 451, GW 513 X GW 533 and WR 544 X HI 1544 in F_2 generation exhibited high *per se* performance with significant SCA effects. Similar results were reported by Ali *et al.* (2020) and Darwish *et al.* (2024) in wheat.

In case of grain yield per plant (Table 6), four crosses *viz*, MACS 6222 X GW 513, UAS 3011 X DBW 187, MACS 6222 X GW 451 and HD 2967 X HI 1544 in F_1 generation and four crosses *viz*, UAS 3011 X DBW 187, HI 1544 X MACS 6222, HD 2967 X GW 513 and WR 544 X DBW 187 in F_2 generation exhibited high *per se* performance with significant SCA effects. These above crosses are most desirable to increase grain yield, which could be utilized in further plant breeding programme. El-Gammaal, and Yahya (2018), Kutlu and Sirel (2019), Ali *et al.* (2020), Shah *et al.* (2020), Dawwam *et al.* (2022) and Darwish *et al.* (2024) in wheat reported similar findings for grain yield per plant.

In case of biological yield per plant, four crosses were common which reported high *per se* performance with significant SCA effects in F_1 *viz*, UAS 3011 X DBW 187,

Table 5: Estimation of specific combining ability (SCA) effects of hybrids for days to heading, days to maturity, grain filling period, plant height, number of tillers per plant, length of main spike, number of spikelets per spike and number of grains per spike

Crosses	Days to heading		Days to maturity		Grain filling period		Plant height	
	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
WR 544 X GW 451	1.199*	0.604	2.162**	1.058*	1.614**	1.295**	3.558*	1.735
WR 544 X DBW 187	1.338**	2.242**	0.023	5.669**	-1.220*	3.434**	-2.470	-2.793
HD 2967 X HI 1544	-1.773**	-0.619	-2.866**	0.919*	-0.803	1.684**	0.780	2.707
HD 2967 X MACS 6222	-0.384	-0.396	-1.894**	-2.553**	-1.525**	-2.177**	1.725	-1.571
HD 2967 X GW 533	-1.939**	-1.008*	-2.949**	-2.359**	-0.942	-1.510**	3.169*	-2.793
UAS 3011 X DBW 187	6.227**	2.548**	10.578**	-2.442**	1.225*	-5.760**	0.530	4.235*
CG 1029 X HI 1544	0.116	0.159	0.134	0.614	0.253	0.545	1.141	-4.404**
CG 1029 X GW 533	3.283**	-0.563	9.384**	-1.331**	5.780**	-0.649	-2.136	1.763
MACS 6222 X GW 451	1.199*	0.437	0.606	-1.525**	-0.414	-2.232**	2.003	6.568**
MACS 6222 X GW 513	-2.301**	1.242**	1.106*	-0.386	3.003**	-2.177**	-1.914	0.985
S. E. (S_{ij}) ±	0.509	0.454	0.460	0.421	0.524	0.459	1.483	1.653

Crosses	No. of tillers per plant		Length of main spike		Number spikelets per spike		Number of grains per spike	
	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
WR 544 X GW 451	0.321	1.275	0.763	1.152**	0.306	-0.056	5.750*	-1.374
WR 544 X DBW 187	1.543*	1.553	0.540	-0.043	-0.833*	2.111**	-3.556	7.987**
HD 2967 X HI 1544	3.932**	-1.225	1.679**	-0.126	1.361**	0.417	6.056*	2.987
HD 2967 X MACS 6222	-0.374	-1.197	-1.210**	-0.515	0.722	1.222**	-5.444*	4.737
HD 2967 X GW 533	4.293**	0.497	-0.126	-0.626	-0.500	0.167	2.222	-2.263
UAS 3011 X DBW 187	4.737**	4.359**	-0.960*	0.679	1.472**	1.000*	6.472*	-1.152
CG 1029 X HI 1544	0.126	1.914*	-0.348	0.179	0.194	0.250	1.722	6.404*
CG 1029 X GW 533	-1.179	2.636**	0.513	0.346	1.000*	0.001	-0.444	2.487
MACS 6222 X GW 451	0.265	0.081	-0.182	0.429	0.056	-0.250	2.083	2.626
MACS 6222 X GW 513	3.432**	0.470	0.429	0.707	-0.472	0.972*	4.167	6.293*
S. E. (S_{ij}) ±	0.664	0.847	0.395	0.423	0.391	0.432	2.525	2.574

*, ** Significant at 5 % and 1 % levels, respectively

Table 6: Estimation of specific combining ability (SCA) effects of hybrids for 100 grain weight, grain yield per plant, biological Yield, harvest index, chlorophyll content-15 DAA, chlorophyll content-21 DAA, CTD-15 DAA and CTD-21 DAA

Crosses	**100 grain weight**		**Grain yield per plant**		**Biological yield per plant**		**Harvest index**	
	F_1	**F_2**	**F_1**	**F_2**	**F_1**	**F_2**	**F_1**	**F_2**
WR 544 X GW 451	0.198	-0.144	2.544*	0.980	25.194**	15.191**	-9.255**	-6.783**
WR 544 X DBW 187	0.026	-0.072	2.528*	6.881**	8.790*	17.152**	-2.144	-0.477
HD 2967 X HI 1544	0.329*	0.073	7.092**	-1.656	7.501*	-4.129	6.745**	-1.255
HD 2967 X MACS 6222	0.426**	-0.066	4.211**	-1.786	11.277**	-6.582	0.051	1.134
HD 2967 X GW 533	0.121	0.248*	5.229**	-0.486	7.069*	0.375	4.162**	-1.727
UAS 3011 X DBW 187	0.215	-0.852**	8.568**	11.859**	24.112**	35.231**	-1.255	0.051
CG 1029 X HI 1544	-0.157	-0.099	3.004**	3.882**	12.141**	16.364**	-1.894	-1.561
CG 1029 X GW 533	-0.232	-0.124	1.712	6.145**	1.732	18.475**	1.189	-0.366
MACS 6222 X GW 451	0.373**	0.592**	4.972**	0.205	9.132**	3.120	2.384	-1.616
MACS 6222 X GW 513	-1.002**	-0.355**	5.769**	2.766*	7.402*	-1.535	4.606**	5.051*
S. E. (S_{ij}) ±	0.129	0.122	1.148	1.305	3.529	4.711	1.572	2.026

Crosses	**Chlorophyll content-15 DAA**		**Chlorophyll content-21 DAA**		**CTD-15 DAA**		**CTD-21 DAA**	
	F_1	**F_2**	**F_1**	**F_2**	**F_1**	**F_2**	**F_1**	**F_2**
WR 544 X DBW 187	-0.525	0.952	1.304	-0.780	-0.016	-0.112	0.426*	-0.271
WR 544 X GW 513	-1.316**	-0.628	0.660	-1.340	0.127	-0.078	1.441**	0.353
HD 2967 X HI 1544	0.371	-0.144	0.905	1.375	1.617**	0.324	0.262	0.448
HD 2967 X MACS 6222	-1.713**	0.527	-0.292	-1.966*	0.318	-0.862*	0.752**	-0.461*
HD 2967 X GW 533	0.536	-0.076	2.299**	1.033	-1.109**	-0.265	-0.437*	-0.116
UAS 3011 X DBW 187	-0.937	1.329*	-0.446	-1.162	-0.807**	-0.717	0.458*	0.476*
CG 1029 X HI 1544	0.032	0.834	-0.788	1.173	1.361**	-1.572**	-0.133	0.017
CG 1029 X GW 533	0.267	-1.022	1.464*	-1.922*	-0.891**	0.112	0.089	-0.160
MACS 6222 X GW 451	1.325**	0.106	-1.492*	0.601	1.851**	0.112	0.073	0.350
MACS 6222 X GW 513	1.633**	-0.434	1.634*	0.919	0.355	-0.277	0.206	-0.48*
S. E. (S_{ij}) ±	0.503	0.530	0.706	0.788	0.244	0.374	0.193	0.231

*, ** Significant at 5 % and 1 % levels, respectively

HD 2967 X MACS 6222, WR 544 X GW 451 and HD 2967 X CG 1029, whereas three crosses were common *viz*., UAS 3011 X DBW 187, HI 1544 X MACS 6222 and HI 1544 X GW 451 which showed high *per se* performance with significant SCA effects in F_2 generation. This finding is in confirmation with the findings of El-Gammaal, and Yahya (2018), Bajaniya *et al.* (2019) and Shah *et al.* (2020) in wheat.

With respect to harvest index, four crosses *viz*., UAS 3011X MACS 6222, HD 2967 X HI 1544, MACS 6222 X GW 513 and HI 1544 X DBW 187 in F_1 generation reported high *per se* with significant SCA effects. In F_2 generation, crosses *viz*, HD 2967 X GW 451 and WR 544 X UAS 3011 exhibited high *per se* performance with significant SCA effects. This result is in confirmation with the results of El-Gammaal, and Yahya (2018), Bajaniya *et al.* (2019) and Shah *et al.* (2020) in wheat.

In case of chlorophyll content-15 DAA (Table 6), four crosses *viz*, MACS 6222 X GW 451, MACS 6222 X GW 533, GW 451 X DBW 187 and MACS 6222 X GW 513 in F_1 generation and four crosses *viz*, HD 2967 X UAS 3011, WR 544 X GW 451, CG 1029 X MACS 6222 and UAS 3011 X DBW 187 in F_2 generation exhibited high *per se* performance with significant SCA effects. Desale and Mehta (2013), Kutlu and Sirel (2019) and Kumar *et al.* (2019) in wheat reported similar findings for chlorophyll content-15 DAA.

For chlorophyll content-21 DAA, three crosses UAS 3011X MACS 6222, WR 544 X HD 2967 and HD 2967 X GW 533 in F_1 generation and three crosses *viz.,* HI 1544 X GW 451, UAS 3011X MACS 6222 and CG 1029 X MACS 6222 in F_2 generation exhibited high *per se* performance with significant SCA effects. Similar results were reported by Desale and Mehta (2013), Kutlu and Sirel (2019) and Kumar *et al.* (2019) in wheat.

In case of CTD-15 DAA, two crosses were observed with high *per se* performance and significant SCA effects in F_1 generation *viz*, MACS 6222 X GW 451 and MACS 6222 X DBW 187, whereas in F_2 generation, four crosses *viz* DBW 187 X GW 513, WR 544 X GW 451, HI 1544 X MACS 6222 and WR 544 X MACS 6222 reflected high *per se* performance with significant SCA effects. Kutlu and Sirel (2019), Kumar *et al.* (2019) and Khan *et al.* (2020) in wheat observed similar results for CTD-15 DAA.

Among the top five crosses studied for CTD-21 DAA (Table 6), three crosses, WR 544 X GW 513, HD 2967 X MACS 6222 and CG 1029 X GW 513 showed high *per se* performance with significant SCA effects in F_1 generations, whereas in F_2 generation, crosses *viz*, UAS 3011X HI 1544, DBW 187 X GW 513, HD 2967 X GW 513 and MACS 6222 X GW 533 showed high *per se* performance with significant SCA effects. Similar with findings were reported by Kutlu and Sirel (2019), Kumar *et al.* (2019) and Khan *et al.* (2020) in wheat.

The findings of the present study indicated that the best combinations mostly involved high × low and low × low general combiners for the studied characters. In few best cross combinations, high × high general combiners were involved. Similar type of results was also reported by Kumar *et al.* (2016) in wheat. Thus, it is evident that good specific combiners are not always obtained between high general combiners but may be obtained between low × low or high × low general combiners. This might be probably due to the presence of dominant and epistatic gene interactions.

From the present study, following broad inferences could be drawn (i) none of the crosses was consistently superior for all the traits (ii) the crosses displaying significant SCA effects did not always involve parents with high GCA effects, suggesting that the inter-allelic interactions were also important for the traits (iii) crosses having significant SCA effects for grain yield may or may not have high SCA effects for all the yield attributing characters (iv) best performing parents were mostly good general combiners for majority of the characters (v) crosses exhibiting high SCA in both the generations showing low inbreeding depression and may be exploited for development of high yielding stable lines in wheat. The present study demonstrates that both additive (fixable) and non-additive (non fixable) components of genetic variance were involved in governing the inheritance of grain yield and component traits in the present set of breeding material. Therefore, bi-parental mating and diallel selective mating would be useful to exploit both type of gene action (additive and non-additive).

Conclusion

Based on the study of combining ability in wheat using 10 x 10 half-diallel mating design, it was concluded that among the parents, UAS 3011, MACS 6222 and

GW 513 registered high GCA effects and good *per se* performance for grain yield and some desirable traits in both generations. These three parents can be used in the hybridization programme to isolate superior segregants. Out of forty-five crosses, twelve crosses and ten crosses had significant and positive SCA effects in F_1 and F_2 generations, respectively. The significant and positive SCA effects were observed in the crosses WR 544 X DBW 187, UAS 3011 X DBW 187, CG 1029 X HI 1544 and MACS 6222 X GW 513 in both the generations for grain yield per plant.

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Author's contribution

Conceptualization of research (DMV and AGP); Designing of the experiments (DMV, AGP); Contribution of experimental materials (AGP, DMV and CS); Execution of field/lab experiments and data collection (DMV, AGP, CS and CJR); Analysis of data and interpretation (DMV, AGP and CS); Preparation of the manuscript (DMV, AGP, CS and CJR).

Conflict of interest

The authors declare that there is no conflict of interest.

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical Approval

The article doesn't contain any study involving ethical approval.

Use of Generative AI or AI assisted technologies

Authors declare that no Generative AI or AI assisted technologies have been used in preparation of this manuscript.

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