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Heterosis analysis of yield contributing traits in F_1 hybrids developed by using CMS background in sorghum [*Sorghum bicolor* (L.) Moench]

Rukhsar Bamji, Bharat Davda, Ketan Kanjariya and Krina Patel

Abstract

The present investigation was conducted at Main Sorghum Research Station, NAU, Surat. The study involved two CMS lines having same cytoplasmic source *i.e.*, A_1 (milo) used as female and crossed with seventy diverse male parental lines during late *kharif* 2021. Fifty male parents which produced successful hybrid seeds with both the CMS lines were selected for further assessment. Total of sixty three F_1 hybrids from both the CMS lines were evaluated further during *kharif* 2022. The heterosis was estimated for various yield attributing traits *viz.*, days to 50 per cent flowering, days to maturity, plant height (cm), panicle length (cm), 1000 seed weight (g), grain yield per plant (g) and dry fodder yield per plant (g). The magnitude of heterosis over mid and better parent was found to be higher for hybrids with 296A as compared to 28A for most of the characters studied. The F_1s 296A × SGP-GS-39, 296A × SGP-GS-41, 296A × SGP-GS-49, 296A × SGP-GS-199; 28A × SGP-GS-85, 28A × SGP-GS-173, 28A × SGP-GS-195, 28A × SGP-GS-196, 28A × SGP-GS-198 and 28A × SGP-GS-199 registered highest desirable relative heterosis and heterobeltiosis for almost all the characters studied.

Keywords: CMS, restorers, maintainers, relative heterosis, heterobeltiosis

Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) being the world's fifth leading cereal crop after major cereal crops is diploid in nature with ten pairs of chromosomes *i.e.*, 2n = 20 and belongs to the kingdom *Plantae*, order *Cyperales*, family *Poaceae* and genus *Sorghum*. It is considered likely to be evolved from its diploid wild species *Sorghum arundinaeceae* (Singh and Khare, 2002) [26]. Based on panicle and spikelet morphology, cultivated sorghum is classified into five major races: *bicolor, caudatum, durra, guinea,* and *kafir,* and ten intermediate races (Harlan and De Wet, 1972) [7]. It is primarily a self-pollinated crop, but cross-pollination has been reported to be as high as thirty per cent in Sudan grass. It is a native crop to Africa, originating in Ethiopia but the transfer of sorghum races from Africa to the east was most likely facilitated by a commerce route between East Africa and India *via* Arabia.

Sorghum is regarded as the "King of Millet" or "Great Millet" on an account of its huge grain size among all millets. It is a chief staple food and fodder crop in developing nations, making it a 'failsafe' crop, but it is predominantly utilized as an animal feed in developed countries (Mace *et al.*, 2008) [20]. Apart from being a key food, feed, and forage crop, it also serves as a raw material for the manufacture of starch, fiber, dextrose syrup, biofuels, alcohol, and other items (Jeya Prakash *et al.*, 2006) [9]. Sorghum is a crop with great diversity, but a major characteristic is its mechanism for tolerating heat, drought and many biotic and abiotic stresses (Singh and Khare, 2002) [26]. It is widely planted in tropical and subtropical areas and has good potential for growth during both the *kharif* and *rabi* seasons.

India ranks fifth in total production of sorghum in the world. According to statistical data, the area of about 4.10 million hectares comes under sorghum cultivation in India with an annual production of 4.40 million tonnes and productivity of 1100 kg/ha during 2022-2023 (Anonymous, 2023a) [1]. It is popularly known as "Jowar" in India and mainly concentrated in the peninsular and central India which includes Maharashtra, Karnataka, Andhra Pradesh, Madhya Pradesh, Gujarat, Rajasthan, Uttar Pradesh (the Bundelkhand region) and Tamil Nadu as major jowar growing states. In Gujarat, it occupies an area of 0.03 million hectares with an annual production of 0.04 million tones with productivity of 1394 kg/ha during 2022-2023 (Anonymous, 2023b) [2].

The production of high yielding varieties and hybrids with superior quality, disease resistance, drought tolerance, and other valuable agronomic features is a goal of sorghum breeding round the world (Klein *et al.*, 2008) [17]. In the developed countries, grain sorghum breeding programmes use a large part of their approach to leverage heterosis utilizing F_1 hybrid cultivars. In order to produce large amounts of hybrid seed economically, this approach solely relies on cytoplasmic nuclear male sterility (CMS). The discovery and characterization of a stable and heritable cytoplasmic male sterility (CMS) mechanism in numerous crop species allowed for intensive hybrid breeding and seed production (Kante *et al.*, 2018) [13]. The detection of CMS lines made it possible to use hybrid vigour in sorghum in a practical manner. Cytoplasmic male sterility (CMS) is a maternally inherited feature in which female fertility is unaffected but pollen formation or proper anther dehiscence are compromised (Pring *et al.*, 1995) [23].

Sorghum heterosis was initially noted in 1927, but commercial exploitation wasn't viable until Stephens and Holland in 1954 discovered the cytoplasmic genetic male sterility mechanism which resulted from the interaction of ‘‘milo’’ or A_1 cytoplasm and genes of ‘‘kafir’’ origin and produced plants that were male sterile and normal female fertile (Jordan *et al.*, 2011) [11]. The milo (A_1) cytoplasm acts as the primary basis for the majority of commercial hybrids that are grown over the world (Reddy *et al.*, 2007) [24] despite having many different cytoplasmic sources identified, including the A_2, A_3, A_4, Indian A_4 (A_4M, A_4VZM, A_4G), A_5, A_6, 9E, and KS cytoplasms (Reddy *et al.*, 2010) [25].

The ability to develop male parent lines (also known as restorer or R lines), which carry dominant genes that restore male fertility in hybrid cultivars, has been a crucial component of the A_1 CMS system's success (Jordan *et al.*, 2010) [10]. A group of *Rf* genes known to be governed by two major and several modifying genes (Klein *et al.*, 2001) [16] which are encoded in the nucleus have the influence to suppress the male sterile phenotype and, as a result, restore the production of pollen in plants with the harmful mitochondrial genome. This can restore male fertility for a specific cytoplasm. The restoration of male fertility in F_1 hybrids is essential for the production of hybrid seeds. Thus, the CMS/*Rf* systems significantly helps in hybrid seed production by eradicating the need for tedious hand emasculation, in which male sterile line (A-line) used as female parent, a maintainer line (B-line) which is isogenic line of A-line and is needed to maintain A-line, and a restorer line (R-line) which is male fertile line used as pollen parent in commercial seed production plot and guarantees that each seed is a result of cross-pollination (Bentolila *et al.*, 2002) [4].

The term "heterosis" or "hybrid vigour" refers to the improved or reduced vigour, growth, fitness, or yield of a hybrid over its parental values, which results from the mating of genetically dissimilar parents. According to Hochholdinger and Hoecker (2007) [8], the potential of sorghum hybrids is determined by the percentage increase or decrease in performance over the better parent (heterobeltiosis) and mid parent (average heterosis). In contrast to mid-parent heterosis, which compares the hybrid with the mean of the two parents, heterobeltiosis reveals the performance of the hybrid in comparison with the best parent, making it more practical and attainable, claim Lamkey and Edwards (1999) [18]. Due to the availability of a reliable and heritable CMS system to increase productivity, heterosis has been commercially used. So, it is crucial to identify maintainers and restorers among the lines produced by traditional breeding techniques. Both maintainers and restorers should have strong adaptation and combining ability. The increase in yield, which in turn depends on the contribution of multiple component features, is the typical manifestation of heterosis. To determine the value of a cross, heterosis manifestation in the yield as well as its contributing characters should be examined. Hence, the purpose of the study was to evaluate the performance and estimate percentage of heterosis of F_1 hybrids obtained from cross with CMS lines.

Material and Methods

The experimental materials used in present study consisted of two CMS lines *viz.*, 28A and 296A both having similar cytoplasmic source *i.e.*, A_1 (milo) and seventy diverse male lines obtained from Main Sorghum Research Station, Surat, NAU, Navsari. For the synchronization of flowering between male and female lines two staggered sowing with the gap of fifteen days was achieved for male lines, containing about fifteen plants in each row. Similarly, both female lines (*i.e.*, 28A and 296A) each containing twenty four rows were sown in two sets by keeping the interval of fifteen days between two sets. Thus, ensuring availability of pollens throughout the crossing programme for effective pollination enabling maximum amount of seed setting. The two CMS lines were crossed as female to seventy male parental genotypes during late *kharif* 2021-22. All the resulting F_1 hybrids along with parents (CMS and male parental lines) were sown in a single row of 5.0 m length in a spacing of 45 × 15 cm. Each row consisted of fifteen plants out of which five competitive plants were randomly selected per line from each of the P_1, P_2 and F_1. The observations for all the characters were recorded on these selected plants except for days to 50 per cent flowering and days to maturity which were recorded on population basis. The characters studied were days to 50 per cent flowering, days to maturity, plant height (cm), panicle length (cm), 1000 seed weight (g), grain yield per plant (g) and dry fodder yield per plant (g).

Forty two successful F_1s with 296A female line and twenty one with 28A female line were obtained. Due to the male sterility of CMS lines, the maintainer lines 296B and 28B, which are fertile counterparts of male sterile lines, were employed to evaluate yield and the characteristics that contribute to it. Heterosis was calculated as a percentage increase or decrease in values with regard to various qualities above the mid parent (relative heterosis) and better parent (heterobeltiosis) for all the F_1 hybrids. Therefore, the respective female and male plant of a given cross was used to calculate the mid parent values, and for the mean values of the better parent, the better parent *i.e.*, either the CMS lines (296A and 28A) or the male line of a specific cross for a given character was used.

Heterosis was estimated as per cent deviation in the mean value of F_1s over the mid parent, *i.e.*, relative heterosis (Briggle, 1963) [5] and over the better parent, *i.e.*, heterobeltiosis (Fonseca and Patterson, 1968) [6].

Results and Discussion

Estimation of heterosis for yield and its attributing traits

Heterosis analysis results for various yield characters are given below (Table 1):

1) Days to 50 per cent flowering

Negative heterosis is desirable for days to 50 per cent flowering as it indicates early flowering in hybrids as compared to their parents. While considering for 296A female, heterosis for hybrids over mid parent ranged from -15.65 to 33.80 per cent and over better parent from -8.82 to 39.71 per cent. Cross combination 296A × SGP-GS-198 showed highest desirable heterosis over mid parent (-15.65 %) and over better parent (-8.82 %) (Table 1). For 28A female, heterosis over mid parent ranged from -10.56 to 10.26 per cent and over better parent from -6.49 to 16.88 per cent. Among crosses with 28A, cross 28A × SGP-GS-243 revealed maximum desirable heterosis over mid parent (-10.56 %) as well as over better parent (-6.49 %) (Table 1). A wide range of heterotic values from negative to positive has been reported by Totre *et al.* (2020) [29], Tambe *et al.* (2022) [27], Begna *et al.* (2023) [3], Kariyannanavar *et al.* (2023) [14].

2) Days to maturity

Similar to days to 50 per cent flowering, negative heterosis for days to maturity is desirable as it indicates early maturity of the genotype. For 296A female, while considering heterosis for F_1 hybrids over mid parent ranged from -13.88 to 14.69 per cent whereas over better parent it ranged from -7.22 to 29.90 per cent. Among crosses, 296A × SGP-GS-198 showed highest desirable heterosis over mid parent (-13.88 %) and better parent (-7.22 %) (Table 1). However, for 28A female, heterosis over mid parent ranged from -8.60 to 7.49 per cent and over better parent from -7.34 to 11.93 per cent. Among crosses, 28A × SGP-GS-198 showed highest desirable heterosis over mid parent (-8.60 %) and better parent (-7.22 %) (Table 1). Such results were in accordance with Prasad *et al.* (2018) [22], Tiwari *et al.* (2019) [28], Totre *et al.* (2020) [29], Tambe *et al.* (2022) [27], Begna *et al.* (2023) [3], Kariyannanavar *et al.* (2023) [14].

3) Plant height (cm)

Plant height is regarded as a favourable character due to important role of stem as a source in supplementing assimilates during grain development and as a stove yield (Joshi *et al.*, 2003). For 296A female, while considering heterosis for F_1s, relative heterosis over mid parent ranged from -32.33 to 30.39 per cent whereas, for heterobeltiosis it ranged from -25.98 to 38.58 per cent. For F_1 crosses, 296A × SGP-GS-95 exhibited highest desirable heterosis over mid parent (30.39 %) and cross 296A × SGP-GS-131 over better parent (38.58 %) (Table 1). However, for 28A line, relative heterosis over mid parent ranged from -16.41 to 19.40 per cent whereas, for heterobeltiosis it ranged from -12.31 to 29.67 per cent (Table 1). Such results were also recorded by Khadi *et al.* (2018) [15], Prasad *et al.* (2018) [22], Tiwari *et al.* (2019) [28], Totre *et al.* (2020) [29], Tambe *et al.* (2022) [27], Begna *et al.* (2023) [3], Kariyannanavar *et al.* (2023) [14].

4) Panicle length (cm)

Positive heterosis is preferred for panicle length since longer panicles directly result in more seeds being set, which increases sorghum production. When heterosis was considered with respect to panicle length for F_1s with 296A female line, relative heterosis over mid parent ranged from

Table 1: Estimation of heterosis among n F_1 hybrids with both CMS lines for yield and its attributing traits

Sr. No.	Cross	Days to 50 per cent flowering		Days to maturity		Plant height (cm)		Panicle length (cm)	
		Heterosis (%) over		Heterosis (%) over		Heterosis (%) over		Heterosis (%) over	
		MP	BP	MP	BP	MP	BP	MP	BP
1	296A × SGP-GS-1	18.92	29.41	11.32	21.65	-13.91	-13.23	15.98	-6.62
2	296A × SGP-GS-2	20.53	33.82	9.27	15.46	-16.36	-11.02	17.30	2.21
3	296A × SGP-GS-3	2.04	10.29	4.31	12.37	-21.75	-14.17	2.07	-9.56
4	296A × SGP-GS-6	-5.33	4.41	0.49	6.19	-23.70	-19.37	23.41	3.68
5	296A × SGP-GS-7	11.56	20.59	9.71	16.49	-0.28	12.60	11.87	2.21
6	296A × SGP-GS-8	4.11	11.76	2.39	10.31	15.56	22.20	24.48	10.29
7	296A × SGP-GS-9	4.05	13.24	0.93	12.37	17.58	22.68	13.95	8.09
8	296A × SGP-GS-20	-0.67	8.82	-0.94	8.25	14.42	33.70	2.01	-6.62
9	296A × SGP-GS-53	-2.67	7.35	-3.35	4.12	14.23	30.87	7.88	-4.41
10	296A × SGP-GS-22	-4.83	1.47	-5.77	1.03	21.00	33.86	17.01	3.68
11	296A × SGP-GS-24	5.96	17.65	7.98	18.56	21.09	29.76	1.38	0.29
12	296A × SGP-GS-25	7.69	13.24	3.41	9.28	25.21	30.24	7.22	4.85
13	296A × SGP-GS-39	-7.04	-2.94	-5.47	-2.06	21.01	31.97	15.50	9.56
14	296A × SGP-GS-41	-6.94	-1.47	-8.37	-4.12	11.53	30.24	20.16	12.21
15	296A × SGP-GS-49	-7.91	-5.88	-2.54	-1.03	18.61	34.49	23.72	10.07
16	296A × SGP-GS-51	24.00	36.76	14.69	24.74	27.81	33.54	25.78	18.38
17	296A × SGP-GS-99	4.05	13.24	3.38	10.31	13.08	31.34	24.48	20.59
18	296A × SGP-GS-86	-0.68	7.35	-3.81	4.12	10.69	33.70	14.39	11.97
19	296A × SGP-GS-94	6.74	39.71	9.09	29.90	-32.33	-25.98	0.74	0.74
20	296A × SGP-GS-95	6.85	14.71	5.61	16.49	30.39	33.17	0.39	-5.15
21	296A × SGP-GS-59	1.20	23.53	-6.25	8.25	19.07	28.82	1.78	-5.15
22	296A × SGP-GS-63	8.50	22.06	3.77	13.40	21.91	34.96	6.40	-2.21
23	296A × SGP-GS-74	6.76	16.18	9.52	18.56	20.56	29.76	21.46	10.29
24	296A × SGP-GS-77	-6.12	1.47	-9.26	1.03	-5.42	-1.10	12.21	8.09
25	296A × SGP-GS-85	12.93	22.06	13.17	19.59	20.13	22.90	20.47	12.50
26	296A × SGP-GS-161	7.28	19.12	4.19	15.46	2.41	23.62	20.30	19.85
27	296A × SGP-GS-167	7.69	23.53	6.98	18.56	24.32	33.23	20.30	16.32
28	296A × SGP-GS-162	3.11	22.06	2.73	16.49	12.21	30.24	20.00	19.12
29	296A × SGP-GS-158	13.51	23.53	13.33	22.68	19.50	21.57	17.65	17.65
30	296A × SGP-GS-131	-3.95	7.35	0.00	10.31	20.63	38.58	15.23	2.94
31	296A × SGP-GS-101	5.41	14.71	9.09	17.53	11.88	26.77	9.57	3.53
32	296A × SGP-GS-248	-1.82	19.12	-7.21	6.19	29.88	32.44	14.06	4.41

Table 1: Contd…

Sr. No.	Cross	Days to 50 per cent flowering		Days to maturity		Plant height (cm)		Panicle length (cm)	
		Heterosis (%) over		Heterosis (%) over		Heterosis (%) over		Heterosis (%) over	
		MP	BP	MP	BP	MP	BP	MP	BP
33	296A × SGP-GS-247	-0.67	8.82	-2.30	9.28	25.66	34.17	17.65	10.29
34	296A × SGP-GS-245	4.05	13.24	7.18	15.46	4.04	25.83	6.04	1.41
35	296A × SGP-GS-243	-1.32	10.29	0.00	10.31	6.31	23.31	1.86	-4.27
36	296A × SGP-GS-212	18.37	27.94	10.58	18.56	27.39	36.22	18.75	11.76
37	296A × SGP-GS-208	-10.96	-4.41	-7.32	-2.06	28.26	34.02	28.79	25.00
38	296A × SGP-GS-199	-6.94	-1.47	-10.68	-5.15	21.82	36.69	29.32	11.25
39	296A × SGP-GS-198	-15.65	-8.82	-13.88	-7.22	22.63	38.27	22.82	8.82
40	296A × SGP-GS-196	13.51	23.53	8.57	17.53	28.66	31.50	9.16	5.15
41	296A × SGP-GS-194	7.10	22.06	4.67	15.46	-4.06	2.36	3.45	-0.74
42	296A × SGP-GS-175	-8.61	1.47	-5.26	2.06	15.26	16.37	22.35	14.71
43	28A × SGP-GS-74	4.46	6.49	1.80	3.67	10.67	15.43	6.42	-8.44
44	28A × SGP-GS-77	10.26	11.69	6.85	7.34	-13.53	-12.31	-19.29	-26.62
45	28A × SGP-GS-85	-3.85	-2.60	-3.23	-2.78	17.25	23.72	28.31	13.31
46	28A × SGP-GS-173	-4.64	-2.70	-3.29	-0.96	10.48	12.61	18.71	7.14
47	28A × SGP-GS-161	2.50	6.49	1.32	5.50	-16.41	-2.52	-7.27	-12.99
48	28A × SGP-GS-154	-2.56	-1.30	-4.98	-3.67	-14.43	-12.02	16.15	9.74
49	28A × SGP-GS-144	1.75	12.99	0.85	9.17	5.19	5.19	-0.68	-5.84
50	28A × SGP-GS-131	4.35	9.09	2.65	6.42	0.40	11.57	35.63	14.94
51	28A × SGP-GS-125	9.09	16.88	7.49	11.93	8.83	12.72	19.57	7.14
52	28A × SGP-GS-247	10.13	12.99	1.31	6.42	1.94	5.49	10.92	-1.69
53	28A × SGP-GS-246	6.41	7.79	-7.41	-6.54	14.90	18.43	-1.67	-4.55
54	28A × SGP-GS-243	-10.56	-6.49	-7.96	-4.59	5.56	18.40	2.40	2.20
55	28A × SGP-GS-217	8.28	10.39	0.00	1.83	5.27	11.13	0.00	-5.84
56	28A × SGP-GS-213	6.33	9.09	2.24	4.59	-4.69	4.01	4.23	-3.90
57	28A × SGP-GS-212	2.56	3.90	1.82	2.75	5.65	9.50	-0.36	-11.36
58	28A × SGP-GS-199	-1.96	-1.32	-3.67	-3.67	19.40	29.67	27.38	4.22
59	28A × SGP-GS-198	-6.41	-5.19	-8.60	-7.34	7.82	17.66	27.03	6.82
60	28A × SGP-GS-196	-4.46	-2.60	-3.60	-1.83	15.93	16.89	13.57	3.25
61	28A × SGP-GS-195	-4.52	-3.90	-5.12	-3.77	15.71	19.65	16.43	8.12
62	28A × SGP-GS-194	-1.22	5.19	-0.88	2.75	-4.16	-0.89	11.76	1.23
63	28A × SGP-GS-175	-7.50	-3.90	-4.98	-3.67	0.23	4.33	20.88	7.14

Table 1: Contd..

Sr. No.	Cross	1000 seed weight (g)		Grain yield per plant (g)		Dry fodder yield per plant (g)	
		Heterosis (%) over		Heterosis (%) over		Heterosis (%) over	
		MP	BP	MP	BP	MP	BP
1	296A × SGP-GS-1	--	--	-33.91	-45.79	-24.24	-33.03
2	296A × SGP-GS-2	--	--	-84.60	-85.05	-19.29	-23.50
3	296A × SGP-GS-3	--	--	-84.70	-85.80	-2.03	-4.12
4	296A × SGP-GS-6	25.06	18.95	22.98	10.33	-26.40	-29.34
5	296A × SGP-GS-7	--	--	-84.35	-85.35	-15.60	-18.27
6	296A × SGP-GS-8	11.61	5.41	-8.58	-13.88	1.44	0.45
7	296A × SGP-GS-9	--	--	-84.08	-85.08	-1.27	-8.74
8	296A × SGP-GS-20	--	--	-54.32	-55.99	-10.41	-21.92
9	296A × SGP-GS-53	--	--	-17.11	-23.64	11.92	2.97
10	296A × SGP-GS-22	-7.97	-23.48	18.20	8.19	17.16	6.25
11	296A × SGP-GS-24	--	--	-67.70	-70.27	15.85	11.87
12	296A × SGP-GS-25	30.88	23.25	-17.22	-21.78	-16.83	-24.02
13	296A × SGP-GS-39	20.74	8.67	21.71	13.17	-18.55	-25.42
14	296A × SGP-GS-41	28.66	21.94	30.63	28.32	-23.61	-24.01
15	296A × SGP-GS-49	34.25	33.91	31.35	25.40	-23.54	-30.06
16	296A × SGP-GS-51	--	--	-57.42	-57.77	-6.27	-15.00
17	296A × SGP-GS-99	--	--	-73.17	-76.44	1.15	-12.44
18	296A × SGP-GS-86	31.14	27.87	5.99	0.96	-23.95	-29.03
19	296A × SGP-GS-94	--	--	-97.81	-98.15	-26.28	-37.94
20	296A × SGP-GS-95	--	--	-53.44	-54.18	2.78	-11.83
21	296A × SGP-GS-59	30.89	27.78	-10.02	-11.50	-12.79	-19.35
22	296A × SGP-GS-63	--	--	-78.77	-80.55	29.07	27.90
23	296A × SGP-GS-74	--	--	-57.09	-59.67	16.18	10.29
24	296A × SGP-GS-77	28.47	23.67	17.09	16.17	22.22	8.14
25	296A × SGP-GS-85	--	--	-74.57	-74.72	-22.72	-30.26
26	296A × SGP-GS-161	--	--	-64.96	-65.17	18.40	10.52

27	296A × SGP-GS-167	--	--	-67.20	-72.02	-23.98	-31.70
28	296A × SGP-GS-162	--	--	-47.86	-52.05	-17.13	-19.24
29	296A × SGP-GS-158	--	--	-51.68	-53.21	-29.68	-32.14
30	296A × SGP-GS-131	1.47	-7.54	5.21	5.07	-7.02	-15.73
31	296A × SGP-GS-101	23.95	18.79	3.93	3.60	-9.74	-14.34
32	296A × SGP-GS-248	25.70	18.31	21.83	19.77	-4.37	-11.60

Table 1: Contd..

Sr. No.	Cross	1000 seed weight (g)		Grain yield per plant (g)		Dry fodder yield per plant (g)	
		Heterosis (%) over		Heterosis (%) over		Heterosis (%) over	
		MP	BP	MP	BP	MP	BP
33	296A × SGP-GS-247	15.51	3.93	13.63	11.15	9.43	1.58
34	296A × SGP-GS-245	17.91	6.76	-8.94	-14.13	-10.82	-22.54
35	296A × SGP-GS-243	--	--	-23.30	-25.32	-0.66	-12.69
36	296A × SGP-GS-212	12.16	11.02	-1.85	-4.24	33.15	18.98
37	296A × SGP-GS-208	29.06	28.95	3.34	-0.85	15.49	2.13
38	296A × SGP-GS-199	27.29	21.28	28.65	27.65	27.75	15.53
39	296A × SGP-GS-198	20.83	10.41	14.48	9.59	17.66	4.53
40	296A × SGP-GS-196	--	--	-81.72	-81.83	15.09	10.98
41	28A × SGP-GS-194	--	--	-50.93	-53.90	17.24	14.49
42	28A × SGP-GS-175	--	--	-71.87	-72.14	0.15	-0.15
43	28A × SGP-GS-74	--	--	-67.40	-70.66	-29.01	-35.86
44	28A × SGP-GS-77	--	--	-55.32	-57.03	-25.94	-37.38
45	28A × SGP-GS-85	23.46	8.14	25.74	19.32	-7.45	-20.28
46	28A × SGP-GS-173	14.19	12.43	19.06	12.52	-11.23	-11.84
47	28A × SGP-GS-161	--	--	-52.32	-54.24	-36.04	-37.15
48	28A × SGP-GS-154	17.23	7.24	19.14	14.11	-26.70	-32.16
49	28A × SGP-GS-144	--	--	-84.89	-85.58	-22.93	-26.80
50	28A × SGP-GS-131	3.06	2.74	-16.28	-19.99	-7.21	-11.61
51	28A × SGP-GS-125	--	--	-83.99	-85.69	-25.05	-26.34
52	28A × SGP-GS-247	-7.83	-9.39	-9.56	-11.80	-15.29	-17.24
53	28A × SGP-GS-246	--	--	-82.60	-82.95	-27.71	-33.10
54	28A × SGP-GS-243	22.48	6.90	18.78	16.38	-23.99	-29.92
55	28A × SGP-GS-217	--	--	-60.16	-64.31	-5.63	-8.21
56	28A × SGP-GS-213	--	--	-85.19	-85.50	-6.38	-12.11
57	28A × SGP-GS-212	8.79	0.34	13.51	5.83	-9.66	-15.24
58	28A × SGP-GS-199	18.41	13.31	26.32	21.48	13.99	8.32
59	28A × SGP-GS-198	25.52	25.52	25.17	16.43	8.64	1.31
60	28A × SGP-GS-196	17.14	3.45	27.65	22.54	2.52	0.83
61	28A × SGP-GS-195	9.20	8.83	25.88	22.90	19.54	12.23
62	28A × SGP-GS-194	--	--	-33.07	-39.79	-0.57	-3.45
63	28A × SGP-GS-175	29.99	14.48	18.80	14.45	-15.45	-20.00

MP: Mid parent; BP: Better parent
-- : insufficient amount of seed so unable to estimate heterosis

0.39 to 29.32 per cent and better parent from -9.56 to 25 per cent, respectively. Among F_1 hybrids of 296A line, cross 296A × SGP-GS-199 showed highest and positive heterosis over mid parent (29.32 %), whereas cross 296A × SGP-GS-208 over better parent (25.00 %) (Table 1). For 28A line, relative heterosis over mid parent ranged from -19.29 to 35.63 per cent and better parent from -26.22 to 14.94 per cent. Whereas among cross combinations, cross 28A × SGP-GS-131 showed highest and positive heterosis over mid parent (35.63 %) and over better parent (14.94 %) (Table 1). The results were in agreement with Meena *et al.* (2017) [21], Khadi *et al.* (2018) [15], Prasad *et al.* (2018) [22], Begna *et al.* (2023) [3], Kariyannanavar *et al.* (2023) [14].

5) 1000 seed weight (g)

Positive heterosis for test weight is directly correlated to increase in grain yield in sorghum. For heterosis among F_1s of 296A female line over mid parent, it ranged from -7.97 to 34.25 per cent, whereas for better parent it ranged from -23.48 to 33.91 per cent. Among hybrids with 296A line, cross 296A × SGP-GS-49 exhibited highest positive heterosis over mid parent (34.25 %) as well as over better parent (33.91 %) (Table 1). For 28A female, relative heterosis ranged from -7.83 to 29.99 per cent whereas heterobeltiosis from -9.39 to 25.52 per cent among F_1 hybrids. Among cross combinations, cross 28A × SGP-GS-175 showed highest positive heterosis over mid parent (29.99 %) whereas cross 28A × SGP-GS-198 over better parent (25.52 %) (Table 1). Such results were observed by Kalpande *et al.* (2015) [12], Tiwari *et al.* (2019) [28], Totre *et al.* (2020) [29], Tambe *et al.* (2022) [27], Begna *et al.* (2023) [3].

6) Grain yield per plant (g)

Any breeding program's main goal is to enhance grain yield, hence positive heterosis for grain yield is preferred as it signifies an increase in grain yield. While considering relative heterosis for grain yield per plant of F_1s with 296A female line, it ranged from -97.81 to 31.35 per cent whereas heterobeltiosis ranged from -98.15 to 28.32 per cent. Among cross combinations with 296A line, cross 296A × SGP-GS-49 showed highest desirable heterosis over mid parent (31.35 %), whereas cross 296A × SGP-GS-41 showed highest desirable heterosis over better parent (28.32 %) (Table 1). Moreover, for 28A female, relative heterosis ranged from -84.89 to 27.65 per cent and heterobeltiosis from -85.69 to 22.90 per cent. Among F_1s with 28A line, 28A × SGP-GS-196 showed highest desirable heterosis over mid parent (27.65 %), whereas cross 28A × SGP-GS-195 showed highest desirable heterosis over better parent (22.90 %) (Table 1). The results were in accordance with Khadi *et al.* (2018) [15], Prasad *et al.* (2018) [22], Tiwari *et al.* (2019) [28], Totre *et al.* (2020) [29], Tambe *et al.* (2022) [27], Begna *et al.* (2023) [3], Kariyannanavar *et al.* (2023) [14].

7) Dry fodder yield per plant (g)

Positive heterosis for dry fodder yield along with grain yield is preferred because it increases grain and dry fodder yields, making it suited for dual purpose use. While considering heterosis over mid parent for dry fodder yield of F_1s with 296A female line, it ranged from -29.85 to 33.15 per cent whereas over better parent it ranged from -37.94 to 27.90 per cent. Among cross combinations of 296A line, cross 296A × SGP-GS-212 showed highest desirable heterosis over mid parent (33.15 %), whereas cross 296A × SGP-GS-63 showed highest desirable heterosis over better parent (27.90 %) (Table 1). For 28A female, relative heterosis for F_1s ranged from -36.04 to 19.54 per cent and heterobeltiosis from -37.38 to 12.23 per cent. Among crosses, 28A × SGP-GS-195 showed desirable heterosis over mid parent (19.54 %) and over better parent (19.54 %) (Table 1). The results were in accordance with Laxman (2001) [19], Meena *et al.* (2017) [21], Totre *et al.* (2020) [29] and Tambe *et al.* (2022) [27].

Conclusion

The present study revealed that the magnitude of heterosis over mid and better parent was found to be higher for hybrids with 296A as compared to 28A for most of the characters studied. This indicated that the hybrids with 296A line outperformed the hybrids with 28A lines and can be used further for breeding programme. The cross combinations with higher heterotic values should be assessed for stability across environments/locations, while their male parents should be evaluated for general combining ability with CMS containing A_1 cytoplasm as well as with various sources for their use in the future commercial hybrid breeding programmes and thus developing an efficient CGMS system in sorghum.

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