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Combining Ability and Heterosis for Grain Yield and Yield-Attributing Traits in Post-rainy Season Sorghum (*Sorghum bicolor* L. Moench)

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Abstract

The present investigation was undertaken to assess combining ability, heterosis, and heterotic grouping for grain yield and its component traits in sorghum using a diallel mating design (excluding reciprocals). The analysis of variance revealed highly significant differences among genotypes, with both general combining ability (GCA) and specific combining ability (SCA) effects being significant for all the traits studied, indicating the involvement of additive as well as non-additive gene actions. However, the predominance of non-additive gene action was evident from higher SCA variances and GCA/SCA ratios less than unity for all traits. Among the parents, IS-4634, SLB-124, Solapur Dagadi, and Barshi Jute were identified as superior general combiners for grain yield and associated traits, while ICSB-450B was a good combiner for earliness. The estimation of SCA effects and heterosis revealed several superior hybrid combinations, among which SLB-12 × ICSB-450B exhibited the highest SCA effect and heterosis for grain yield per plant, whereas PMS-20B × ICSB-29B showed exceptional performance for stover yield. Crosses such as SLR-31 × AKMS-66-2B and SLR-31 × ICSB-450B also demonstrated consistent superiority across multiple traits. The high magnitude of heterosis and SCA effects observed in these crosses highlights the importance of dominance and epistatic interactions in governing yield traits. The study further facilitated the identification of promising heterotic patterns, which can be effectively utilized in hybrid breeding programs. Overall, the results suggest that exploitation of heterosis would be the most effective approach for improving grain and biomass yield in sorghum, while the identified superior parents can be used in population improvement strategies.

Key words: Sorghum, Combining ability, Heterosis, Diallel analysis, Hybrid breeding

Sorghum (*Sorghum bicolor* L. Moench) is the fifth most important cereal crop globally and serves as a staple food for more than 500 million people across over 90 countries, particularly in the semi-arid tropics [1]. As a C_4 plant, sorghum possesses high photosynthetic efficiency and remarkable adaptability to diverse and marginal environments, making it a resilient crop under conditions of drought and low-input agriculture. Beyond its role as a food grain, sorghum is widely utilized as feed, fodder, fuel, and fibre, enhancing its significance in global agricultural systems [2]. However, global sorghum productivity remains relatively low due to the continued cultivation of traditional, low-yielding varieties and suboptimal agronomic practices. With the projected increase in global population and demand for food, feed, and bio-based products by 2050, there is an urgent need to develop high-yielding, climate-resilient sorghum cultivars [3].

In India, sorghum cultivation has undergone notable structural changes in recent years. According to the Production, Supply and Distribution (PS&D) database of the United States Department of Agriculture Foreign Agricultural Service (FAS USDA, 2025), the area under sorghum declined from 6.08 million hectares in 2015–16 to 3.54 million hectares in 2022–23, before partially recovering to 4.80 million hectares in 2023-24. Despite this reduction in cultivated area, productivity improved substantially from 0.70 t ha^{-1} to 1.25 t ha^{-1} during the same period, indicating advancements in varietal adoption and crop management practices. Consequently, production remained relatively stable, reaching a peak of 6.00 million tonnes in 2023–24. At the global level, sorghum production is concentrated among a few key countries, with the United States, Nigeria, Brazil, and India collectively contributing nearly half of the global output (USDA, 2024–25). These trends highlight a gradual shift from area-driven to productivity-driven growth in sorghum cultivation.

Hybrid technology has played a crucial role in enhancing sorghum productivity. The development of cytoplasmic male sterility systems enabled large-scale hybrid seed production, leading to widespread adoption of sorghum hybrids since the late 1950s [4]. Hybrids exhibit significant heterosis, often resulting in a 30–40% increase in grain yield along with

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improved yield stability, especially under stress conditions [5]. While hybrid technology has substantially improved productivity in *kharif* sorghum, its impact on *rabi* sorghum remains limited, necessitating focused breeding efforts to exploit heterosis in post-rainy season environments [6].

Understanding the genetic architecture of yield and its component traits is essential for the development of superior hybrids. Diallel mating design is a powerful tool widely used to assess the nature of gene action governing quantitative traits and to estimate general combining ability (GCA) and specific combining ability (SCA) effects [7]. The concept of combining ability, introduced by Sprague and Tatum [8], distinguishes additive gene effects (GCA) from non-additive gene effects (SCA), which are critical for selecting suitable parents and identifying promising hybrid combinations. The variation among half-sib families provides an estimate of GCA variance, whereas variation among full-sib families reflects SCA variance. Thus, combining ability analysis offers valuable insights into breeding strategies, particularly in hybrid development programs [9].

Heterosis, defined as the superiority of F_1 hybrids over their parents, is a key phenomenon exploited in crop improvement [10]. It is commonly measured as mid-parent heterosis (MPH) and better-parent heterosis (BPH), both of which provide critical information for selecting high-performing hybrids. The integration of combining ability and heterosis studies enables plant breeders to efficiently identify elite parental lines and superior cross combinations, thereby accelerating the development of high-yielding hybrids with desirable agronomic traits. In this context, the present investigation was undertaken to estimate the general combining ability (GCA) of parental lines and specific combining ability (SCA) of hybrids, to assess the magnitude of heterosis in terms of mid-parent (MPH) and better-parent heterosis (BPH) for grain yield and its component traits, and to identify superior parents and promising hybrid combinations while elucidating the nature of gene action governing these traits in *rabi* sorghum for effective hybrid breeding programmes.

MATERIALS AND METHODS

Experimental site

The study was conducted at the Centre on Rabi Sorghum, ICAR-Indian Institute of Millets Research, Shelgi, Solapur, Maharashtra, India (17°40′N, 75°54′E; 473 m altitude). The site receives an average annual rainfall of 721.3 mm, with mean temperatures ranging from 17.0°C (minimum) to 33.7°C (maximum).

Plant materials and hybrid development

Twelve diverse sorghum (*Sorghum bicolor* L. Moench) genotypes differing in grain yield, biomass, maturity duration, grain size, and grain color were selected as parental lines (Table 1). These genotypes were crossed in a diallel mating design excluding reciprocals, following the hand emasculation and controlled pollination technique during the rabi season of 2022-23. A total of 66 F_1 hybrids were successfully developed. The resulting hybrids, along with their parents, were evaluated during the rabi season of 2023-24 to study combining ability and heterosis for yield and its component traits.

Table 1 List of Parental genotypes used for diallel study

S. No.	Genotype	Origin / Source	Character
1.	M-31-2B	NRCS, Hyderabad	High yielding, resistance to pests and diseases (M-line)
2.	SLB-124	AICSIP	High yielding, Resistance to grain mould and aphid resistance (M line)
3.	SLR-31	AICSIP	Resistance to Sugarcane aphid-Melanaphis sacchari (significant pest affecting sorghum crops) (M-line)
4.	SLB-12	AICSIP	High yielding, resistance to sugarcane aphid-Melanaphis sacchari (significant pest affecting sorghum crops) (M-line)
5.	PMS-20B	AICSIP	resistance to pests and diseases (M-line)
6.	PU-26	UAS, Pune, Maharashtra	High yielding, disease resistance (M-line)
7.	Barshi Jute	Barshi, Solapur, Maharashtra	Local variety, High yielding and bold seeds
8.	Solapur Dagadi	Mohol Station, Solapur, Maharashtra	Traditional variety, high yielding (both grain and fodder)
9.	IS-4634	ICRISAT	(R-line), drought tolerance, pest resistance and high yielding
10.	ICSB-29B	ICRISAT	drought tolerance, pest resistance and high yielding
11.	ICSB-450B	ICRISAT	drought tolerance, pest resistance and high yielding
12.	AKMS-66-2B	Dr. PDKV, Akola, Maharashtra	High yielding, Fertility restoration and hybrid vigour

Experimental design and crop management

The parents and their hybrids were evaluated during Rabi 2023-24 in a randomized block design (RBD) with two replications. Each entry was grown in a single 3 m row with spacing of 45 cm × 15 cm. Recommended agronomic and plant protection practices were followed, including application of NPK (60:30:0) and urea.

Data collection: Data were recorded physiological traits: days to flowering, plant height, panicle weight per plant, grain weight per plant, stover yield per plant, 100-seed weight. Trait observations were taken on five randomly selected plants per entry per replication, except for flowering and maturity, which were recorded on a plot basis.

Statistical analysis: Combining ability analysis was performed following Griffing's Method-II, Model-I [11]. Mean values were subjected to diallel analysis to estimate general combining ability (GCA) and specific combining ability (SCA). Variance among half-sib families was used to determine GCA, whereas variance among full-sib families provided SCA estimates. ANOVA for combining ability was generated accordingly to evaluate genetic effects and cross performance.

RESULTS AND DISCUSSION

Analysis of variance (ANOVA) for yield and its component traits

The analysis of variance (ANOVA) for combining ability (Table 2) revealed highly significant differences among genotypes for all the traits studied, indicating the presence of substantial genetic variability. The mean squares due to general combining ability (GCA) and specific combining ability (SCA) were highly significant ($p \leq 0.01$ or $p \leq 0.001$) for days to flowering, plant height, panicle weight per plant, grain yield per plant, stover yield per plant, and 100 seed weight, suggesting the involvement of both additive and non-additive gene effects in the inheritance of these traits. However, the magnitude of specific combining ability (SCA) variance was consistently higher than that of general combining ability (GCA) variance for all traits, as evident from the higher SCA mean squares and further supported by the low GCA / SCA ratios (<1) presented in (Table 3). This indicates the predominance of non-additive gene action, particularly for grain yield and its associated traits, which is a common feature in quantitatively inherited characters [8], [11]. The relatively low GCA / SCA ratios for grain yield (0.14), stover yield (0.18), and panicle weight (0.17) emphasize the greater role of dominance and epistatic interactions in controlling these traits. Nevertheless, the presence of significant general combining ability (GCA) effects also suggests that additive gene action is not negligible and can be effectively utilized through selection in advanced generations. Therefore, the results clearly indicate that while selection-based breeding approaches may be useful for traits with appreciable additive variance, heterosis breeding and hybrid development would be more effective strategies for improving grain yield and related traits in sorghum due to the predominance of non-additive gene action.

Table 2 Analysis of variance (ANOVA) for general and specific combining ability effects for yield and related traits in sorghum

Source of variation		DF (50%)	Plant height (cm)	Panicle weight per plant (g)	Grain weight per plant (g)	Stover yield per plant (g)	100 SW (g)
Due to GCA	DF	11	11	11	11	11	11
	Sum Sq	294.44	29550	6709.8	4244.6	19198	4.3131
	Mean Sq.	26.7573	2686.32	609.98	385.87	1745.26	0.3921
	F value	3.8718	77.235	42.476	26.36	48.379	88.607
	Pr(>F)	0.0001839***	<2.2e-19***	<2.2e-16***	<2.2e-16***	<2.2e-16***	<2.2e-16***
Due to SCA	DF	66	66	66	66	66	66
	Sum Sq	871.93	37567	17197	13072.2	47118	6.2954
	Mean Sq.	13.2111	569.19	260.56	198.06	713.91	0.09538
	F value	1.9109	16.365	18.144	13.53	19.79	21.555
	Pr(>F)	0.0032114**	<2.2e-19***	<2.2e-16***	<2.2e-16***	<2.2e-16***	<2.2e-16***
Error	DF	77	77	77	77	77	77
	Sum Sq	532.33	2678	1105.8	1127.2	2778	0.3407
	Mean Sq.	6.9134	34.78	14.36	14.64	36.07	0.00443

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 3 Analysis of additive and non-additive gene effects for various quantitative traits under diallel analysis (excluding reciprocals)

Genetic components	DF (50%)	Plant height (cm)	Panicle weight per plant (g)	Grain weight per plant (g)	Stover yield per plant (g)	100 SW (g)
Replication	2	2	2	2	2	2
Treatment	78	78	78	78	78	78
Parents	12	12	12	12	12	12
Hybrids	66	66	66	66	66	66
GCA	1.42	189.40	42.54	26.52	122.08	0.03
SCA	6.30	534.41	246.20	183.43	677.83	0.09
GCA / SCA	0.23	0.35	0.17	0.14	0.18	0.30

Table 4 Estimates of GCA effects of parents for yield and yield related traits in sorghum

Parents	DF	PH	PWPP	GYPP	SYPP	100 SW
M-31-2B	2.381	14.406	0.988	1.373	17.570	0.070
SLB-124	0.881	7.977	6.033	4.493	1.049	0.112
SLR-31	1.988	15.227	-2.804	-2.485	-0.641	0.011
SLB-12	-0.155	14.334	-0.270	-0.500	-4.990	0.054
PMS-20B	0.417	-8.761	-0.792	-2.185	-1.639	0.257
PU-26	-0.548	5.441	-2.995	0.098	7.879	-0.194
Barshi Jute	1.274	1.441	4.620	3.654	3.233	-0.017
Solpaur Dagadi	-0.619	7.334	4.417	4.307	9.090	-0.018
IS-4634	-1.012	2.066	5.164	4.714	10.387	0.232
ICSB-29B	-1.548	-23.029	-18.554	-14.348	-15.144	-0.268
ICSB-450B	-1.655	-22.773	0.718	-1.743	-22.939	-0.239
AKMS-66-2B	-1.405	-13.666	3.474	2.620	-3.854	0.001

Estimation of general combining ability (GCA): The estimates of general combining ability (GCA) effects revealed substantial variability among the parental lines for grain yield and its component traits, indicating the predominance of additive gene action in the inheritance of these characters and the effectiveness of selection-based breeding strategies. Based on GCA effects, the parental line IS-4634 was identified as the best general combiner for grain yield and associated traits, exhibiting significant positive effects for GYPP, PWPP, SYPP, and 100 seed weight, followed by SLB-124, Solapur Dagadi, and Barshi Jute, which also showed favorable GCA effects for yield and its components. For specific traits, ICSB-450B (-1.655) was the superior general combiner for days to flowering (DF), indicating its suitability for earliness, while SLR-31 (15.227) was the best combiner for plant height (PH). For grain yield per plant (GYPP), IS-4634 (4.714) recorded the highest positive GCA effect, whereas M-31-2B (17.570) emerged as the most promising general combiner for stover yield per plant (SYPP), highlighting its potential for dual-purpose breeding. In the case of 100 seed weight, PMS-20B (0.257) was identified as the superior general combiner. Overall, the identified superior parents can be effectively utilized in hybridization and population improvement programs aimed at enhancing grain yield and its contributing traits in sorghum [12-13].

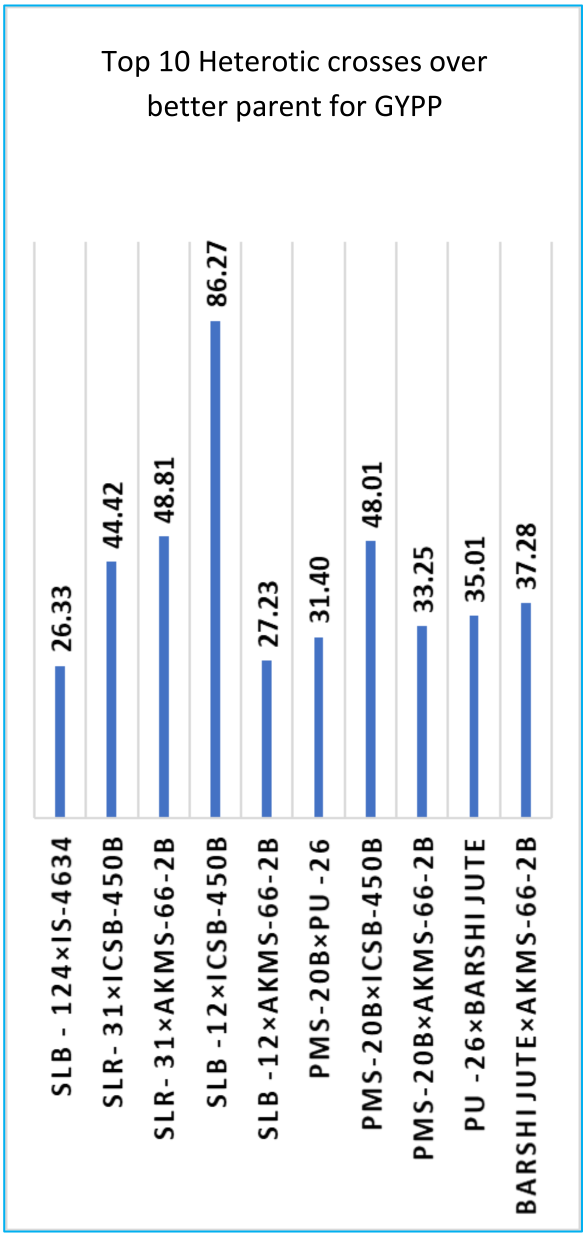

Fig 1 Graphical representation of top 10 heterotic hybrids over better parent for GYPP

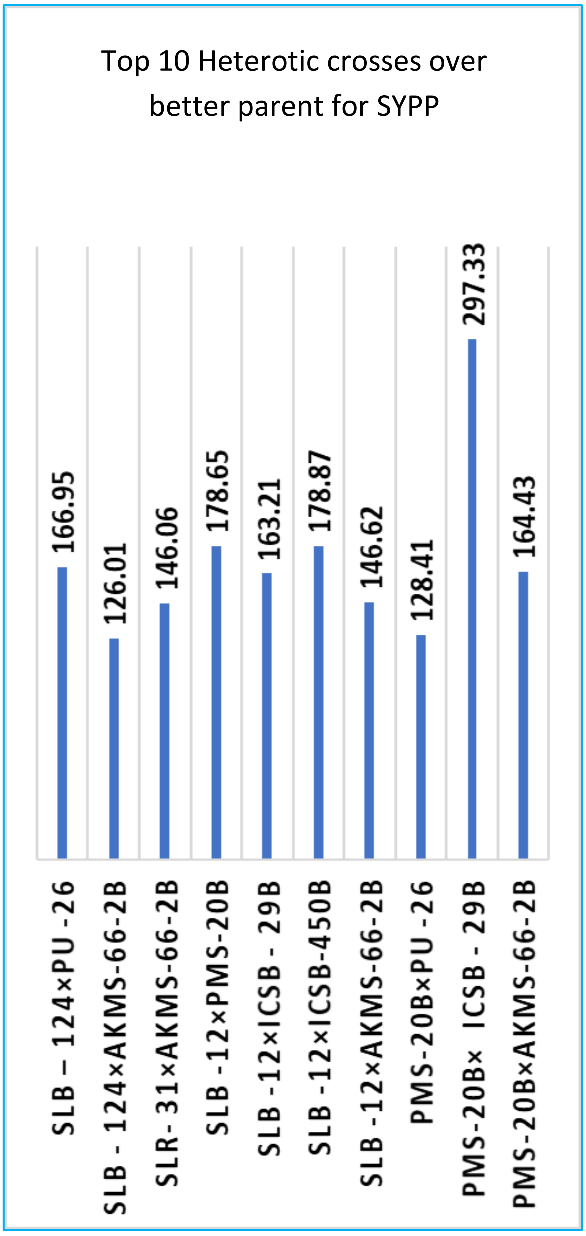

Fig 2 Graphical representation of top 10 heterotic hybrids over better parent for SYPP

Estimation of specific combining ability (SCA) of hybrids

The estimation of specific combining ability (SCA) effects revealed a predominance of non-additive gene action governing yield and its component traits, as evidenced by the identification of several superior cross combinations. M-31-2B × Solapur Dagadi (-5.505) was the best specific combiner for days to flowering, contributing towards earliness, while Barshi Jute × ICSB-450B (45.348) exhibited the highest positive specific combining ability (SCA) effect for plant height. For panicle weight per plant, SLR-31 × AKMS-66-2B (50.58) emerged as the most promising cross, whereas SLB-12 × ICSB-450B (30.432) showed superior performance for grain yield per plant (GYPP). Notably, for GYPP, namely SLB-12 × ICSB-450B (30.432) followed by SLR-31 × ICSB-450B (30.016), SLR-31 × AKMS-66-2B (28.053), etc. consistently exhibited high specific combining ability (SCA) effects, highlighting their strong potential for yield improvement through heterosis breeding. For stover yield per plant, PMS-20B × IS-4634 (91.026) recorded exceptionally high specific combining ability (SCA) effects, indicating its suitability for dual-purpose sorghum, while M-31-2B × SLR-31 (0.738) was identified as the best cross for 100 seed weight. Furthermore, the recurrence of crosses such as SLR-31 × AKMS-66-2B, Barshi Jute × ICSB-450B, and PMS-20B × IS-4634 among the top-performing hybrids across multiple traits underscores the importance of dominance and epistatic interactions. Overall, the high magnitude and consistency of specific combining ability (SCA) effects for key traits, particularly grain and stover yield, clearly indicate that exploitation of heterosis through hybrid breeding would be an effective strategy for enhancing sorghum productivity, and these findings are in close agreement with earlier reports [14-16].

Table 5 Specific combining ability effects of crosses for yield and yield related traits in sorghum

S. No.	Crosses	DF	PH	PWPP	GYPP	SYPP	100 SW
1.	M-31-2B×SLB -124	5.495	-74.331	-10.271	-12.203	-13.631	-0.263
2.	M-31-2B×SLR -31	12.387	-16.081	-8.234	-12.000	21.059	0.738
3.	M-31-2B×SLB-12	5.530	-16.188	0.158	-0.084	16.226	0.544
4.	M-31-2B×PMS-20B	2.959	1.908	18.754	13.700	-25.740	-0.099
5.	M-31-2B×PU-26	-3.077	-9.295	-13.242	-6.183	-6.689	-0.222
6.	M-31-2B×Barshi Jute	1.102	2.205	-7.657	-5.738	12.076	-0.354
7.	M-31-2B×Solapur Dagadi	-5.505	-6.688	-5.554	-7.392	-6.728	0.052
8..	M-31-2B×IS- 4634	-3.113	5.080	-19.102	-13.099	-18.969	-0.078
9.	M-31-2B×ICSB- 29B	-0.577	23.675	-22.433	-23.237	2.490	-0.063
10.	M-31-2B×ICSB-450B	-0.970	38.919	21.344	11.158	-0.926	-0.162
11.	M-31-2B×AKMS- 66-2B	-0.220	25.312	-5.112	5.595	3.939	-0.038
12.	SLB - 124×SLR- 31	-1.613	9.848	-23.765	-20.791	12.994	-0.359
13.	SLB - 124×SLB -12	-6.970	-7.259	-15.212	-12.904	-3.070	-0.093
14.	SLB - 124×PMS-20B	-0.541	19.836	-19.491	-21.620	0.870	-0.041
15.	SLB – 124×PU -26	2.923	4.634	32.713	13.947	28.685	0.236
16.	SLB - 124×Barshi Jute	1.102	5.634	-11.302	-9.658	14.664	-0.061
17..	SLB - 124×Solapur Dagadi	-2.505	-2.759	17.676	17.238	18.405	-0.035
18.	SLB - 124×IS-4634	1.387	7.009	19.153	18.181	6.497	0.315
19.	SLB - 124×ICSB - 29B	5.923	25.104	10.872	14.043	9.716	0.320
20.	SLB - 124×ICSB-450B	0.030	24.348	5.699	8.238	-6.478	0.096
21.	SLB - 124×AKMS-66-2B	-0.220	25.741	-0.840	12.925	13.567	0.125
22.	SLR- 31×SLB -12	-5.077	-1.509	-12.675	-16.826	-25.202	-0.076
23.	SLR- 31×PMS-20B	-1.648	20.086	-6.754	2.358	-24.791	-0.159
24.	SLR- 31×PU -26	-2.184	-0.616	-5.650	-2.225	0.274	-0.438
25.	SLR- 31×Barshi Jute	5.995	-13.116	-14.665	-19.580	-24.576	-0.590
26.	SLR- 31×Solapur Dagadi	5.387	-14.009	-21.362	-15.934	-6.999	0.371
27.	SLR- 31×IS-4634	0.780	-3.741	-1.735	-2.441	-9.808	0.082
28.	SLR- 31×ICSB - 29B	-0.184	22.354	16.109	16.455	20.508	0.472
29.	SLR- 31×ICSB-450B	-3.577	-6.902	21.836	30.016	-12.431	-0.392
30.	SLR- 31×AKMS-66-2B	-0.827	44.491	50.580	28.053	79.031	0.047
31.	SLB -12×PMS-20B	0.495	-9.521	-12.287	-0.426	6.140	-0.018
32.	SLB -12× PU -26	-3.041	10.777	5.599	-0.559	6.278	0.278
33.	SLB -12×Barshi Jute	-1.363	-5.223	-4.099	4.510	8.216	0.257
34.	SLB -12×Solapur Dagadi	0.530	-1.116	6.304	1.582	12.888	-0.293
35.	SLB -12×IS-4634	0.423	-2.848	23.957	13.475	13.432	-0.192
36.	SLB -12×ICSB - 29B	-0.541	11.247	-5.175	-2.446	15.322	-0.012
37.	SLB -12×ICSB-450B	2.566	29.491	38.602	30.432	27.501	0.299
38.	SLB -12×AKMS-66-2B	3.316	8.384	-6.554	0.269	3.333	-0.302
39.	PMS-20B×PU -26	-4.613	19.872	3.663	10.500	14.605	0.450
40.	PMS-20B×Barshi Jute	3.066	-26.628	6.923	-0.847	-28.106	0.474
41	PMS-20B×Solapur Dagadi	7.959	-21.021	8.626	5.666	29.537	0.124
42.	PMS-20B×IS-4634	-0.648	-2.253	6.178	11.559	91.026	0.585
43.	PMS-20B× ICSB - 29B	2.887	-7.991	-9.737	-10.345	37.604	0.025
44.	PMS-20B×ICSB-450B	1.995	-25.914	10.490	8.883	-5.933	0.236
45.	PMS-20B×AKMS-66-2B	-2.755	-25.521	4.368	-0.347	5.254	0.465
46.	PU -26×Barshi Jute	-0.470	-5.831	16.726	26.337	57.876	-0.050
47.	PU -26×Solapur Dagadi	1.423	-14.723	-7.071	-7.617	-1.398	-0.234
48.	PU -26×IS-4634	2.316	2.044	14.482	9.576	-13.421	-0.039
49.	PU -26×ICSB - 29B	3.852	15.140	-2.400	-2.962	0.480	0.116
50.	PU -26×ICSB-450B	1.459	27.884	-28.673	-18.867	22.437	0.207
51.	PU -26×AKMS-66-2B	0.709	22.777	-16.029	-8.930	-7.587	-0.258
52.	Barshi Jute×Solapur Dagadi	0.102	-12.223	-8.386	-8.872	-7.153	0.219
53.	Barshi Jute×IS-4634	-2.505	-8.456	-4.283	-6.955	-24.900	-0.161
54.	Barshi Jute×ICSB - 29B	-1.470	38.140	2.352	-6.850	-8.649	-0.286
55.	Barshi Jute×ICSB-450B	0.637	45.384	-1.587	0.078	28.382	0.0004
56.	Barshi Jute×AKMS-66-2B	0.387	13.777	20.957	25.215	2.130	0.335
57.	Solapur Dagadi×IS-4634	-3.113	10.152	-7.830	3.767	0.511	-0.100
58.	Solapur Dagadi ×ICSB-29B	-3.577	19.747	-6.012	-3.371	6.178	0.145
59.	Solapur Dagadi×ICSB - 450B	2.530	20.491	-4.085	-4.976	2.859	0.086
60.	Solapur Dagadi×AKMS-66-2B	-1.220	20.384	10.260	4.161	25.284	0.085
61.	IS-4634×ICSB-29B	0.816	-2.735	-7.610	0.547	14.661	-0.085

62.	IS-4634×ICSB - 450B	2.923	-1.741	-13.465	-15.683	-15.221	0.102
63.	IS-4634×AKMS-66-2B	2.173	-4.348	-16.588	-21.246	-18.836	-0.019
64.	ICSB-29B×ICSB-450B	-0.041	-29.646	-7.614	-6.521	-23.038	-0.083
65.	ICSB-29B×AKMS-66-2B	-0.791	-22.253	2.530	1.716	-21.823	0.031
66.	ICSB-450B×AKMS-66-2B	2.316	-32.509	-2.776	-10.506	-1.885	0.267

Table 6 Top three best ranking heterotic crosses along with range of heterosis and number of crosses showing heterosis in desired direction for various characters in *Sorghum bicolor* L. Moench.

Traits	Range of heterosis		Heterosis over mid parent (MP)			No. of hybrids desirable for MPH	Heterosis over better parent (BP)			No. of hybrids desirable for BPH
	MPH	BPH	Cross No.	Cross	MPH (%)		Cross No.	Cross	BPH (%)	
DF (50%)	28.346 to -10.345	26.357 to -12.030	13	SLB - 124×SLB -12	-10.345	12	13	SLB - 124×SLB -12	-12.030	21
			32	SLB -12× PU -26	-6.513		32	SLB -12× PU -26	-8.271	
			22	SLR- 31×SLB -12	-6.107		22	SLR- 31×SLB -12	-7.519	
Plant height (cm)	43.759 to -28.993	19.900 to -34.888	55	Barshi Jute×ICSB-450B	43.759	51	51	PU -26×AKMS-66-2B	19.900	28
			50	PU -26×ICSB-450B	40.653		50	PU -26×ICSB-450B	17.910	
			54	Barshi Jute×ICSB - 29B	40.260		55	Barshi Jute×ICSB-450B	17.882	
Panicle weight per plant (g)	104.110 to -62.758	88.267 to -72.820	37	SLB -12×ICSB-450B	104.110	30	37	SLB -12×ICSB-450B	88.267	19
			30	SLR- 31×AKMS-66-2B	103.316		30	SLR- 31×AKMS-66-2B	85.510	
			29	SLR- 31×ICSB-450B	55.109		29	SLR- 31×ICSB-450B	35.350	
Grain weight per plant (g)	110.608 to -70.865	86.270 to -78.934	37	SLB -12×ICSB-450B	110.608	34	37	SLB -12×ICSB-450B	86.270	22
			29	SLR- 31×ICSB-450B	78.935		30	SLR- 31×AKMS-66-2B	48.812	
			30	SLR- 31×AKMS-66-2B	71.911		44	PMS-20B×ICSB-450B	48.007	
Stover yield per plant (g)	327.240 to -25.199	297.333 to -43.732	43	PMS-20B× ICSB - 29B	327.240	58	43	PMS-20B× ICSB - 29B	297.333	43
			30	SLR- 31×AKMS-66-2B	233.437		37	SLB -12×ICSB-450B	178.869	
			42	PMS-20B×IS-4634	218.937		31	SLB -12×PMS-20B	178.653	
100 SW (g)	36.478 to -19.251	33.538 to -20.976	45	PMS-20B×AKMS-66-2B	36.478	50	45	PMS-20B×AKMS-66-2B	33.538	32
			42	PMS-20B×IS-4634	34.288		39	PMS-20B×PU -26	28.861	
			39	PMS-20B×PU -26	30.800		44	PMS-20B×ICSB-450B	24.437	

Estimation of MPH and BPH heterosis: The analysis of heterosis (Table 6) revealed a wide range of variability for all the traits studied, indicating substantial scope for the exploitation of hybrid vigor in sorghum. For days to flowering, desirable negative heterosis was observed, with SLB-124 × SLB-12 exhibiting the highest heterosis over both mid-parent (-10.345%) and better parent (-12.030%), followed by SLB-12 × PU-26 and SLR-31 × SLB-12, indicating their potential for developing early maturing hybrids. In the case of plant height, Barshi Jute × ICSB-450B (43.759%) and PU-26 × ICSB-450B (40.653%) showed high positive mid-parent heterosis, while PU-26 × AKMS-66-2B (19.900%) was superior over the better parent, suggesting their utility in improving plant stature. For panicle weight per plant, SLB-12 × ICSB-450B (104.110%) and SLR-31 × AKMS-66-2B (103.316%) recorded exceptionally high heterosis over mid-parent and better parent, indicating strong hybrid vigor. Similarly, for grain yield per plant, SLB-12 × ICSB-450B emerged as the best cross with maximum heterosis over both mid-parent (110.608%) and better parent (86.270%), followed by SLR-31 × ICSB-450B and SLR-31 × AKMS-66-2B, confirming their superiority for yield improvement. This trend was further supported by the top better-parent heterosis (BPH) crosses for grain yield, where SLB-12 × ICSB-450B, SLR-31 × AKMS-66-2B, and SLR-31 × ICSB-450B were among the leading performers, as also depicted in the graphical representations. For stover yield, PMS-20B × ICSB-29B exhibited the highest heterosis (327.240% over mid-parent and 297.333% over better parent), followed by SLR-31 × AKMS-66-2B and PMS-20B × IS-4634, indicating their suitability for dual-purpose sorghum. The superiority of these crosses was further reinforced by BPH estimates, wherein PMS-20B × ICSB-29B, SLB-12 × ICSB-450B, and SLB-12 × PMS-20B were identified as top performers, as illustrated in the corresponding graphs. In the case of 100 seed weight, PMS-20B × AKMS-66-2B (36.478%) showed maximum heterosis over mid-parent and better parent, followed by PMS-20B × IS-4634 and PMS-20B × PU-26. Furthermore, a considerable number of hybrids exhibited heterosis in the desired direction, particularly for stover yield (58 for MP and 43 for BP), plant height (51 for MP), and grain yield (34 for MP and 22 for BP), indicating ample opportunities for selection of superior hybrids. Overall, the high magnitude and consistency of heterosis across traits, especially for grain and stover yield, clearly demonstrate the predominance of non-additive gene action and highlight the effectiveness of heterosis breeding for the improvement of sorghum productivity, and these findings are in close conformity with earlier reports [17-21].

The integrated evaluation of specific combining ability (SCA) effects and better parent heterosis (BPH) for both grain yield per plant (GYPP) and stover yield per plant (SYPP) enabled the identification of elite hybrid combinations with superior performance and high breeding potential in sorghum. For grain yield, SLB-12 × ICSB-450B emerged as the most outstanding hybrid, exhibiting the highest SCA effect (30.432) along with maximum BPH (86.27%), indicating strong non-additive gene action and exceptional hybrid vigor. Other highly promising crosses included SLR-31 × AKMS-66-2B, SLR-31 × ICSB-450B, and PMS-20B × ICSB-450B, which combined high SCA effects with substantial heterosis, making them suitable candidates for yield improvement [22-23].

Similarly, for stover yield, PMS-20B × ICSB-29B was identified as the best performing hybrid with exceptionally high BPH (297.33%) and considerable SCA effect, highlighting its potential for dual-purpose sorghum. Crosses such as SLB-12 × ICSB-450B, SLB-12 × PMS-20B, and SLB-124 × PU-26 also exhibited high heterosis along with moderate to high SCA effects, indicating their suitability for enhancing biomass yield. Notably, certain crosses like SLR-31 × AKMS-66-2B and SLB-12 × ICSB-450B performed consistently well across both grain and stover yield, suggesting their stability and wider adaptability. Overall, the concurrence of high SCA effects and significant heterosis in these elite hybrids clearly indicates the predominance of non-additive gene action governing both grain and stover yield. The identification of such superior cross combinations provides valuable genetic material for the exploitation of heterosis and the development of high-yielding, dual-purpose sorghum hybrids.

Table 7 Top 10 elite hybrids based on combined SCA effects and better parent heterosis for grain and stover yield

Rank	Hybrid combination	SCA effect	BPH (%)	Rank	Hybrid combination	SCA effect	BPH (%)
Grain yield per plant				Stover yield per plant			
1.	SLB-12 × ICSB-450B	30.432	86.27	1.	PMS-20B × ICSB-29B	37.6	297.33
2.	SLR-31 × AKMS-66-2B	28.053	48.81	2.	SLB-12 × ICSB-450B	27.5	178.87
3.	PMS-20B × ICSB-450B	8.883	48.01	3.	SLB-12 × PMS-20B	6.14	178.65
4.	SLR-31 × ICSB-450B	30.016	44.42	4.	SLB-124 × PU-26	28.69	166.95
5.	Barshi Jute × AKMS-66-2B	25.215	37.28	5.	PMS-20B × AKMS-66-2B	5.254	164.43
6.	PU-26 × Barshi Jute	26.337	35.01	6.	SLB-12 × ICSB-29B	15.32	163.21
7.	PMS-20B × PU-26	10.5	31.4	7.	SLR-31 × AKMS-66-2B	79.03	146.06
8.	SLB-12 × AKMS-66-2B	0.269	27.23	8.	SLB-12 × AKMS-66-2B	3.333	146.62
9.	SLB-124 × IS-4634	18.181	26.33	9.	PMS-20B × PU-26	14.61	128.41
10.	SLB-124 × AKMS-66-2B	12.925	25.21	10.	SLB-124 × AKMS-66-2B	13.57	126.01


SLB -12×ICSB-450B SLR-31 × AKMS-66-2B PMS-20B × ICSB-29B

Plate 1 Panicle photos of top promising hybrids

Table 8 Estimates of mid-parent (MPH) and better-parent heterosis (BPH) for agronomic and physiological traits in sorghum hybrids

S. No.	Crosses	DF (50%)		Plant height (cm)		Panicle weight per plant (g)		Grain weight per plant (g)		Stover yield per plant (g)		100 SW (g)	
		MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH
1.	M-31-2B×SLB -124	16.21	14.84	-28.99	-34.89	-26.01	-33.26	-32.65	-41.91	3.34	-31.61	-5.10	-5.23
2.	M-31-2B×SLR -31	28.35	26.36	-4.86	-10.45	-29.09	-40.58	-40.77	-50.31	26.42	-4.59	17.95	17.02
3.	M-31-2B×SLB-12	12.40	9.02	-7.18	-10.82	-10.82	-28.82	-13.18	-33.09	43.00	-12.11	18.04	14.88
4.	M-31-2B×PMS-20B	14.17	12.80	-7.42	-12.69	11.38	-9.36	10.17	-18.09	-6.59	-43.73	12.43	3.08
5.	M-31-2B×PU-26	0.40	-0.78	1.07	-11.57	-34.25	-46.18	-23.98	-39.90	17.48	-20.33	-5.70	-12.33
6.	M-31-2B×Barshi Jute	9.88	8.59	1.77	-8.77	-25.60	-31.97	-26.26	-34.94	15.97	-8.77	-10.65	-11.13
7.	M-31-2B×Solapur Dagadi	-2.40	-2.40	-5.29	-9.89	-25.90	-29.92	-31.52	-36.18	8.12	-19.37	4.79	-0.27
8..	M-31-2B× IS- 4634	1.20	0.80	-0.70	-7.46	-39.15	-43.70	-36.06	-42.75	-16.23	-28.34	0.99	-0.90
9.	M-31-2B×ICSB- 29B	7.44	4.00	20.15	-9.89	-62.76	-72.82	-70.87	-78.93	16.20	-31.67	2.91	-10.05
10.	M-31-2B×ICSB-450B	8.40	3.20	27.23	-4.10	26.41	-4.95	11.99	-20.69	-1.81	-40.85	0.46	-11.93
11.	M-31-2B×AKMS- 66-2B	6.50	4.80	17.72	-5.78	-10.71	-30.46	4.06	-22.18	26.79	-21.24	4.58	-2.14
12.	SLB - 124×SLR- 31	2.72	2.33	12.83	9.73	-34.96	-40.14	-39.17	-41.15	80.75	47.77	-9.99	-10.82
13.	SLB - 124×SLB -12	-10.34	-12.03	2.66	-2.23	-14.22	-25.30	-13.31	-24.27	111.85	81.01	1.79	-0.81
14.	SLB - 124×PMS-20B	4.80	2.34	6.51	3.37	-23.31	-31.73	-30.67	-42.05	144.32	99.47	15.52	6.05
15.	SLB – 124×PU -26	6.25	6.25	15.19	9.40	50.86	35.21	36.15	22.65	179.82	166.95	8.88	1.34
16.	SLB - 124×Barshi Jute	6.25	6.25	10.78	8.05	-14.83	-16.10	-13.98	-16.21	78.01	39.23	-1.48	-1.88

17.	SLB - 124×Solapur Dagadi	-1.19	-2.34	2.69	-1.24	18.57	12.77	23.63	13.70	115.19	78.43	3.67	-1.21
18.	SLB - 124×IS-4634	4.76	3.13	7.03	5.18	24.40	21.01	31.81	26.33	52.72	11.11	12.57	10.32
19.	SLB - 124×ICSB - 29B	14.29	9.38	32.31	5.82	8.35	-14.86	21.48	-1.88	143.06	87.68	16.13	1.61
20.	SLB - 124×ICSB-450B	6.22	0.00	31.29	5.59	27.90	4.02	39.41	9.74	55.48	26.94	9.80	-3.63
21.	SLB - 124×AKMS-66-2B	2.81	0.00	28.22	10.29	16.86	-1.05	48.73	25.21	158.39	126.01	10.62	3.63
22.	SLR- 31×SLB -12	-6.11	-7.52	5.27	3.04	-16.24	-21.18	-32.11	-38.94	5.72	-23.35	-1.50	-4.88
23.	SLR- 31×PMS-20B	4.38	1.55	6.75	6.53	-9.33	-12.58	8.30	-6.95	17.98	-17.30	7.97	-1.72
24.	SLR- 31×PU -26	-0.39	-0.78	12.69	4.23	-11.80	-14.33	-4.33	-11.15	62.77	38.30	-14.37	-20.98
25.	SLR- 31×Barshi Jute	15.18	14.73	2.45	-2.75	-25.04	-31.95	-40.21	-43.60	-14.48	-19.25	-19.25	-20.32
26.	SLR- 31×Solapur Dagadi	12.60	10.85	-1.78	-2.89	-37.50	-45.05	-37.14	-43.90	30.87	28.56	11.17	5.01
27.	SLR- 31×IS-4634	5.14	3.10	2.56	1.48	-7.09	-16.61	-10.55	-16.93	5.30	-9.62	2.80	1.68
28.	SLR- 31×ICSB - 29B	5.69	0.78	30.09	1.90	13.74	-4.46	16.50	-3.41	98.89	33.82	16.41	1.06
29.	SLR- 31×ICSB-450B	1.65	-4.65	13.83	-10.36	55.11	35.35	78.94	44.42	-2.52	-31.67	-9.24	-20.98
30.	SLR- 31×AKMS-66-2B	3.20	0.00	37.11	15.22	103.32	85.51	71.91	48.81	233.44	146.06	4.40	-3.03
31.	SLB -12×PMS-20B	2.75	-1.50	-8.15	-9.92	-8.71	-10.98	20.72	14.65	194.43	178.65	17.77	10.76
32.	SLB -12× PU -26	-6.51	-8.27	14.73	4.05	17.95	14.16	15.34	11.41	145.25	101.56	11.51	6.37
33.	SLB -12×Barshi Jute	-1.15	-3.01	3.16	-4.05	-1.06	-14.94	15.51	-1.34	73.41	21.39	8.31	5.96
34.	SLB -12×Solapur Dagadi	0.00	-3.01	1.02	0.00	9.55	-8.57	3.35	-15.93	117.05	59.17	-2.61	-4.82
35.	SLB -12×IS-4634	-0.39	-3.76	0.31	-2.83	40.03	19.11	31.91	11.13	69.58	12.14	0.20	-4.26
36.	SLB -12×ICSB - 29B	0.00	-6.02	20.21	-7.29	-15.90	-25.54	-9.87	-17.81	197.78	163.21	7.28	-3.97
37.	SLB -12×ICSB-450B	6.50	-1.50	29.24	0.20	104.11	88.27	110.61	86.27	194.65	178.87	17.67	5.67
38.	SLB -12×AKMS-66-2B	4.72	0.00	15.44	-4.66	15.49	11.73	32.86	27.23	153.47	146.62	-0.59	-4.53
39.	PMS-20B×PU -26	-4.00	-6.25	10.83	2.32	10.85	10.01	42.98	31.40	190.09	128.41	30.80	28.86
40.	PMS-20B×Barshi Jute	11.20	8.59	-14.44	-18.95	12.34	-1.30	6.60	-12.75	9.47	-25.71	27.35	17.34
41	PMS-20B×Solapur Dagadi	17.41	16.00	-14.91	-15.70	9.85	-6.40	11.93	-12.48	171.76	92.50	22.84	18.10
42.	PMS-20B×IS-4634	3.25	2.42	-7.25	-8.42	10.42	-4.05	30.55	5.49	218.94	105.40	34.29	21.03
43.	PMS-20B× ICSB - 29B	11.30	9.02	0.49	-21.40	-28.38	-37.96	-30.06	-32.99	327.24	297.33	23.05	16.72
44.	PMS-20B×ICSB-450B	11.49	7.38	-9.50	-28.84	43.99	29.79	59.58	48.01	92.00	92.00	30.74	24.44
45.	PMS-20B×AKMS-66-2B	0.41	0.00	-10.41	-24.84	31.34	24.01	34.43	33.25	186.71	164.43	36.48	33.54
46.	PU -26×Barshi Jute	1.56	1.56	10.04	7.06	22.76	8.57	53.41	35.01	159.91	110.71	-2.68	-9.08
47.	PU -26×Solapur Dagadi	2.77	1.56	1.35	-7.23	-16.06	-28.02	-14.24	-28.26	81.80	56.81	-3.57	-5.93
48.	PU -26×IS-4634	3.97	2.34	9.13	1.94	18.52	3.67	22.13	5.96	27.95	-3.97	2.12	-6.71
49.	PU -26×ICSB - 29B	8.57	3.91	33.73	11.44	-18.94	-30.24	-13.15	-23.24	120.70	64.89	9.09	2.03
50.	PU -26×ICSB-450B	6.22	0.00	40.65	17.91	-35.28	-42.06	-18.76	-30.28	150.77	97.45	12.72	5.77
51.	PU -26×AKMS-66-2B	2.01	-0.78	33.15	19.90	-10.45	-16.05	8.17	0.21	105.06	72.30	-1.94	-2.62
52.	Barshi Jute×Solapur Dagadi	3.56	2.34	-1.87	-7.85	-17.52	-20.41	-20.40	-24.96	28.74	19.55	7.65	2.98
53.	Barshi Jute×IS-4634	-0.79	-2.34	-0.23	-4.32	-9.29	-10.44	-12.95	-14.38	-14.24	-22.54	-2.97	-5.29
54.	Barshi Jute×ICSB - 29B	2.86	-1.56	40.26	14.35	-10.33	-30.30	-26.99	-42.19	26.67	-17.21	-6.02	-17.48
55.	Barshi Jute×ICSB-450B	7.88	1.56	43.76	17.88	11.47	-10.39	15.84	-10.53	83.55	24.55	3.38	-8.94
56.	Barshi Jute×AKMS-66-2B	4.42	1.56	22.09	7.29	46.43	22.47	66.57	37.28	60.68	14.32	13.40	6.64
57.	Solapur Dagadi×IS-4634	-3.61	-4.00	3.91	1.65	-17.18	-19.08	-1.12	-5.31	34.20	13.48	2.97	-3.74
58.	Solapur Dagadi ×ICSB-29B	-2.48	-5.60	22.61	-4.75	-28.13	-45.53	-24.69	-42.90	92.97	31.06	12.82	3.12
59.	Solapur Dagadi×ICSB - 450B	9.24	4.00	22.49	-4.34	2.31	-19.93	-1.65	-27.12	58.87	12.54	11.49	2.23
60.	Solapur Dagadi×AKMS-66-2B	0.00	-1.60	19.35	-0.62	23.92	0.72	17.23	-7.75	143.37	81.72	11.33	9.35
61.	IS-4634×ICSB-29B	4.56	1.61	10.94	-12.42	-27.28	-43.99	-11.57	-30.84	63.28	1.86	4.88	-9.81
62.	IS-4634×ICSB - 450B	9.70	4.84	11.02	-11.88	-8.32	-27.00	-16.84	-36.52	-9.23	-41.54	10.99	-4.26
63.	IS-4634×AKMS-66-2B	5.31	4.03	7.26	-9.07	-12.39	-27.47	-24.28	-38.40	13.76	-23.72	7.51	-1.16
64.	ICSB-29B×ICSB-450B	6.96	5.13	11.85	11.03	-11.06	-14.96	-12.07	-15.00	-25.20	-30.43	8.04	7.65
65.	ICSB-29B×AKMS-66-2B	2.52	0.83	13.56	4.04	11.53	1.74	13.68	8.00	47.52	27.33	11.92	4.00
66.	ICSB-450B×AKMS-66-2B	9.40	5.79	6.06	-2.17	35.23	28.70	18.43	8.96	82.54	68.36	20.30	12.15

CONCLUSION

The present investigation on combining ability, heterosis, and heterotic grouping in sorghum clearly demonstrated the existence of substantial genetic variability among the parental lines and their hybrids for grain yield and associated traits. The ANOVA revealed highly significant general combining ability (GCA) and specific combining ability (SCA) effects for all traits, indicating the involvement of both additive and non-additive gene actions; however, the predominance of non-additive gene action was evident from higher and specific combining ability (SCA) variances and GCA / SCA ratios less than unity. Among the parents, IS-4634, SLB-124, Solapur Dagadi, and Barshi Jute were identified as superior general combiners for yield and its components, while ICSB-450B proved to be a good source for earliness. The estimation of and SCA effects and heterosis led to the identification of several outstanding hybrids, with SLB-12 × ICSB-450B emerging as the most promising cross for grain yield, and PMS-20B × ICSB-29B for stover yield, exhibiting exceptionally high heterotic response. Additionally, crosses such as SLR-31 × AKMS-66-2B, SLR-31 × ICSB-450B, and SLB-12 × PMS-20B showed consistent superiority across traits, indicating their potential as elite hybrids. The concurrence of high SCA effects and significant better parent heterosis in these crosses underscores the importance of dominance and epistatic interactions in governing yield traits. Overall, the results strongly suggest that heterosis breeding would be the most effective strategy for improving grain and biomass yield in sorghum, while the identified good general combiners can be effectively utilized in population improvement programs. The elite hybrids identified in this study hold great promise for the development of high-yielding, dual-purpose sorghum cultivars suitable for diverse agro-climatic conditions.

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