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Research Article

Combining ability and heterosis studies in different crop sites for yield and yield contributing traits in sorghum (*Sorghum bicolor* (L.) Moench)

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Abstract
Forty eight hybrids, utilizing six male sterile lines and eight restorers of Sorghum (*Sorghum bicolor* (L.) Moench) were evaluated for general and specific combining ability, variance components and standard heterosis. Among the lines ICSA 427 and ICSA 433 and testers ICSR 13009 and ICSR 13031 were found to be good general combiners for grain yield per plot and other yield contributing traits. The estimates of σ^2_{gca} and σ^2_{sca} suggested a non-additive genetic variance for all the traits studied. Most of the cross combinations showed higher magnitude of specific combining ability effects volving high × high (H × H) and high × low (H × L) combining ability effects of lines and testers for grain yield per plot and other yield contributing traits. The estimates of standard heterosis for grain yield per plot ranged from -49.53 and -50.46 (ICSA 435 × ICSR 13004) to 41.96 and 39.35 (ICSA 433 × ICSR 13043) over CSV-41 and CSH-16, respectively. Out of 48 cross combinations, six registered highly significant positive heterosis (over CSV-41 and CSH-16) for grain yield per plot.

Key words: Sorghum, male sterility, heterosis, combining ability.

INTRODUCTION

The success of a hybrid breeding programme is decided by the parents chosen and a thorough knowledge of the traits. One of the most effective tools for determining the best parents for hybridization is combining ability. Majority of sorghum breeding efforts are intended to take advantage of genetic variation and develop high-yielding varieties. Sorghum [*Sorghum bicolor* (L.) Moench] is an often cross pollinated crop with a significant amount of genetic variability for yield (Tomar *et al*., 2012, Amare *et al*., 2015, and Yaqoob Muhammad, 2015) that can be profitably exploited through heterosis breeding.

The commercial utilization of heterosis in sorghum has been made possible by the discovery of male sterility (Stephens and Holland, 1954) and its frequent out crossing nature. It also helps in the choice of proper cross combinations for recombination breeding. The degree of heterosis establishes the basis for genetic variety and drives the selection of desirable parents for developing superior hybrids. Nevertheless, since environmental effects greatly influence estimates, heterosis and combining ability studies in a single location may not provide precise information. In the present investigation, efforts were made to study the heterosis and combining ability effects for yield and its components in sorghum over three locations to identify the superior hybrids and parents for yield and its contributing traits.

MATERIALS AND METHODS

Eight testers (used as males, restorers), ICSR 13004, ICSR13009, ICSR 13025, ICSR 13031, ICSR 13042, ICSR 13043, ICSR 13046 and ICSR 29 were crossed with six male sterile (female) lines *viz.,* ICSA 418, ICSA 419, ICSA 427, ICSA 433, ICSA 435 and ICSA 29004 in a line × tester mating design during *Kharif*, 2020. Forty-eight hybrids along with their 14 parents and two standard checks CSV-41 and CSH-16 were sown in a completely randomized block design in two replications simultaneously at three locations *viz*., Regional Agricultural Research Station (RARS) Palem, Agricultural Research Station (ARS), Tandur and College Farm, Rajendranagar during *Rabi* 2020-21. Each plot consisted 2 rows of 4 meter length with inter row spacing of 45 cm and intra row spacing of 10 cm. Normal recommended cultural practices were followed to raise a successful crop for better phenotypic expression of characters. In each location, five plants were selected randomly from each plot for recording observations on days to flowering (counted as the number of days from sowing to when 50% of the plants flowered), days to maturity (counted as the number of days from sowing to when 95% of the plants reached physiological maturity), plant height (measured in cm from the base to tip of the panicle after flowering), 100 seed weight (g), grain yield per plant (g), grain yield per plot (kg), fodder yield per plant (g) and fodder yield per plot (kg). Days to 50 % flowering and days to maturity were recorded on plot basis. Progeny mean scores pooled over environments were analyzed to estimate combining ability and heterosis using windostat software (version 9.2) at University Computer Centre, Rajendranagar, Hyderabad.

RESULTS AND DISCUSSION

Pooled analysis of variance for combining ability revealed that the mean squares due to general (GCA) and specific combining ability (SCA) variance were significant for all the characters both additive and non-additive genetic variance in their inheritance. Interaction of lines and testers showed significant differences for all the traits (**Table 1**). The estimates of σ^2_{sca} were more than σ^2_{sca} for all the traits studied and the ratio of $\sigma^2_{sca/}\sigma^2_{gca}$ is more than unity indicating non-additive gene action operating in the inheritance of yield contributing traits. Similar results have also been reported in sorghum by Mengistu *et al*. (2020), Kumari *et al*. (2018), Akata *et al*. (2017), Sayed and Said (2016), and Aruna *et al*. (2010). The findings of this study, such as non-additive genetic variance for grain yield and yield components, suggested that in early generations of sorghum, selection and accumulation of desired alleles for the enhancement of yield and yield components is likely to be effective.

The general combining ability effects (**Table 2**) revealed that among the lines ISCA 435 and ICSA 433 were good general combiners for days to 50 % flowering, days to maturity and plant height. For 100 seed weight, ICSA 418 and ICSA 419 were good general combiners whereas, lines ICSA 427 and ICSA 433 were found to be good general combiners for grain yield per plant, grain yield per

Table 1. Analysis of variance for combining ability for yield and yield related traits in sorghum

Source of variation	Degrees of freedom	Mean Sum of Squares							
		Days to 50% flowering	Days to maturity	Plant height	100 Seed weight	Grain yield per plot	Grain yield per plant	Fodder yield per plot	Fodder yield per plant
Replication	1	2.531	7.031*	2.000	0.492**	0.088	1.216	0.027	1.158
Location (l)	2	77.469***	87.875***	64.691***	0.391**	7.691***	3638.418***	3.551***	7523.535***
Lines (L)	5	206.181*	214.915	13647.160	7.766 ***	0.146	998.264	2.128	4329.541
Testers (T)	7	30.353	52.587	19338.570 *	1.125	1.100	1089.004	3.395	7991.861
Lines × testers	35	81.481***	124.018***	6611.670 ***	1.163 ***	1.080 ***	1284.368 ***	2.309***	11736.430 ***
L × l	10	3.431	4.671	8.103	0.497 **	0.356 ***	52.706 *	0.225	62.205 **
T × l	14	1.231	4.740	27.266	0.222	0.104	16.054	0.191	15.787
L × T × l	70	2.822 ***	5.369 ***	20.003 ***	0.157 ***	0.090 ***	25.689 ***	0.189 ***	19.960
Error	141	0.805	1.088	1.792	0.062	0.041	7.591	0.039	24.959
σ^2_{gca}		2.797	3.159	392.645	0.104	0.014	24.668	0.065	146.089
σ^2_{sca}		13.446	20.488	1101.646	0.183	0.173	212.796	0.378	1951.911
$\sigma^2_{sca/}\sigma^2_{gca}$		4.807	6.485	2.805	1.759	12.357	8.626	5.815	13.361

*P = 0.05; **P = 0. 01; ***P = 0.001

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Table 2. Estimates of general combining ability (*gca*) effects of parents for yield and its related characters in sorghum (pooled)

S.No.	Parents	Days to 50% flowering	Days to maturity	Plant height	100 Seed weight	Grain yield per plot	Grain yield per plant	Fodder yield per plot	Fodder yield per plant
				Females (A lines)					
1	ICSA 418	0.802***	1.531***	-12.076***	0.444***	-0.032	-3.351***	0.214***	2.357**
2	ICSA 419	3.156***	3.260***	32.882***	0.550***	-0.057	-1.731***	0.153***	4.370***
3	ICSA 427	0.302*	-0.385*	-3.264***	-0.058	0.067 *	7.842***	-0.020	3.785***
4	ICSA 433	-1.156***	-1.052***	-3.722***	-0.223***	0.072 *	3.160***	0.113***	10.330***
5	ICSA 435	-3.073***	-2.802***	-13.014***	-0.333***	-0.030	-3.574***	-0.100***	-3.782***
6	ICSA 29004	-0.031	-0.552***	-0.806***	-0.381***	-0.019	-2.346***	-0.360***	-17.059***
	S.E. ±	0.129	0.149	0.193	0.036	0.028	0.398	0.028	0.730
	CD @ 5%	0.256	0.298	0.382	0.071	0.058	0.786	0.056	1.426
	CD @ 1%	0.338	0.390	0.504	0.094	0.074	1.040	0.073	1.907
				Males (R- lines)					
1	ICSR 13004	1.441***	1.066***	12.542 ***	0.023	-0.247 ***	-5.157***	0.122***	2.248**
2	ICSR13009	-0.226	-1.323***	2.792***	0.125**	0.213 ***	9.216***	-0.389***	-20.485***
3	ICSR 13025	-1.031***	-0.295	4.708***	-0.158***	-0.115 ***	0.304	0.274***	20.861***
4	ICSR 13031	-0.170	0.094	-14.792***	0.011	0.267 ***	4.469***	-0.187***	-14.468***
5	ICSR 13042	-0.642***	-0.517**	11.958***	0.245***	-0.110 **	-4.895***	0.140***	17.710***
6	ICSR 13043	0.080	0.483**	-47.625***	0.150***	0.010	-4.364***	0.493***	6.549***
7	ICSR 13046	1.302***	2.066***	-0.292	-0.108*	-0.081 *	4.519***	-0.323***	-11.267***
8	ICSR 29	-0.753***	-1.573***	30.708***	-0.289***	0.062	-4.091***	-0.129***	-1.148***
	S.E. ±	0.149	0.172	0.223	0.041	0.033	0.460	0.032	0.843
	CD @ 5%	0.296	0.344	0.441	0.082	0.066	0.908	0.065	1.646
	CD @ 1%	0.391	0.450	0.582	0.109	0.086	1.201	0.085	2.203

*P = 0.05; **P = 0.01; ***P = 0.001

plot, fodder yield per plot (except ICSA 427) and fodder yield per plant (**Table 2**). In case of testers ICSR 13009 and ICSR 13031 found to be good general combiners for grain yield per plant and grain yield per plot. Tester ICSR 13043 recorded the highest desirable *gca* (-47.625) for plant height and desirable *gca* for 100 seed weight, fodder yield per plot and fodder yield per plant. For traits *viz*., days to 50 % flowering and days to maturity, ICSR 13042 and ICSR 29 found to be good general combiners. The above parents were identified as good sources of favourable genes for improving grain yield *via* various yield contributing traits and it was found that using these parental lines to improve grain yield in sorghum would be more profitable. Therefore, it is critical to understand the parents' combining ability, especially for hybrid cultivar production, in order to improve the breeding strategy. In sorghum, Da silva *et al*. (2020) found that *gca* impacts outweighed *sca* effects for grain yield and several yield-related characteristics.

Out of 48 crosses, 18 for days to 50 % flowering, 16 for days to maturity, 19 for plant height, 10 for 100 seed weight, 14 for grain yield per plot, 21 for grain yield per plant 15 for fodder yield per plot and 19 for fodder yield per plant manifested significant desirable specific combining ability values. The majority of the cross combinations showed to be promising for exploiting hybrid vigour. None of the F_1 hybrids (**Table 3**) had significant *sca* estimates for all of the traits examined simultaneously. For days to 50 % flowering, ICSA 29004 ICSR 13004 (-7.608), ICSA 427 × ICSR 13046 (-6.96), and ICSA 427 × ICSR 13043 (-5.747) recorded the best *sca* performance, while for days to maturity, ICSA 427 × ICSR 13046 (-9.253), ICSA 29004 × ICSR 13004 (-8.420), ICSA 427 × ICSR 13043 (-8.337), and ICSA 29004 × ICSR 13025 (-8.226) were found to be best specific combiners. The highest negative desirable *sca* effects for plant height exhibited by ICSA 419 × ICSR 13046 (- 66.521), ICSA 419 × ICSR 29 (-59.188), ICSA 418 × ICSR 13042 (-56.979) and ICSA 418 × ICSR 13004 (-53.229) whereas, the highest positive desirable *sca* for 100 seed weight recorded in ICSA 427 × ICSR 13004 (0.936), ICSA 418 × ICSR 29 (0.778), ICSA 418 × ICSR 13046 (0.681) and ICSA 433 × ICSR 13043 (0.639).

Table 3. Estimates of specific combining ability (*sca*) effects of hybrids for yield and yield component traits in sorghum (pooled)

Hybrids	Days to 50% flowering	Days to maturity	Plant height	100 Seed weight	Grain yield per plot	Grain yield per plant	Fodder yield per plot	Fodder yield per plant
ICSA 418 × ICSR 13004	0.059	-0.170	-53.229***	-0.950***	-0.360 ***	-14.870***	-0.821***	-37.004***
ICSA 418 × ICSR 13009	-4.441***	-5.615***	-29.646***	-0.169	-0.044	3.881***	0.084	-2.204
ICSA 418 × ICSR 13025	1.365***	1.858***	-31.063***	-0.302**	0.078	4.276***	0.169*	17.829***
ICSA 418 × ICSR 13031	-2.163***	0.969*	8.771***	0.145	-0.263 **	15.496***	0.919***	44.392***
ICSA 418 × ICSR 13042	1.142**	1.247**	-56.979***	-0.089	-0.046	-10.299***	-0.189*	1.418
ICSA 418 × ICSR 13043	0.087	-0.753	22.104***	-0.094	-0.236 **	2.248*	-0.495***	-40.066***
ICSA 418 × ICSR 13046	1.198**	-0.503	74.938***	0.681***	0.507 ***	-0.676	-0.069	-10.931***
ICSA 418 × ICSR 29	2.753***	2.969***	65.104***	0.778***	0.364 ***	-0.057	0.402***	26.566***
ICSA 419 × ICSR 13004	-0.128	-0.066	51.813***	0.177	0.125	0.126	0.437***	8.158***
ICSA 419 × ICSR 13009	2.205***	3.656***	41.396***	0.091	-0.238 **	4.017***	0.051	-12.669***
ICSA 419 × ICSR 13025	0.344	0.462	9.813***	0.191	-0.146	-4.525***	-0.282***	-41.934***
ICSA 419 × ICSR 13031	0.816*	-1.260**	19.146***	0.139	0.012	-8.744***	-0.088	10.244***
ICSA 419 × ICSR 13042	-1.378***	-1.149**	31.896***	0.422***	-0.073	-11.334***	0.227**	-6.004**
ICSA 419 × ICSR 13043	0.066	0.184	-28.354***	0.466***	0.389 ***	2.416*	0.014	25.916***
ICSA 419 × ICSR 13046	-2.323***	-1.899***	-66.521***	-0.792***	-0.176 *	5.862**	-1.099***	-53.329***
ICSA 419 × ICSR 29	0.399	0.073	-59.188***	-0.695***	0.107	12.182***	0.740***	69.619***
ICSA 427 × ICSR 13004	0.559	3.247***	21.625***	0.936***	0.697 ***	33.394***	0.750***	58.518***
ICSA 427 × ICSR 13009	4.892***	4.302***	6.875***	0.066	-0.283 ***	-14.104***	0.262**	-4.083*
ICSA 427 × ICSR 13025	3.365***	3.441***	-13.708***	-0.284**	-0.351 ***	-20.769***	-0.451***	-23.787***
ICSA 427 × ICSR 13031	1.003**	3.219***	-0.208	0.014	0.368 ***	2.625*	-0.265**	-18.750***
ICSA 427 × ICSR 13042	2.809***	3.830***	-0.625	-0.186	-0.379 ***	3.635**	-0.089	8.928***
ICSA 427 × ICSR 13043	-5.747***	-8.337***	3.792***	-0.659***	0.088	-6.244***	-0.010	10.182***
ICSA 427 × ICSR 13046	-6.969***	-9.253***	2.125***	0.383***	0.233 **	23.666***	-0.878***	-64.197***
ICSA 427 × ICSR 29	0.087	-0.448	-19.875***	-0.270**	-0.374 ***	-22.203***	0.681***	33.188***
ICSA 433 × ICSR 13004	2.351***	1.413**	-20.583***	0.234*	-0.293 ***	-6.276***	-0.506***	-43.877***
ICSA 433 × ICSR 13009	-3.316***	-3.865***	5.667***	-0.086	0.040	-6.595***	-0.564***	-19.026***
ICSA 433 × ICSR 13025	1.990***	5.608***	7.583***	0.014	-0.053	4.641***	0.493***	40.241***
ICSA 433 × ICSR 13031	-3.372***	-3.115***	-12.417***	-0.489***	-0.058	-4.168***	0.119	-20.933***
ICSA 433 × ICSR 13042	-2.733***	-3.337***	16.667***	0.045	0.087	7.050***	0.298***	28.688***
ICSA 433 × ICSR 13043	3.545***	3.163***	1.917***	0.639***	0.960 ***	30.482***	0.548***	45.832***
ICSA 433 × ICSR 13046	5.323***	3.080***	-2.917***	-0.152	-0.165 *	-8.838***	-0.093	2.431
ICSA 433 × ICSR 29	-3.788***	-2.948***	4.083***	-0.205*	-0.519 ***	-16.296***	-0.295***	-33.357***
ICSA 435 × ICSR 13004	4.767***	3.997***	-26.292***	-0.273**	-0.473 ***	-8.496***	0.105	18.413***
ICSA 435 × ICSR 13009	-2.399***	-2.781***	-10.708***	0.358***	0.087	10.423***	0.484***	39.043***
ICSA 435 × ICSR 13025	-2.427***	-3.142***	4.875***	0.258*	-0.001	2.247*	-0.399***	-45.328***
ICSA 435 × ICSR 13031	2.712***	-0.365	-3.958***	-0.011	0.398 ***	2.546*	-0.484***	-18.606***
ICSA 435 × ICSR 13042	-3.149***	-5.253***	8.958***	-0.145	0.773 ***	16.771***	-0.259**	-25.508***
ICSA 435 × ICSR 13043	3.628***	6.413***	4.375***	-0.334**	-0.581 ***	-18.909***	0.680***	46.495***
ICSA 435 × ICSR 13046	-2.594***	3.997***	18.042***	-0.059	-0.455 ***	-22.551***	1.075***	73.385***
ICSA 435 × ICSR 29	-0.538	-2.865***	4.708***	0.205*	0.251 **	17.968***	-1.201***	-87.894***
ICSA 29004 × ICSR 13004	-7.608***	-8.420***	26.667***	-0.125	0.303 ***	-3.878***	0.035	-4.208*
ICSA 29004 × ICSR 13009	3.059***	4.302***	-13.583***	-0.261*	0.438 ***	2.377*	-0.318***	-1.060
ICSA 29004 × ICSR 13025	-4.635***	-8.226***	22.500***	0.123	0.473 ***	14.130***	0.471***	52.978***
ICSA 29004 × ICSR 13031	1.003**	0.552	-11.333***	0.203*	-0.458 ***	-7.754***	-0.202*	3.653
ICSA 29004 × ICSR 13042	3.309***	4.663***	0.083	-0.047	-0.363 ***	-5.824***	0.013	-7.522***
ICSA 29004 × ICSR 13043	-1.580***	-0.670	-3.833***	-0.019	-0.621 ***	-9.993***	-0.738***	-88.359***
ICSA 29004 × ICSR 13046	5.365***	4.580***	-25.667***	-0.061	0.056	2.536*	1.065***	52.640***
ICSA 29004 × ICSR 29	1.087**	3.219***	5.167***	0.186	0.171 *	8.406***	-0.326***	-8.122***
S.E. ±	0.366	0.422	0.546	0.101	0.081	1.127	0.079	2.066
CD @ 5 %	0.724	0.842	1.080	0.201	0.163	2.224	0.158	4.032
CD @ 1 %	0.958	1.103	1.427	0.267	0.211	2.943	0.208	5.396

*P = 0.05; **P = 0.01

Table 4. Estimation of heterosis over standard checks (CSV- 41 and CSH-16) for days to 50% flowering, days to maturity, plant height and 100 seed weight in sorghum (in per cent)

S.No.	Hybrids	Days to 50 % flowering		Days to maturity		Plant height		100 seed weight	
		CSV-41	CSH-16	CSV-41	CSH-16	CSV-41	CSH-16	CSV-41	CSH-16
1	ICSA 418 × ICSR 13004	4.81**	10.99**	3.36**	2.42**	-32.21**	-38.28**	-35.98**	-33.15**
2	ICSA 418 × ICSR 13009	-4.56**	1.07	-3.82**	-4.69**	-24.20**	-30.99**	-7.94	-3.87
3	ICSA 418 × ICSR 13025	3.04**	9.12**	3.97**	3.03**	-23.92**	-30.73**	-21.16**	-17.68**
4	ICSA 418 × ICSR 13031	-1.01	4.83**	3.51**	2.57**	-12.15**	-20.02**	-1.59	2.76
5	ICSA 418 × ICSR 13042	3.29**	9.38**	3.21**	2.27**	-34.72**	-40.56**	-1.59	2.76
6	ICSA 418 × ICSR 13043	2.78**	8.85**	2.29**	1.36*	-23.43**	-30.29**	-4.76	-0.55
7	ICSA 418 × ICSR 13046	6.33**	12.60**	3.97**	3.03**	34.52**	22.48**	11.64*	16.57**
8	ICSA 418 × ICSR 29	5.57**	11.80**	3.82**	2.87**	46.77**	33.63**	8.99	13.81**
9	ICSA 419 × ICSR 13004	8.10**	14.48**	5.04**	4.08**	54.58**	40.74**	3.17	7.73
10	ICSA 419 × ICSR 13009	9.11**	15.55**	6.26**	5.30**	42.91**	30.11**	3.70	8.29
11	ICSA 419 × ICSR 13025	5.06**	11.26**	4.27**	3.33**	25.75**	14.49**	-2.12	2.21
12	ICSA 419 × ICSR 13031	7.09**	13.40**	3.05**	2.12**	19.86**	9.13**	1.59	6.08
13	ICSA 419 × ICSR 13042	3.04**	9.12**	2.60**	1.66**	42.72**	29.94**	17.99**	23.20**
14	ICSA 419 × ICSR 13043	6.33**	12.60**	4.73**	3.78**	-26.62**	-33.19**	16.40**	21.55**
15	ICSA 419 × ICSR 13046	4.56**	10.72**	4.27**	3.33**	-21.31**	-28.36**	-31.75**	-28.73**
16	ICSA 419 × ICSR 29	5.57**	11.80**	2.75**	1.82**	0.87	-8.17**	-34.39**	-31.49**
17	ICSA 427 × ICSR 13004	4.81**	10.99**	4.73**	3.78**	16.20**	5.79**	7.94	12.71**
18	ICSA 427 × ICSR 13009	8.86**	15.28**	3.51**	2.57**	2.03**	-7.11**	-16.40**	-12.71**
19	ICSA 427 × ICSR 13025	5.32**	11.53**	3.66**	2.72**	-8.78**	-16.94**	-36.51**	-33.70**
20	ICSA 427 × ICSR 13031	3.04**	9.12**	3.82**	2.87**	-12.25**	-20.11**	-21.69**	-18.23**
21	ICSA 427 × ICSR 13042	5.06**	11.26**	3.82**	2.87**	2.99**	-6.23**	-20.63**	-17.13**
22	ICSA 427 × ICSR 13043	-6.84**	-1.34	-6.41**	-7.26**	-28.93**	-35.29**	-38.62**	-35.91**
23	ICSA 427 × ICSR 13046	-6.84**	-1.34	-5.80**	-6.66**	-2.51**	-11.24**	-13.76**	-9.94*
24	ICSA 427 × ICSR 29	0.76	6.70**	-1.07	-1.97**	2.70**	-6.50**	-40.21**	-37.57**
25	ICSA 433 × ICSR 13004	5.32**	11.53**	2.44**	1.51**	-8.49**	-16.68**	-19.58**	-16.02**
26	ICSA 433 × ICSR 13009	-5.82**	-0.27	-4.58**	-5.45**	1.06*	-7.99**	-26.46**	-23.20**
27	ICSA 433 × ICSR 13025	1.01	6.97**	5.04**	4.08**	3.28**	-5.97**	-32.28**	-29.28**
28	ICSA 433 × ICSR 13031	-5.82**	-0.27	-2.60**	-3.48**	-19.58**	-26.78**	-42.86**	-40.33**
29	ICSA 433 × ICSR 13042	-5.57**	0.00	-3.36**	-4.24**	12.73**	2.63**	-18.52**	-14.92**
30	ICSA 433 × ICSR 13043	5.06**	11.26**	3.51**	2.57**	-30.28**	-36.52**	-2.65	1.66
31	ICSA 433 × ICSR 13046	9.62**	16.09**	4.89**	3.93**	-5.69**	-14.14**	-35.98**	-33.15**
32	ICSA 433 × ICSR 29	-7.34**	-1.88*	-3.97**	-4.84**	16.30**	5.88**	-43.39**	-40.88**
33	ICSA 435 × ICSR 13004	6.08**	12.33**	3.21**	2.27**	-17.16**	-24.58**	-39.15**	-36.46**
34	ICSA 435 × ICSR 13009	-7.34**	-1.88*	-5.19**	-6.05**	-13.79**	-21.51**	-15.87**	-12.15*
35	ICSA 435 × ICSR 13025	-8.61**	-3.22**	-4.58**	-5.45**	-3.66**	-12.29**	-28.04**	-24.86**
36	ICSA 435 × ICSR 13031	0.51	6.43**	-1.68**	-2.57**	-20.06**	-27.22**	-31.22**	-28.18**
37	ICSA 435 × ICSR 13042	-9.11**	-3.75**	-6.72**	-7.56**	2.89**	-6.32**	-28.04**	-24.86**
38	ICSA 435 × ICSR 13043	2.28**	8.31**	4.89**	3.93**	-34.23**	-40.12**	-37.04**	-34.25**
39	ICSA 435 × ICSR 13046	-5.32**	0.27	4.12**	3.18**	1.06*	-7.99**	-36.51**	-33.70**
40	ICSA 435 × ICSR 29	-5.32**	0.27	-5.50**	-6.35**	11.28**	1.32**	-33.86**	-30.94**
41	ICSA 29004 × ICSR 13004	-8.10**	-2.68**	-6.11**	-6.96**	20.54**	9.75**	-35.98**	-33.15**
42	ICSA 29004 × ICSR 13009	5.57**	11.80**	3.36**	2.42**	-8.39**	-16.59**	-37.04**	-34.25**
43	ICSA 29004 × ICSR 13025	-7.34**	-1.88*	-7.18**	-8.02**	13.60**	3.42**	-33.86**	-30.94**
44	ICSA 29004 × ICSR 13031	2.53**	8.58**	1.22*	0.30	-17.26**	-24.67**	-25.93**	-22.65**
45	ICSA 29004 × ICSR 13042	5.32**	11.53**	4.43**	3.48**	4.82**	-4.57**	-26.46**	-23.20**
46	ICSA 29004 × ICSR 13043	-1.01	4.83**	0.46	-0.45	-31.92**	-38.02**	-28.57**	-25.41**
47	ICSA 29004 × ICSR 13046	11.39**	17.96**	6.72**	5.75**	-17.16**	-24.58**	-38.10**	-35.36**
48	ICSA 29004 × ICSR 29	1.77*	7.77**	2.14**	1.21*	18.61**	7.99**	-35.98**	-33.15**
	S.E. ±	0.518	0.518	0.597	0.597	0.773	0.773	0.144	0.144
	CD @ 5 %	1.227	1.227	1.413	1.413	1.828	1.828	0.342	0.342
	CD @ 1 %	1.816	1.816	2.092	2.092	2.705	2.705	0.506	0.506

*P = 0.05; **P = 0.01

Table 5. Estimation of heterosis over standard checks (CSV- 41 and CSH-16) for grain yield per plot, grain yield per plant, fodder yield per plot and fodder yield per plant in sorghum (in per cent)

S.No.	Hybrids	Grain yield per plot		Grain yield per plant		Fodder yield per plot		Fodder yield per plant	
		CSV-41	CSH-16	CSV-41	CSH-16	CSV-41	CSH-16	CSV-41	CSH-16
1	ICSA 418 × ICSR 13004	-43.91**	-44.95**	-24.65**	-29.48**	-21.62**	-30.86**	-24.97**	-32.98**
2	ICSA 418 × ICSR 13009	-4.26	-6.02	22.06**	14.24**	-8.96*	-19.69**	-17.84**	-26.61**
3	ICSA 418 × ICSR 13025	-14.81*	-16.37**	10.05**	3.00	15.13**	1.56	18.45**	5.81**
4	ICSA 418 × ICSR 13031	-12.68*	-14.29*	31.75**	23.31**	24.46**	9.80**	13.27**	1.18
5	ICSA 418 × ICSR 13042	-20.85**	-22.31**	-17.84**	-23.10**	-0.70	-12.40**	6.89**	-4.52**
6	ICSA 418 × ICSR 13043	-24.43**	-25.81**	0.61	-5.84**	0.80	-11.07**	-24.24**	-32.33**
7	ICSA 418 × ICSR 13046	8.85	6.85	9.01**	2.03	-11.75**	-22.15**	-17.55**	-26.35**
8	ICSA 418 × ICSR 29	8.85	6.85	-2.26	-8.52**	9.66**	-3.27	10.61**	-1.20
9	ICSA 419 × ICSR 13004	-20.43**	-21.89**	-1.22	-7.55**	16.90**	3.12	2.92	-8.06**
10	ICSA 419 × ICSR 13009	-15.40*	-16.96**	24.54**	16.56**	-11.96**	-22.34**	-22.84**	-31.07**
11	ICSA 419 × ICSR 13025	-27.49**	-28.82**	-0.08	-6.48**	-1.34	-12.97**	-15.69**	-24.69**
12	ICSA 419 × ICSR 13031	0.09	-1.75	-0.15	-6.55**	-9.92**	-20.54**	-5.73**	-15.79**
13	ICSA 419 × ICSR 13042	-23.49**	-24.90**	-17.01**	-22.33**	10.73**	-2.32	3.69*	-7.38**
14	ICSA 419 × ICSR 13043	6.21	4.26	3.13	-3.48	15.24**	1.66	15.96**	3.59*
15	ICSA 419 × ICSR 13046	-27.32**	-28.65**	20.52**	12.79**	-46.89**	-53.15**	-41.43**	-47.68**
16	ICSA 419 × ICSR 29	-5.53	-7.27	17.29**	9.77**	18.56**	4.59	37.25**	22.61**
17	ICSA 427 × ICSR 13004	15.15*	13.03*	59.20**	49.00**	21.41**	7.10*	32.35**	18.23**
18	ICSA 427 × ICSR 13009	-11.40	-13.03*	12.48**	5.28*	-10.73**	-21.25**	-18.10**	-26.84**
19	ICSA 427 × ICSR 13025	-31.66**	-32.92**	-9.48**	-15.28**	-12.34**	-22.67**	-5.31**	-15.41**
20	ICSA 427 × ICSR 13031	24.60**	22.31**	29.38**	21.09**	-21.19**	-30.48**	-23.22**	-31.41**
21	ICSA 427 × ICSR 13042	-32.77**	-34.00**	17.60**	10.06**	-4.99	-16.19**	12.17**	0.20
22	ICSA 427 × ICSR 13043	-2.81	-4.59	4.42	-2.27	8.91*	-3.93	6.31**	-5.03**
23	ICSA 427 × ICSR 13046	-0.09	-1.92	59.13**	48.93**	-45.33**	-51.77**	-48.20**	-53.73**
24	ICSA 427 × ICSR 29	-23.74**	-25.15**	-17.71**	-22.98**	11.11**	-1.99	15.37**	3.05*
25	ICSA 433 × ICSR 13004	-35.15**	-36.34**	-3.35	-9.54**	-14.75**	-24.80**	-24.32**	-32.40**
26	ICSA 433 × ICSR 13009	5.36	3.43	16.47**	9.01**	-33.05**	-40.94**	-23.07**	-31.28**
27	ICSA 433 × ICSR 13025	-16.17**	-17.71**	19.75**	12.08**	22.32**	7.90*	36.42**	21.86**
28	ICSA 433 × ICSR 13031	3.06	1.17	13.20**	5.94**	-4.56	-15.81**	-20.64**	-29.11**
29	ICSA 433 × ICSR 13042	-8.77	-10.44	15.81**	8.39**	11.75**	-1.42	27.73**	14.10**
30	ICSA 433 × ICSR 13043	41.96**	39.35**	49.61**	40.02**	31.12**	15.66**	31.26**	17.26**
31	ICSA 433 × ICSR 13046	-20.17**	-21.64**	6.68**	-0.15	-15.77**	-25.70**	-4.93**	-15.08**
32	ICSA 433 × ICSR 29	-30.89**	-32.16**	-15.98**	-21.36**	-16.04**	-25.93**	-20.11**	-28.64**
33	ICSA 435 × ICSR 13004	-49.53**	-50.46**	-15.98**	-21.36**	-1.93	-13.49**	4.16*	-6.95**
34	ICSA 435 × ICSR 13009	2.55	0.67	30.97**	22.58**	-6.17	-17.23**	2.92	-8.06**
35	ICSA 435 × ICSR 13025	-18.72**	-20.22**	6.88**	0.03	-13.25**	-23.47**	-22.52**	-30.79**
36	ICSA 435 × ICSR 13031	21.19**	18.96**	13.17**	5.92**	-30.79**	-38.95**	-27.61**	-35.33**
37	ICSA 435 × ICSR 13042	21.11**	18.88**	20.03**	12.33**	-13.04**	-23.28**	-12.66**	-21.98**
38	ICSA 435 × ICSR 13043	-41.96**	-43.02**	-29.55**	-34.06**	28.54**	13.39**	23.31**	10.15**
39	ICSA 435 × ICSR 13046	-40.17**	-41.27**	-22.15**	27.14**	14.97**	1.42	28.68**	14.94**
40	ICSA 435 × ICSR 29	3.23	1.34	22.85**	14.97**	-52.04**	-57.69**	-60.70**	-64.89**
41	ICSA 29004 × ICSR 13004	-9.36	-11.03	-7.73**	-13.65**	-12.55**	-22.86**	-17.06**	-25.91**
42	ICSA 29004 × ICSR 13009	21.02**	18.80**	21.36**	13.58**	-40.34**	-47.37**	-28.64**	-36.26**
43	ICSA 29004 × ICSR 13025	6.04	4.09	25.37**	17.33**	6.38	-6.15	27.76**	14.12**
44	ICSA 29004 × ICSR 13031	-21.96**	-23.39**	0.38	-6.06**	-30.10**	-38.33**	-22.30**	-30.59**
45	ICSA 29004 × ICSR 13042	-36.34**	-37.51**	-10.11**	-15.87**	-12.66**	-22.95**	-9.88**	-19.50**
46	ICSA 29004 × ICSR 13043	-43.40**	-44.44**	-15.24**	-20.67**	-25.48**	-34.26**	-64.27**	-68.09**
47	ICSA 29004 × ICSR 13046	-13.53*	-15.12*	14.96**	7.59**	6.28	-6.25	8.56**	-3.02*
48	ICSA 29004 × ICSR 29	-0.34	-2.17	11.09**	3.98	-32.24**	-40.23**	-21.38**	-29.77**
	S.E. ±	0.114	0.114	1.594	1.594	0.112	0.112	2.922	2.922
	CD @ 5 %	0.271	0.271	3.769	3.769	0.266	0.266	6.911	6.911
	CD @ 1 %	0.401	0.401	5.579	5.579	0.394	0.394	10.228	10.228

*P = 0.05; **P = 0.01

However, top specific combiners for important trait, grain yield per plot were ICSA 433 × ICSR 13043 (0.960), ICSA 435 × ICSR 13042 (0.773), ICSA 427 × ICSR 13004 (0.697) and ICSA 418 × ICSR 13046 (0.507), whereas hybrids such as ICSA 427 ICSR 13004 (33.394), ICSA 433 ICSR 13043 (30.482), ICSA 427 ICSR 13046 (23.666) and ICSA 435 ICSR 29 (17.968) found to be best specific combiners for the trait grain yield per plant. The best specific crosses for fodder yield per plot were ICSA 435 × ICSR 13046 (73.385), ICSA 419 × ICSR 29 (69.619), ICSA 427 × ICSR 13004 (58.518), and ICSA 29004 × ICSR 13025 (52.978), while for fodder yield per plot ICSA 435 × ICSR 13046 (1.075), ICSA 29004 × ICSR 13046 (1.065), ICSA 418 × ICS R 13031(0.919) and ICSA 427 × ICSR 13004 (0.750) were good specific combiners. Similar results were reported earlier by Mengistu *et al*. (2020), Akata *et al*. (2017), Sayed and Said (2016), Aruna *et al*. (2010) and Kenga *et al*. (2004).

The estimates of standard heterosis over both checks are presented in **Tables 4 and 5**. For days to 50 % flowering, 14 and 6 crosses exhibited significant negative (desirable) heterosis over the varietal check CSV-41 and hybrid check CSH -16, respectively (**Table 4**). Hybrids ICSA 435 × ICSR 13042 (-9.11 % and -3.75 %) and ICSA 435 × ICSR 13025 (-8.61 % and -3.22 %), respectively reported the highest negative heterosis over CSV -41 and CSH -16, both of which were found to be early flowering hybrids. However, for days to maturity, hybrids *viz*., ICSA 29004 × ICSR 13025 (-7.18 % and -8.02 %) and ICSA 435 × ICSR 13042 (-6.72 % and -7.56 %) exhibited the highest standard heterosis over CSV-41 and CSH-16, respectively. ICSA 418 × ICSR 13042 had the lowest standard heterosis (over CSV-41 and CSH-16) values for plant height of -34.72 % and -40.56 %, respectively, whereas ICSA 419 × ICSR 13004 had the highest values of 54.58 per cent and 40.74 per cent. ICSA 418 × ICSR 13042 (-34.2 % and -40.56 %) recorded the maximum negative (desirable) standard heterosis for plant height, followed by ICSA 435 × ICSR 13043 (-34.23 % and -40.12 %), ICSA 418 × ICSR 13004 (-32.21 % and -38.28 %) and ICSA 29004 × ICSR 13043 (-31.92 % and -38.02 %) over CSV-41 and CSH-16, respectively. For 100 seed weight, three hybrids exhibited significant positive heterosis over CSV-41 while five over CSH-16 (**Table 4**). Hybrids with the highest maximum standard heterosis over CSV-41 and CSH-16 were ICSA 419 × ICSR 13042 (17.99 % and 23.20 %), ICSA 419 × ICSR 13043 (16.40 % and 21.55 %), and ICSA 418 × ICSR 13046 (11.64 % and 16.57 %).

Over both checks, CSV-41 and CSH-16, standard heterosis values for essential trait *i.e* grain yield per plot, ranged from -49.53 and -50.46 to 41.96 and 39.35 over CSV-41 and CSH-16, respectively. Six hybrids showed significant positive standard heterosis for this trait (**Table 5**). The best hybrids with significant high positive standard heterosis (over CSV-41 and CSH-16, respectively) were ICSA 433 × ICSR 13043 (41.96 % and 39.35 %), ICSA 427 × ICSR 13031 (24.60 % and 22.31 %), ICSA 435 × ICSR 13031(21.19 % and 18.96 %), ICSA 435 × ICSR 13042 (21.11 % and 18.88 %), ICSA 29004 × ICSR 13009 (21.02 % and 18.80 %) and ICSA 427 × ICSR 13004 (15.15 % and 13.03 %). Out of the 48 crosses, 27 (56 %) exhibited positive and significant heterosis values for grain yield per plant with maximum heterosis values by ICSA 427 × ICSR 13004 (33.394). For trait, fodder yield per plant, 12 hybrids showed significant positive heterosis over the both checks CSV-41 and CSH-16 (**Table 5**). The highest positive standard heterosis (over CSV-41 and CSH-16, respectively) for fodder yield per plant exhibited by ICSA 419 × ICSR 29 (37.25 % and 22.61 %), ICSA 433 × ICSR 13025 (36.42 % and 21.86 %), ICSA 427 × ICSR 13004 (32.35 % and 18.23 %) and ICSA 433 × ICSR 13043 (31.26 % and 17.26 %), while for fodder yield per plot, maximum positive standard heterosis found in ICSA 433 × ICSR 13043 (31.12 % and 15.66 %), ICSA 435 × ICSR 13043 (28.54 % and 13.39 %) and ICSA 418 × ICSR 13031(24.46 % and 9.80 %) over CSV-41 and CSH-16, respectively.

A large number of hybrids showed positive significant heterosis over both checks for the traits of plant height, grain yield per plant, and fodder yield per plant. The least heterotic effects were observed for days to 50% flowering, 100 seed weight, and fodder yield per plot, in contrast to these. Many researchers have observed significant positive heterosis for grain yield (Mengistu *et al*., 2020, Prateeksha *et al*., 2018, Aaref *et al*., 2016, Choudhari *et al*., 2016, Mindaye *et al*., 2016, More *et al*., 2016, Gite *et al*., 2015 and Kalpande *et al*., 2015).

To identify promising sorghum hybrids for further selection and breeding, the current study analyzed combining ability and heterosis for yield and its contributory traits. According to the findings, both additive and non-additive gene effects are important, with non-additive gene effects predominating in governing yield-related traits. Females, ICSA 427 and ICSA 433 and males ICSR 13009 and ICSR 13031 males were found to be the best general combiners for grain yield per plot with consistent performance across locations. ICSA 433 × ICSR 13043, ICSA 435 × ICSR 13042, ICSA 427 × ICSR 13004, and ICSA 418 × ICSR 13046 were the best specific combination crosses for high grain yield per plot over locations. However, cross ICSA 427 × ICSR 13031 had the highest heterotic effects of all the crosses over both check followed by crosses ICSA 435 × ICSR 13031, ICSA 435 × ICSR 13042, ICSA 29004 × ICSR 13009 and ICSA 427 × ICSR 13004 indicating that these hybrids could be used in future breeding programmes to develop high yielding cultivars.

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