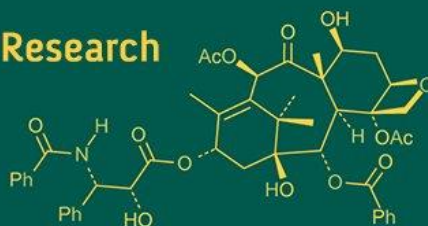


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AM Dange
Ph.D. Scholar, Department of
Agricultural Botany, Dr PDKV,
Akola, Maharashtra, India

NR Potdukhe
Retd. Senior Research Scientist,
Cotton Research Unit, Dr
PDKV, Akola, Maharashtra,
India

Swati G Bharad
Senior Research Scientist, Wheat
Research Unit, Dr PDKV,
Akola, Maharashtra, India

SJ Gahukar
Senior Research Scientist,
Oilseed and Cotton Research
Unit, Dr PDKV, Akola,
Maharashtra

NV Kayande
Cotton Breeder, Cotton Research
Unit, Dr PDKV, Akola,
Maharashtra, India

RD Walke
Associate Professor (Statistics),
College of Agriculture, PDKV,
Dr Akola, Maharashtra, India

VV Ujjainkar
Head of Section, Agriculture
Botany, College of Agriculture,
Dr PDKV, Akola, Maharashtra,
India

SP Patil
Assistant Professor, College of
Agriculture, Dr PDKV, Akola,
Maharashtra, India

Dhanshila S Sutar
PhD. Scholar, Department of
Agricultural Botany, Dr PDKV,
Akola, Maharashtra, India

Corresponding Author:
AM Dange
Ph.D. Scholar, Department of
Agricultural Botany, Dr PDKV,
Akola, Maharashtra, India

Combining ability analysis in bread wheat (*Triticum aestivum* L.) for yield and its associated traits over the environments

AM Dange, NR Potdukhe, Swati G Bharad, SJ Gahukar, NV Kayande, RD Walke, VV Ujjainkar, SP Patil and Dhanshila S Sutar

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Abstract

The 45 direct crosses and 45 reciprocal crosses were made during *rabi*-2023-24 by using 10 diverse origin potential parental genotypes through full diallel cross design in bread wheat (*Triticum aestivum* L.) were analyzed for combining ability for grain yield and yield associated traits over two locations during *rabi*-2024-25. The evaluation was done at Wheat Research Unit, Dr PDKV, Akola and at Agriculture Research Station, Niphad, Dist.-Nashik under, MPKV, Rahuri. The Analysis of Variance for combining ability revealed that the mean sum of squares due to gca of the parents and sca of direct and reciprocal crosses were found significant for all the characters exhibiting additive and non-additive gene effects involved in governing the traits over the environments at both locations and on pooled basis also. However, the variances due to sca were more than the variances due to gca for almost all the traits at both the locations indicating predominance of non-additive gene action for controlling these traits. Among the parents, good general combiners were GW-2010-288 for days to heading, days to maturity, spike length, number of spikelets spike⁻¹, number of grains spike⁻¹, grain weight spike⁻¹ and 1000 grain weight followed by AKAW-2862-1 for days to heading, days to maturity, grain weight spike⁻¹, 1000 grain weight, grain yield plant⁻¹ over the environments. These parents can suitably be used in the hybridization for the improvement of individual characters *per se*. Estimates of GCA effects of the parents revealed that none of the parent was consistently good general combiner for all the traits under study. Among the crosses two direct crosses AKAW-2862-1 x SSN-2021-41 and AKAW-2862-1 x HD-3086 were identified as best combinations since they exhibited significant SCA effects and both the parents involved in these crosses expressed high x high gca effects and four direct crosses viz, AKAW-1071 x MACS-6478, GW-2010-288 x MACS-6478, AKAW-2862-1 x GW-2010-288 and AKAW-2862-1 x MACS-6478 and three reciprocal crosses viz., MACS-6478 x HD-3086, GW-2010-288 x AKAW-2862-1 and GW-2010-288 x HI-1633 had high x low, low x high and low x low gca effects for grain yield over the environments.

Keywords: Wheat, combining ability, GCA effects, SCA effects, grain yield, pooled environments

Introduction

Wheat stands equally with Maize ensuring global food security. India achieved the feat of "deficit to surplus" status with the introduction of Mexican dwarf wheat that brought the great green revolution in India during the sixties. One third of the Indian population depends on wheat as their main food. India is the second largest producer of wheat after China claiming the position of a significant stakeholder in Global wheat production. Bread wheat (*Triticum aestivum* L.) is the most important food grain crop among the cereals and stands next to rice in India. It is one of the ancient grain crops consumed as primary food by human beings since the dawn of civilization and is known as the protector of man from hunger. It is a self-pollinated crop belonging to the family Poaceae. It is a hexaploid species (2n=6x=42: AABBDD genomes) with 21 pairs of chromosomes. It significantly contributed towards the success of the "Green Revolution" and has greatly helped to transform our country from a situation of ship to mouth to become a self-sufficient. In India, it is the second most important crop after rice and occupies 318.33 lakh hectares with a total production of 1132.92 lakh tonnes and productivity of 3560 kg/ha during 2024-25 crop season (USDA Report, 2024-25). It is third ranking cereal crop in the world in terms of area and production followed by maize and rice.

Major wheat growing states in India are Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, Rajasthan, Bihar and Gujarat.

The concept of combining ability introduced by Sprague and Tatum (1942) [15] assumes greater importance in crop improvement program. The knowledge of combining ability is essential in selection of the appropriate parents in breeding program. The combining ability estimates helps in the identification of promising parents and desirable combinations for the improvement of plant characters through the process of selection and hybridization. The estimates of general combining ability and specific combining ability helps to identify the relative importance of additive and non-additive actions. The GCA effects are the sum of the total effects of additive and additive x additive variances whereas, the SCA effects are the total effects of the dominance and additive x dominance variances. With the advancement in biometrical genetics, several techniques are now available, which permit quantitative genetic analysis and the selection of promising parents and hybrids for further exploitation. The parents who produce promising progenies on crossing are of immense value to the plant breeder. In a crop improvement program the success depends upon the isolation of the valuable cross combinations. This emphasizes the importance of testing the parents for their combining ability because many times the high yielding parents may not combine well to give good segregants.

Materials and Methods

The present investigation was carried out at two locations viz, Wheat Research Unit, Dr PDKV, Akola (M.S.) and Agriculture Research Station, Niphad under MPKV, Rahuri (M.S.). The experimental material used was ten varieties of bread wheat (*Triticum aestivum* L.) viz, AKAW-3717, AKAW-2862-1, AKAW-2344, AKAW-1071, HD-3086, HI-1633, GW-2010-288, SSN-2021-41, AKW-381 and MACS-6478. These parental lines were crossed in all possible combinations including reciprocals during *rabi*-2023-24 at Wheat Research Unit, Dr PDKV, Akola. Total 90 crosses comprising 45 direct crosses and 45 reciprocal crosses were

attempted in full diallel fashion.

These 90 crosses along with ten parents and a check variety MACS-6478 were evaluated in an experiment with full diallel fashion using Randomized Block Design with three replications at two locations viz, Wheat Research Unit, Dr PDKV, Akola (M.S.) and at Agriculture Research Station, Niphad, Dist-Nashik (M.S.) during *rabi*-2024-25. All recommended package of practices were followed at both the locations to raise the healthy crop. Ten observations were recorded viz, days to heading, days to maturity, plant height (cm), number of effective tillers plant⁻¹, spike length (cm), number of spikelets spike⁻¹, number of grains spike⁻¹, grain weight spike⁻¹ (g), 1000 grain weight (g) and grain yield plant⁻¹ (g).

The Analysis of Variance and the combining ability analysis for individual location and pooled analysis were carried out as per standard procedure (Singh and Chaudhary, 1977) [14] for all the characters under investigation. The combining ability estimation was done by the method given by Griffing (1956b) [4] utilizing experimental method I and model. In this model, experimental material was regarded as population about which inference was to be drawn and combining ability effects of parents could be compared when these parents themselves are used as tester to identify the good combiner. It was assumed that variety and block effects were constant, but error (environment and other uncontrollable components) was variable and normally and independently distributed with mean zero and variance.

Results and Discussion

The Analysis of Variance for combining ability (Table 1) revealed that the mean sum of squares due to GCA of the parents were found significant for all the characters exhibiting additive gene effects. The mean sum of squares due to the SCA of the cross combinations were significant for all the characters except for the trait days to maturity at Niphad location exhibiting non-additive gene effects in determining the traits. The mean sum of squares due to reciprocal crosses was also significant for all the reciprocal crosses exhibiting non-additive genetic effects in determining the traits.

Table 1: Analysis of Variance for Combining ability over the locations and pooled basis

Sr. No.	Source of variation	Location	Days to heading	Days to maturity	Plant height	No. of effective tillers plant ⁻¹	Spike length	No. of spikelets spike ⁻¹	No. of grains spike ⁻¹	Grains wt. spike ⁻¹	1000 grain wt.	Grain yield plant ⁻¹
1	GCA	Akola	37.660**	51.185**	68.053**	0.170**	2.450**	4.139**	25.377**	0.187**	23.893**	14.209**
		Niphad	23.494**	25.335**	85.479**	0.450**	1.884**	4.249**	56.516**	0.210**	28.673**	12.552**
		Pooled	26.804**	33.253**	58.285**	0.264**	2.127**	4.030**	38.100**	0.195**	23.845**	13.002**
2	SCA (direct crosses)	Akola	6.317**	8.703**	34.582**	0.436**	0.445**	0.497**	19.788**	0.058**	12.043**	9.685**
		Niphad	2.959**	3.002	23.154**	0.475**	0.503**	0.432**	17.607**	0.043**	11.762**	6.236**
		Pooled	3.119**	3.621*	23.666**	0.417**	0.443**	0.413**	16.670**	0.047**	10.150**	7.634**
3	SCA (reciprocal crosses)	Akola	5.133**	7.378**	29.553**	0.391**	0.640**	0.798**	25.225**	0.078**	11.045**	11.218**
		Niphad	6.401**	5.963**	27.251**	0.339**	0.379**	0.711**	24.266**	0.054**	12.992**	6.687**
		Pooled	4.455**	4.849**	22.914**	0.326**	0.463**	0.673**	22.386**	0.061**	9.978**	8.534**
4	Error	Akola	1.270	2.421	7.327	0.058	0.066	0.131	3.256	0.003	2.628	0.178
		Niphad	1.487	2.345	7.329	0.064	0.082	0.118	2.892	0.002	2.481	0.206
		Pooled	1.379	2.383	7.328	0.061	0.074	0.125	3.074	0.003	2.554	0.192
5	Environments		84.067**	946.125**	964.253**	5.185**	2.856**	9.866**	1063.912**	1.939**	2.257	87.427**
6	GCA*Environments		3.773**	5.007*	18.481**	0.046	0.04	0.164	2.847	0.003	2.438	0.378*
7	SCA crosses*Environments		1.519	2.232	5.203	0.038	0.031	0.051	2.028	0.003	1.753	0.327**
8	SCA Reciprocals*Environments		1.312	1.822	5.488	0.039	0.047	0.081	2.36	0.004**	2.041	0.419**
9	GCA variance	Pooled	1.271	1.544	3.908	0.010	0.103	0.195	1.751	0.010	1.065	0.641
10	SCA variance	Pooled	1.740	1.238	15.826	0.356	0.369	0.289	13.596	0.044	7.596	7.442
11	GCA variance Vs. SCA variance	Akola	0.360	0.388	0.111	0.015	0.314	0.548	0.067	0.168	0.113	0.074
		Niphad	0.748	1.750	0.247	0.047	0.214	0.657	0.182	0.256	0.141	0.102
		Pooled	0.731	1.247	0.247	0.029	0.278	0.677	0.129	0.217	0.14	0.086

The Pooled Analysis of Variance over the two locations Akola and Nipad for analysis of combining ability revealed that the mean sum of squares due to GCA, and SCA due to direct and reciprocal crosses were highly significant for all important characters. The variances due to GCA x Environment interaction were found significant for the characters viz., days to heading, days to maturity, plant height (cm), grain weight plant⁻¹, grain yield plot⁻¹ and membrane thermostability index at 60 DAS. While the variances due to SCA crosses x environment was found significant for the characters viz., grain weight plant⁻¹, grain yield plot⁻¹ and membrane thermostability index at 60 DAS. The variances due to SCA reciprocals x Environment

interaction was found significant for grain weight spike⁻¹, grain weight plot⁻¹, grain yield plot⁻¹, membrane thermostability index at 60 DAS and membrane thermostability index at 75 DAS.

The similar results which revealed that mean sum of squares due to GCA as well as SCA were exhibited significant results for all the characters, indicating the importance of both additive and non-additive gene actions in the inheritance of characters were reported by Kumar and Kerkhi (2015)^[6], Patel (2017)^[9], Gommaal A. A. (2018)^[3], Ranjitha *et al.* (2018)^[11], Sharma *et al.* (2019a)^[13], Tayade *et al.* (2019)^[16], Saini *et al.* (2020)^[2], Chaudhary *et al.* (2022)^[12] and Kajla *et al.* (2022)^[5].

Table 2: General combining ability effects of the parents for Grain yield plant⁻¹ over the environments.

Sr. No.	Genotypes	Grain yield plant ⁻¹		
		Akola	Nipad	Pooled
1	AKAW-3717	-1.198**	-1.108**	-1.152**
2	AKAW-2862-1	1.750**	1.457**	1.604**
3	AKAW-2344	-1.044**	-1.098**	-1.072**
4	AKAW-1071	-0.353**	0.042	-0.155
5	HD-3086	0.571**	0.406**	0.489**
6	HI-1633	0.109	-0.209	-0.051
7	GW-2010-288	0.120	0.008	0.064
8	SSN-2021-41	0.481**	0.829**	0.655**
9	AKW-381	-0.199	-0.430**	-0.314**
10	MACS-6478	-0.237*	0.102	-0.067
	SE (gi) ±	0.089	0.096	0.093
	SE (gi-gj) ±	0.133	0.144	0.139
	CD 5%	0.302	0.325	0.313
	CD 1%	0.434	0.466	0.450

At Akola, among the parents, AKAW-2862-1 (1.750) revealed significantly highest desirable GCA effects and was found as best general combiner for grain yield plant⁻¹ (Table 2), followed by HD-3086 (0.571). Whereas the parent AKAW-3717 (-1.198) exhibited significantly lowest

negative GCA effect. At Nipad, among the parents, AKAW-2862-1 (1.457) revealed significantly highest desirable GCA effects and was found as best general combiner for grain yield plant⁻¹, followed by SSN-2021-41.

Table 3: Specific combining ability effects of the direct and reciprocal crosses for grain yield plant⁻¹ over the environments.

S. N.	Crosses	Grain yield plant ⁻¹			S. N.	Crosses	Grain yield plant ⁻¹		
		Akola	Nipad	Pooled			Akola	Nipad	Pooled
	Direct crosses					Reciprocal crosses			
1	AKAW-3717 x AKAW-2862-1	-3.289**	-3.177**	-3.234**	46	AKAW-2862-1 x AKAW-3717	0.000	0.130	0.066
2	AKAW-3717 x AKAW-2344	-0.494	-0.491	-0.493	47	AKAW-2344 x AKAW-3717	1.538**	1.026**	1.282**
3	AKAW-3717 x AKAW-1071	-0.160	-0.349	-0.255	48	AKAW-2344 x AKAW-2862-1	-2.308**	-2.051**	-2.179**
4	AKAW-3717 x HD-3086	-1.597**	-1.611**	-1.604**	49	AKAW-1071 x AKAW-3717	0.769*	1.026**	0.897**
5	AKAW-3717 x HI-1633	0.404	0.287	0.345	50	AKAW-1071 x AKAW-2862-1	5.128**	2.821**	3.974**
6	AKAW-3717 x GW-2010-288	-0.120	-0.187	-0.154	51	AKAW-1071 x AKAW-2344	0.769*	0.769*	0.769*
7	AKAW-3717 x SSN-2021-41	0.545*	0.916**	0.729*	52	HD-3086 x AKAW-3717	1.282**	0.641	0.962**
8	AKAW-3717 x AKW-381	3.916**	2.558**	3.237**	53	HD-3086 x AKAW-2862-1	0.513	0.256	0.385
9	AKAW-3717 x MACS-6478	-1.430**	-0.024	-0.728*	54	HD-3086 x AKAW-2344	0.513	0.385	0.449
10	AKAW-2862-1 x AKAW-2344	0.660*	0.534	0.597*	55	HD-3086 x AKAW-1071	-2.051**	-1.410**	-1.731**
11	AKAW-2862-1 x AKAW-1071	-1.571**	-1.119**	-1.345**	56	HI-1633 x AKAW-3717	2.821**	1.923**	2.372**
12	AKAW-2862-1 x HD-3086	1.864**	1.337**	1.601**	57	HI-1633 x AKAW-2862-1	3.974**	2.949**	3.462**
13	AKAW-2862-1 x HI-1633	-1.648**	-0.483	-1.065**	58	HI-1633 x AKAW-2344	1.026**	0.641	0.833**
14	AKAW-2862-1 x GW-2010-288	4.111**	2.761**	3.436**	59	HI-1633 x AKAW-1071	-3.846**	-2.692**	-3.269**
15	AKAW-2862-1 x SSN-2021-41	2.340**	2.325**	2.332**	60	HI-1633 x HD-3086	0.000	0.256	0.128
16	AKAW-2862-1 x AKW-381	-2.109**	-1.929**	-2.019**	61	GW-2010-288 x AKAW-3717	2.821**	1.923**	2.372**
17	AKAW-2862-1 x MACS-6478	2.031**	1.513**	1.772**	62	GW-2010-288 x AKAW-2862-1	-0.513	-0.256	-0.385
18	AKAW-2344 x AKAW-1071	-1.083**	-1.128**	-1.105**	63	GW-2010-288 x AKAW-2344	-0.128	0.256	0.064
19	AKAW-2344 x HD-3086	-0.725*	-1.364**	-1.044**	64	GW-2010-288 x AKAW-1071	2.821**	2.436**	2.628**
20	AKAW-2344 x HI-1633	1.019**	0.790**	0.906**	65	GW-2010-288 x HD-3086	2.564**	2.179**	2.372**
21	AKAW-2344 x GW-2010-288	-1.940**	-0.837*	-1.389**	66	GW-2010-288 x HI-1633	-4.231**	-3.077**	-3.654**
22	AKAW-2344 x SSN-2021-41	0.391	0.393	0.392	67	SSN-2021-41 x AKAW-3717	-1.795**	-0.513	-1.154**
23	AKAW-2344 x AKW-381	3.378**	2.549**	2.964**	68	SSN-2021-41 x AKAW-2862-1	2.435**	-0.128	1.153**

24	AKAW-2344 x MACS-6478	-2.353**	-1.995**	-2.174**	69	SSN-2021-41 x AKAW-2344	4.615**	3.333**	3.974**
25	AKAW-1071 x HD-3086	-1.930**	-0.965**	-1.448**	70	SSN-2021-41 x AKAW-1071	1.154**	0.641	0.897**
26	AKAW-1071 x HI-1633	0.071	-0.350	-0.139	71	SSN-2021-41 x HD-3086	0.256	-1.410**	-0.577
27	AKAW-1071 x GW-2010-288	-0.196	-0.824**	-0.510	72	SSN-2021-41 x HI-1633	0.000	-0.513	-0.256
28	AKAW-1071 x SSN-2021-41	3.417**	1.689**	2.553**	73	SSN-2021-41 x GW-2010-288	-0.385	-1.795**	-1.090**
29	AKAW-1071 x AKW-381	0.250	-0.130	0.060	74	AKW-381 x AKAW-3717	1.923**	1.410**	1.667**
30	AKAW-1071 x MACS-6478	1.186**	2.108**	1.647**	75	AKW-381 x AKAW-2862-1	-1.923**	-1.538**	-1.731**
31	HD-3086 x HI-1633	3.762**	2.235**	2.999**	76	AKW-381 x AKAW-2344	-2.308**	-1.923**	-2.115**
32	HD-3086 x GW-2010-288	-1.120**	-1.444**	-1.283**	77	AKW-381 x AKAW-1071	-1.667**	-1.154**	-1.410**
33	HD-3086 x SSN-2021-41	-0.712*	0.556	-0.079	78	AKW-381 x HD-3086	-3.718**	-2.821**	-3.269**
34	HD-3086 x AKW-381	0.352	0.147	0.250	79	AKW-381 x HI-1633	0.000	-0.385	-0.192
35	HD-3086 x MACS-6478	3.467**	3.077**	3.272**	80	AKW-381 x GW-2010-288	-1.923**	-1.538**	-1.731**
36	HI-1633 x GW-2010-288	0.753**	0.581	0.667*	81	AKW-381 x SSN-2021-41	-1.923**	-0.128	-1.026**
37	HI-1633 x SSN-2021-41	3.597**	2.838**	3.217**	82	MACS-6478 x AKAW-3717	1.154**	0.128	0.641*
38	HI-1633 x AKW-381	-3.160**	-2.699**	-2.929**	83	MACS-6478 x AKAW-2862-1	1.154**	1.410**	1.282**
39	HI-1633 x MACS-6478	-3.891**	-2.718**	-3.304**	84	MACS-6478 x AKAW-2344	-0.385	0.295	-0.045
40	GW-2010-288 x SSN-2021-41	-1.414**	-0.200	-0.808**	85	MACS-6478 x AKAW-1071	4.103**	4.692**	4.397**
41	GW-2010-288 x AKW-381	-2.017**	-1.249**	-1.634**	86	MACS-6478 x HD-3086	-3.462**	-3.462**	-3.462**
42	GW-2010-288 x MACS-6478	1.483**	0.783**	1.132**	87	MACS-6478 x HI-1633	0.513	-0.128	0.192
43	SSN-2021-41 x AKW-381	-1.352**	-0.660*	-1.007**	88	MACS-6478 x GW-2010-288	5.385**	3.846**	4.615**
44	SSN-2021-41 x MACS-6478	-2.340**	-3.243**	-2.792**	89	MACS-6478 x SSN-2021-41	-0.641*	-0.641	-0.641*
45	AKW-381 x MACS-6478	0.263	-0.190	0.037	90	MACS-6478 x AKW-381	0.769*	0.641	0.706*
	SE (sij) ±	0.270	0.291	0.281		SE (rij) ±	0.298	0.321	0.310
	SE (sij-skl) ±	0.377	0.406	0.392		SE (rij-rkl) ±	0.422	0.454	0.438

(0.829). Whereas, the parent AKAW-3717 (-1.808) exhibited significantly lowest negative GCA effect. In pooled data, among the parents, AKAW-2862-1 (1.604) revealed significantly highest desirable GCA effects and was found as best general combiner for grain yield plant⁻¹, followed by SSN-2021-41 (0.655). Whereas, the parent AKAW-3717 (-1.152) exhibited significantly lowest negative GCA effect.

At Akola, out of total crosses including reciprocal crosses, thirty-six crosses exhibited the significant sca effects in the desirable direction for grain weight plant⁻¹ (Table-3). The reciprocal cross MACS-6478 x GW-2010-288 (5.385) recorded the highest positive significant sca effect followed by the reciprocal crosses AKAW-1071 x AKAW-2862-1 (5.128) and SSN-2021-41 x AKAW-2344 (4.615). Out of the remaining crosses, reciprocal cross GW-2010-288 x HI-1633 (-4.231) exhibited the significantly lowest negative sca effect. At Nipahad, out of total crosses including reciprocal

crosses, twenty-eight crosses exhibited the significant sca effects in the desirable direction for grain weight plant⁻¹. The reciprocal cross MACS-6478 x AKAW-1071 (4.692) recorded the highest positive significant sca effect followed by reciprocal crosses MACS-6478 x GW-2010-288 (3.846) and cross SSN-2021-41 x AKAW-2344 (3.333). Out of the remaining crosses, reciprocal cross MACS-6478 x HD-3086 (-3.462) exhibited the significant lowest negative sca effect. In pooled data, out of total crosses including reciprocal crosses, thirty-six crosses exhibited the significant sca effects in the desirable direction for grain weight plant⁻¹. The reciprocal cross MACS-6478 x GW-2010-288 (4.615) recorded the highest positive significant sca effect followed by reciprocal crosses MACS-6478 x AKAW-1071 (4.397) and SSN-2021-41 x AKAW-2344 (3.974). Out of the remaining crosses, reciprocal cross GW-2010-288 x HI-1633 (-3.654) exhibited the significantly lowest negative sca effect.

Table 4: GCA effects of promising parents in desirable direction for yield and other traits over the environments

Sr. No	Genotypes	GCA									
		Days to heading	Days to maturity	Plant height	Number of effective tillers plant ⁻¹	Spike length	Number of spikelets spike ⁻¹	Number of grains spike ⁻¹	Grain weight spike ⁻¹	1000 grain weight	Grain yield plant ⁻¹
		Parents									
1	AKAW-3717	-	-	-	-	-	-	-	-	-	-
2	AKAW-2862-1	-1.088**	-1.175**	-	0.168*	-	-	-	0.081**	1.387**	1.604**
3	AKAW-2344	-	-	-1.479*	-	0.689**	1.048**	-	-	-	-
4	AKAW-1071	-	-	-	-	-	-	-	-	-	-
5	HD-3086	-	-	-	-	-	-	-	-	-	0.489**
6	HI-1633	-	-0.892*	-	-	0.135*	-	-	0.066**	1.309**	-
7	GW-2010-288	-1.014**	-1.183**	-	-	0.213**	0.195*	2.326**	0.175**	1.461**	-
8	SSN-2021-41	-	-	-	-	-	0.201*	-	0.053**	-	0.655**
9	AKW-381	-1.930**	-1.908**	-	-	-	-	-	-	-	-
10	MACS-6478	-	-	-2.801**	-	-	-	-	-	-	-

Table 5: SCA effects of promising crosses in desirable direction for yield and other traits over environments

S.N.	Crosses	SCA									
		Days to heading	Days to maturity	Plant height	No. of effective tillers plant ⁻¹	Spike length	No. of spikelets spike ⁻¹	No. of grains spike ⁻¹	Grain weight spike ⁻¹	1000 grain wt.	Grain yield plant ⁻¹
	Direct crosses										
1	AKAW-3717 x AKAW-2862-1	-	-	-5.893**	-	0.438*	-	-	-	-	-
2	AKAW-3717 x AKAW-2344	-	-	-5.236**	-	-	-	-	-	-	-
3	AKAW-3717 x AKAW-1071	-1.986*	-	-	-	0.401*	-	-	-	-	-
4	AKAW-3717 x HD-3086	-	-	-4.451*	-	-	-	-	-	-	-
5	AKAW-3717 x HI-1633	-	-	-	-	-	-	-	-	-	-
6	AKAW-3717 x GW-2010-288	-	-	-3.703*	-	-	-	-	-	-	-
7	AKAW-3717 x SSN-2021-41	-	-	-	-	-	-	-	-	-	0.729*
8	AKAW-3717 x AKW-381	-	-	-	0.607**	-	-	3.505**	0.180**	-	3.237**
9	AKAW-3717 x MACS-6478	-	-	-	-	-	-	-	-	-	-
10	AKAW-2862-1 x AKAW-2344	-	-	-	-	-	-	-	-	-	0.597*
11	AKAW-2862-1 x AKAW-1071	-	-	-	-	-	-	-	-	-	-
12	AKAW-2862-1 x HD-3086	-	-	-	0.613**	-	-	2.462*	0.186**	-	1.601**
13	AKAW-2862-1 x HI-1633	-	-	-	-	-	-	-	0.090*	-	-
14	AKAW-2862-1 x GW-2010-288	-	-	-	0.717**	0.457*	0.889**	3.168**	0.260**	2.583*	3.436**
15	AKAW-2862-1 x SSN-2021-41	-	-	-	0.327*	-	-	-	0.074*	-	2.332**
16	AKAW-2862-1 x AKW-381	-	-	-	-	-	-	-	-	-	-
17	AKAW-2862-1 x MACS-6478	-	-	-	0.511**	-	-	-	-	-	1.772**
18	AKAW-2344 x AKAW-1071	-	-	-3.585*	-	-	-	-	-	-	-
19	AKAW-2344 x HD-3086	-2.020*	-2.425*	-	-	-	-	-	-	3.737**	-
20	AKAW-2344 x HI-1633	-	-	-	-	-	-	-	-	-	0.906**
21	AKAW-2344 x GW-2010-288	-	-	-	-	-	-	-	-	-	-
22	AKAW-2344 x SSN-2021-41	-	-	-	0.384*	0.853**	0.492*	-	0.111**	-	-
23	AKAW-2344 x AKW-381	-	-	-	0.505**	-	0.677**	3.899**	0.081*	-	2.964**
24	AKAW-2344 x MACS-6478	-1.762*	-	-	-	-	-	-	-	-	-
25	AKAW-1071 x HD-3086	-	-	-	-	-	0.545*	-	-	-	-
26	AKAW-1071 x HI-1633	-1.578*	-2.142*	-	-	-	-	-	-	2.098*	-
27	AKAW-1071 x GW-2010-288	-	-	-	-	-	-	-	-	-	-
28	AKAW-1071 x SSN-2021-41	-	-	-	0.404*	-	0.719**	3.315**	0.151**	-	2.553**
29	AKAW-1071 x AKW-381	-	-	-	-	-	-	-	0.200**	2.163*	-
30	AKAW-1071 x MACS-6478	-	-	-	-	-	-	4.923**	-	-	1.647**
31	HD-3086 x HI-1633	-	-	-	0.525**	0.361*	-	3.965**	0.179**	-	2.999**

32	HD-3086 x GW-2010-288	-	-	-	-	-	-	-	-	-	-
33	HD-3086 x SSN-2021-41	-	-	-	-	-	-	-	-	-	-
34	HD-3086 x AKW-381	-	-	-	-	-	-	-	-	-	-
35	HD-3086 x MACS-6478	-	-	-	0.570**	-	0.642**	-	0.102**	-	3.272**
36	HI-1633 x GW-2010-288	-	-	-	-	-	-	-	-	-	0.667*
37	HI-1633 x SSN-2021-41	-	-	-	0.594**	-	-	3.724**	0.109**	-	3.217**
38	HI-1633 x AKW-381	-	-	-3.563*	-	-	-	-	-	2.690*	-
39	HI-1633 x MACS-6478	-	-	-4.775**	-	-	-	-	-	-	-
40	GW-2010-288 x SSN-2021-41	-	-	-	-	-	0.511*	-	0.209**	3.963**	-
41	GW-2010-288 x AKW-381	-	-	-	-	-	-	-	-	-	-
42	GW-2010-288 x MACS-6478	-	-	-	-	0.386*	-	-	0.395**	4.661**	1.132**
43	SSN-2021-41 x AKW-381	-	-	-	0.322*	-	-	-	-	-	-
44	SSN-2021-41 x MACS-6478	-1.671*	-	-3.924*	-	-	-	-	-	-	-
45	AKW-381 x MACS-6478	-	-	-	-	-	-	-	0.080*	-	-

S.N.	Crosses	SCA									
		Days to heading	Days to maturity	Plant height	No. of effective tillers plant ⁻¹	Spike length	No. of spikelets spike ⁻¹	No. of grains spike ⁻¹	Grain weight spike ⁻¹	1000 grain wt.	Grain yield plant ⁻¹
	Reciprocal crosses										
46	AKAW-2862-1 x AKAW-3717	-	-	-	-	-	-	-	-	-	-
47	AKAW-2344 x AKAW-3717	-	-	-	-	-	0.755**	2.783*	0.150**	-	-
48	AKAW-2344 x AKAW-2862-1	-	-	-	-	-	-	-	-	-	-
49	AKAW-1071 x AKAW-3717	-	-	-	-	-	-	-	-	-	0.897**
50	AKAW-1071 x AKAW-2862-1	-	-	-	0.430*	-	-	4.267**	0.279**	2.434*	3.974**
51	AKAW-1071 x AKAW-2344	-	-	-	-	-	-	2.967*	0.173**	-	0.769*
52	HD-3086 x AKAW-3717	-	-	-	-	-	-	-	0.094*	-	0.962**
53	HD-3086 x AKAW-2862-1	-	-	-	-	-	-	-	0.126**	3.230**	-
54	HD-3086 x AKAW-2344	-	-	-	-	0.593**	0.825**	-	0.166**	2.370*	-
55	HD-3086 x AKAW-1071	-	-	-	-	-	-	-	-	-	-
56	HI-1633 x AKAW-3717	-	-	-	0.359*	-	-	-	-	-	2.372**
57	HI-1633 x AKAW-2862-1	-	-	-	0.718**	-	-	4.050**	0.301**	2.406*	3.462**
58	HI-1633 x AKAW-2344	-	-	-	-	0.513*	0.758**	2.647*	0.081*	-	0.833**
59	HI-1633 x AKAW-1071	-	-	-3.909*	-	-	-	-	-	4.372**	-
60	HI-1633 x HD-3086	-	-	-	-	-	-	-	-	-	-
61	GW-2010-288 x AKAW-3717	-	-	-	0.488**	-	0.567*	-	-	-	2.372**
62	GW-2010-288 x AKAW-2862-1	-	-	-	-	-	-	-	-	3.069**	-
63	GW-2010-288	-	-	-	-	0.518**	1.100**	4.883**	-	-	-

	x AKAW-2344										
64	GW-2010-288 x AKAW-1071	-	-	-	-	-	0.933**	7.367**	0.299**	-	2.628**
65	GW-2010-288 x HD-3086	-	-	-	-	-	-	-	-	-	2.372**
66	GW-2010-288 x HI-1633	-	-	-5.158**	-	-	-	-	-	-	-
67	SSN-2021-41 x AKAW-3717	-	-	-	-	-	-	-	-	-	-
68	SSN-2021-41 x AKAW-2862-1	-	-	-	-	-	-	-	-	-	1.153**
69	SSN-2021-41 x AKAW-2344	-	-	-	0.775**	2.117**	1.683**	7.617**	0.247**	-	3.974**
70	SSN-2021-41 x AKAW-1071	-	-	-	-	-	-	3.533**	0.181**	-	0.897**
71	SSN-2021-41 x HD-3086	-	-	-	-	-	-	-	-	-	-
72	SSN-2021-41 x HI-1633	-	-	-	-	0.398*	-	-	0.113**	2.358*	-
73	SSN-2021-41 x GW-2010-288	-2.167*	-	-	-	0.455*	-	3.283*	0.337**	3.453**	-
74	AKW-381 x AKAW-3717	-	-	-	-	-	-	-	0.159**	-	1.667**
75	AKW-381 x AKAW-2862-1	-	-	-4.840*	-	-	0.603*	-	-	-	-
76	AKW-381 x AKAW-2344	-	-	-	-	-	-	3.883**	-	-	-
77	AKW-381 x AKAW-1071	-	-	-	-	-	0.550*	-	0.131**	-	-
78	AKW-381 x HD-3086	-	-	-	-	-	-	2.500*	-	-	-
79	AKW-381 x HI-1633	-	-	-	-	-	-	-	-	-	-
80	AKW-381 x GW-2010-288	-	-	-	-	-	-	-	-	-	-
81	AKW-381 x SSN-2021-41	-	-	-	-	-	1.233**	-	-	-	-
82	MACS-6478 x AKAW-3717	-	-	-	-	-	-	-	-	-	0.641*
83	MACS-6478 x AKAW-2862-1	-	-	-	0.393*	-	-	2.567*	0.143**	-	1.282**
84	MACS-6478 x AKAW-2344	-	-	-	-	-	-	2.617*	-	-	-
85	MACS-6478 x AKAW-1071	-	-	-	0.674**	-	0.550*	4.267**	-	-	4.397**
86	MACS-6478 x HD-3086	-	-	-	-	-	-	-	-	-	-
87	MACS-6478 x HI-1633	-	-	-	-	-	-	2.700*	0.138**	-	-
88	MACS-6478 x GW-2010-288	-1.750*	-	-	0.513**	1.124**	0.850**	7.950**	0.679**	5.537**	4.615**
89	MACS-6478 x SSN-2021-41	-	-	-4.208*	-	-	-	-	-	-	-
90	MACS-6478 x AKW-381	-1.832*	-	-	-	-	-	-	-	-	0.706*

Among the parents, AKAW-2862-1 was the best general combiner for grain yield plant⁻¹ (1.604) and yield related traits over the environments (Table 4). This parent exhibited the significant and desirable GCA effect for days to heading (-1.088), days to maturity (-1.175), grain weight spike⁻¹ (0.081), 1000 grain weight (1.387), grain weight plant⁻¹ (1.604), protein content (0.184), gluten content (0.157), membrane thermostability index at 60 DAS (1.849) and membrane thermostability index at 75 DAS (1.328) over the environments. Similarly, the parent GW-2010-288 was also a good combiner for days to heading (1.014), days to maturity (1.183), spike length (0.213), number of spikelets spike⁻¹ (0.195), number of grains spike⁻¹ (2.326), grain

weight spike⁻¹ (0.175), 1000 grain weight (1.461) membrane thermostability index at 60 DAS (4.671) and membrane thermostability index at 75 DAS (3.756) over the environments.

Thus, the above promising ten parents having high GCA effects for grain yield plant⁻¹ (g), and yield related traits viz., days to heading, days to maturity, plant height (cm), number of effective tillers plant⁻¹, spike length (cm), number of spikelets spike⁻¹, number of grains spike⁻¹, grain weight spike⁻¹ (g), 1000 grain weight (g) can be suitably used in the hybridization for the improvement of individual characters per se. Estimates of GCA effects of the parents (Table 4)

revealed that none of the parent was consistently good general combiner for all the traits under study.

The similar results were also recorded by Kumar and Kerkhi (2015)^[6], Ahmad *et al.* (2017)^[1], Patel (2017)^[9], Gommaal (2018)^[3], Ranjitha *et al.* (2018)^[11], Nagar *et al.* (2019)^[8], Saini *et al.* (2020)^[12], Kajla *et al.* (2022)^[5], Chaudhary *et al.* (2022)^[2], Tiwari *et al.* (2024)^[17] and Puri *et al.* (2025)^[10].

Among the total 90 crosses including both direct and reciprocal crosses, the direct cross AKAW-2862-1 x GW-2010-288 recorded highest significant SCA effect for grain yield plant⁻¹ (3.436) and other yield contributing traits viz., number of effective tillers plant⁻¹ (0.717), spike length (0.457), number of spikelets spike⁻¹ (0.889), number of grains spike⁻¹ (3.1698), grain weight spike⁻¹ (0.260) and 1000 grain weight (2.583), followed by another direct crosses HD-3086 x MACS-6478 and AKAW-3717 x AKW-381, which were exhibited the significant SCA effects for grain yield plant⁻¹ (3.272 and 3.237 respectively) and for other component traits.

Among the reciprocal crosses, the cross MACS-6478 x GW-2010-288 reported the highest significant SCA effect for grain yield plant⁻¹ (4.615) and other important yield contributing traits viz., days to heading (-1.750), number of effective tillers plant⁻¹ (0.513), spike length (1.124), number of spikelets spike⁻¹ (0.850), number of grains spike⁻¹ (7.950), grain weight spike⁻¹ (0.679) and 1000 grain weight (5.537). While the cross MACS-6478 x AKAW-1071 is at second position and reported significant SCA effect for grain yield plant⁻¹ (4.397) and for other traits.

Similar results were also recorded by Kumar and kerkhi (2015)^[6], Ahmad *et al.* (2017)^[1], Patel (2017)^[9], Gommaal (2018), Ranjitha *et al.* (2018)^[11], Nagar *et al.* (2018)^[8], Saini *et al.* (2020)^[12], Kajla *et al.* (2022)^[5], Chaudhary *et al.* (2022), Tiwari *et al.* (2024)^[17] and Puri *et al.* (2025)^[10].

The Analysis of Variance for combining ability (Table 1) for different characters over the environments on pooled basis showed that the variance due to specific combining ability was higher in magnitude than variance due to general combining ability for the characters viz., days to heading, plant height, number of effective tillers plant⁻¹, spike length, number of spikelets spike⁻¹, number of grains spike⁻¹, grain weight spike⁻¹, 1000 grain weight and grain yield plant⁻¹ which indicates the predominance of non-additive gene action in controlling the expression of these traits. The ratio of GCA variance to the SCA variance was found lower than unity for these characters indicating the predominance of non-additive gene action in controlling the expression of these traits.

The similar results were reported by Ahmad *et al.* (2017)^[1], Patel (2017)^[9], Kumar *et al.* (2017)^a, Ranjitha *et al.* (2018)^[11], Tayade *et al.* (2019)^[16], Saini *et al.* (2020)^[12], Chaudhary *et al.* (2022)^[2] and Tiwari *et al.* (2024)^[17].

Conclusion

Estimates of GCA effects of the parents revealed that none of the parent was consistently good general combiner for all the traits under study. Among the crosses two direct crosses AKAW-2862-1 x SSN-2021-41 and AKAW-2862-1 x HD-3086 were identified as best combinations since they exhibited significant SCA effects and both the parents involved in these crosses expressed high x high gca effects. This explains the important role of additive x additive type of gene interaction in high-ranking performance of these

hybrids. The four direct crosses viz, AKAW-1071 x MACS-6478, GW-2010-288 x MACS-6478, AKAW-2862-1 x GW-2010-288 and AKAW-2862-1 x MACS-6478 and three reciprocal crosses viz., MACS-6478 x HD-3086, GW-2010-288 x AKAW-2862-1 and GW-2010-288 x HI-1633 had high x low, low x high and low x low gca effects for grain yield over the environments. This explains the important role of additive x dominant, dominant x additive and dominant x dominant type of gene interaction in high-ranking performance of these hybrids.

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Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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