E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(8): 683-688
Received: 22-06-2025
Accepted: 26-07-2025

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Heterosis studies for seed yield and it's attributing traits in pearl millet (*Pennisetum glaucum* (L.) R. Br.)

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DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i8j.3623

Abstract
The present heterosis study comprises of twelve parents which includes eight males, four females and thirty two crosses along with two checks of pearl millet. The genotypes were evaluated in Randomized Block Design with two replications during *Kharif* 2024-25, at experimental farm of National Agricultural Research Project, Chh. Sambhajinagar. Observations were recorded for 11 characters *viz.*, days to 50% flowering, days to maturity, plant height, number tillers per plant, panicle length, panicle girth, test weight, grain yield per plant, fodder yield per plant, harvesting index and seed setting percentage. The mean sum of square for parents and crosses exhibited highly significant differences for all the characters. Parent *vs* crosses differed significantly for all the characters. The mean sum of squares for parents further partitioning of the variance due to various source of variation also showed the significant differences for all the characters under study. Among the parents, MS 98222A among lines and PS-4 and R 15241 among testers exhibited significant and desirable GCA effects for seed yield and for most of the traits. This parent can be utilized for future breeding programme to produce high yielding pearl millet crosses. The crosses like MS 98222A x R 15241, MS 00888A x PS-4, MS 97111A x R 15241, and MS98222A x R 16428 exhibited higher *per se* performance, heterobeltosis and standard heterosis. Such crosses can be used for their commercial exploitation in peal millet.

Keywords: Pearl millet, heterosis

Introduction
Pearl millet, also known as *bajra* (*Pennisetum glaucum* (L.) R. Br.), ranks as the sixth most important cereal crop globally and the fourth in India, following rice, wheat, and maize. It is widely referred to by various names such as cat tail millet, spiked millet, bulrush millet, cumbu, and is locally called bajra or bajari in different regions. Pearl millet is cultivated across approximately 28 million hectares in the arid and semi-arid regions of Asia and Africa (Yadav *et al*., 2012) [5], with rainfall ranging from 150 to 700 mm. India is the leading producer of pearl millet, accounting for 45% of the global area and 42% of global production. Pearl millet is an erect annual plant, growing between 5 to 6 feet tall, with varying numbers of tillers. It is known to have a secondary polyploidy nature (Swaminathan and Nath, *et al.* 1956) [10]. Pearl millet has a balanced genetic makeup but exhibits notable inbreeding depression (Harinarayana *et al.* 1980) [3]. Therefore, varieties developed for pearl millet need to be heterozygous to ensure heterosis (hybrid vigor) while also maintaining a homogeneous structure for uniform and synchronous productivity. This crop belongs to the Poaceae (Gramineae) family, under the subfamily Panicoideae, with a chromosome number of 2n = 14, and falls under the Pennisetum genus and glaucum species. Pearl millet is a highly cross-pollinated plant. featuring protogynous flowering where the pistil matures before the stamens and relies on wind for pollination. These characteristics make it ideal for hybrid breeding programs.

Materials and Methods
The experimental material consists of four lines (MS 98222A, MS 00888A, MS 97111A, MS 88004A) and eight diverse testers (R16428, PS-4, R593, AR-20, R15241, R15348, R15385, R15535). The detailed information of parents including lines and testers with salient characteristics and crosses is presented in (table 1 and table 2).

These four lines and eight testers were crossed in Line × Tester mating system and produced thirty-two crosses during *Summer* 2023-24. The experimental material includes total forty six entries comprising thirty-two crosses, four lines and eight testers along with two checks AHB 1200 Fe and AHB 1269 were evaluated during *Kharif* 2024 at the Experimental field of National Agricultural Research Project (NARP) Chh. Sambhajinagar. In the form of modified line x tester design as suggested by *Arunachalam* (1974) [1].

Results and Discussion

Heterosis is a natural phenomenon which makes hybrid offspring of genetically diverse individual and display improved physical and functional characteristics relative to their parents (Shull 1948) [12].

The heterosis over better parent ranged from (-41.38%) to (44.83%). The hybrid MS 00888A x R 15535 (44.83%) showed highest positive significant heterosis over better parent, and hybrid MS 98222A x R 15348 (-41.38%) showed lowest heterosis over better parent. The heterosis over standard hybrid check AHB 1200 Fe (58.33%) MS 97111A x R 15241 and second standard hybrid check AHB 1269 Fe (48.44%) MS 97111A x R 15241 displayed highest positive heterosis over standard check. Similar finding with above invested crosses was conformity with, Mukesh *et al*. (2022%) who noted that the cross ICMA 88004 x BIB 283 exihibited 47.84% heterobeltosis for grain yield.

The heterosis over better parent ranged from (-26.85%) to (22.52%). The hybrid MS 98222A x R 16428 (22.52%) showed highest positive significant heterosis over better parent, and hybrid MS 88004A x R 15385 (-26.85%) showed lowest heterosis over better parent. The heterosis over standard hybrid check AHB 1200 Fe (7.07%) MS 98222A x R 15241 and second standard hybrid check AHB 1269 Fe (22.96%) MS 98222A x R 15241 displayed highest positive heterosis over standard check. Under the investigation for the fodder yield trait, Karvar *et al*. (2017) [4] reported similar results showing highest heterobeltosis for fodder yield (24.20%).

Negative heterosis is desirable for the character days to 50% flowering. The values for better parent heterosis fluctuated between -19.69 to 5.71% whereas, the cross MS 98222A x AR-20 (-19.69%) showed highest negative significant heterosis over better parent. The cross MS 00888A x R 15348 (5.71%) showed positive heterosis over better parent. The heterosis over standard hybrid check AHB 1200 Fe ranged from (-21.10%) to (3.37%) whereas, the cross MS 00888A x PS-4 (-21.10%) recorded highest significant negative heterosis over standard check AHB 1200 Fe. The heterosis over standard check AHB 1269 ranged from (-22.52%) to (1.48%). The cross MS 00888A x PS-4 (-22.52%) showed highest significant negative heterosis. The similar finding was in accordance with S. H. Karvar *et al*. (2017) [4] who reported range of standard heterosis between -20.54% to 12.08% for days to 50% flowering and cross 15A x S-16/12 was reported to have high significant desirable standard heterosis.

Negative heterosis is desirable for days to maturity. The values for better parent heterosis fluctuated between -10.87% to 4.55% whereas, the cross (MS 97111A x R 16428) -10.87% showed highest negative significant heterosis over better parent. The cross (MS 88004A x R 15348) 4.55% showed lowest heterosis over better parent for days to maturity. The heterosis over standard hybrid check AHB 1200 Fe ranged from (-9.04%) to (5.08%) whereas, the cross MS 00888A x PS-4 (-9.04%) showed highest significant negative heterosis over standard check AHB 1200 Fe. The heterosis over standard check AHB 1269 ranged from (-9.55%) to (4.49%) The cross from MS 00888A x PS-4 (-9.55%) showed highest significant negative heterosis. In pearl millet, the significant and negative heterosis for days to maturity was reported earlier by Reshma Krishnam *et al*. (2019).

Table 1: Source and features of parental lines and check.

Sr. No.	Lines	Sr. No.	Testers	Sr. No.	Checks
1.	MS 98222A	1.	R16428	1.	AHB 1200 Fe
2.	MS 00888A	2.	PS-4	2.	AHB 1269
3.	MS 97111A	3.	R593		
4.	MS 88004A	4.	AR-20		
		5.	R15241		
		6.	R15348		
		7.	R15385		
		8.	R15535		

Table 2: Details of Pearl millet crosses.

Sr. No.	Crosses	Sr. No.	Crosses
1.	MS 98222A x R 16428	17.	MS 97111A x R 16428
2.	MS 98222A x PS-4	18.	MS 97111A x PS-4
3.	MS 98222A x R 593	19.	MS 97111A x R 593
4.	MS 98222A x AR-20	20.	MS 97111A x AR-20
5.	MS 98222A x R 15241	21.	MS 97111A x R 15241
6.	MS 98222A x R 15348	22.	MS 97111A x R 15348
7.	MS 98222A x R 15385	23.	MS 97111A x R 15385
8.	MS 98222A x R 15535	24.	MS 97111A x R 15535
9.	MS 00888A x R 16428	25.	MS 88004A x R 16428
10.	MS 00888A x PS-4	26.	MS 88004A x R 593
11.	MS 00888A x R 593	27.	MS 88004A x R 593
12.	MS 00888A x AR-20	28.	MS 88004A x AR-20
13.	MS 00888A x R 15241	29.	MS 88004A x R 15241
14.	MS 00888A x R 15348	30.	MS 88004A x R 15348
15.	MS 00888A x R 15385	31.	MS 88004A x R 15385
16.	MS 00888A x R 15535	32.	MS 88004A x R 15535

Table 3: Analysis of variance for different characters in Pearl millet.

Source	D.F.	Days to 50% flowering	Days to maturity	Plant height (cm)	No. of tillers/plant	Panicle length (cm)	Panicle girth (cm)	Test weight (g)	Grain yield (g)	Fodder yield (g)
Replications	1	1.56	0.25	40.00	0.01	0.69	0.00	0.78	0.10	74.75
Genotypes	43	27.47**	22.46**	460.09**	0.55**	19.31**	0.19**	15.14**	84.11**	77.92**
Parents	11	20.67**	5.75	496.43**	0.16**	9.18**	0.23**	2.10**	14.15*	152.93**
Crosses	31	27.48**	25.54**	457.18**	0.68**	23.35**	0.17**	13.95**	105.05**	49.88**
Parents v/s Crosses	1	101.93**	110.91**	150.69	0.84**	5.43*	0.59**	195.68**	204.82**	122.05*
Error	43	2.16	3.17	87.09	0.01	1.08	0.01	0.69	2.34	23.71

Table 4: The estimates of heterosis over better parent (BP) and standard check (SH) for various characters in Pearl millet.

Sr. No.	Crosses	Days to 50% flowering			Days to maturity			Plant height (cm)		
		BPH	SH1	SH2	BPH	SH1	SH2	BPH	SH1	SH2
1.	MS 98222A x R 16428	-14.02**	-15.60**	-17.12**	-9.78**	-6.21**	-6.74**	-12.48	-16.07*	-16.53*
2.	MS 98222A PS-4	-10.28**	-11.93**	-13.51**	-7.87**	-7.34**	-7.87**	-12.08	-11.51	-11.99
3.	MS 98222A x R 593	0.00	0.92	-0.90	-0.56	0.00	-0.56	0.29	0.94	0.39
4.	MS 98222A x AR-20	-19.69**	-6.42*	-8.11**	-6.18**	-5.65**	-6.18**	-12.09	-13.79*	-14.26*
5.	MS 98222A x R 15241	-8.41**	-10.09**	-11.71**	-7.87**	-7.34**	-7.87**	-0.33	-4.42	-4.94
6.	MS 98222A x R 15348	5.61	3.67	1.80	4.49*	5.08*	4.49*	-8.51	-12.27	-12.75
7.	MS 98222A x R 15385	0.93	-0.92	-2.70	-9.29**	-6.21**	-6.74**	1.92	-2.27	-2.80
8.	MS 98222A x R 15535	-14.41**	-12.84**	-14.41**	-5.62**	-5.08*	-5.62**	-16.96**	-12.62	-13.09
9.	MS 00888A x R 16428	0.00	-3.67	-5.41	-1.63	2.26	1.69	-2.15	-0.28	-0.83
10.	MS 00888A x PS-4	-19.63**	-21.10**	-22.52**	-9.04**	-9.04**	-9.55**	-17.93**	-16.36*	-16.81*
11.	MS 00888A x R 593	-12.73**	-11.93**	-13.51**	-6.21**	-6.21**	-6.74**	-2.93	-1.08	-1.61
12.	MS 00888A x AR-20	-17.32**	-3.67	-5.41	-6.82**	-7.34**	-7.87**	-17.87**	-16.30*	-16.76*
13.	MS 00888A x R 15241	1.89	-0.92	-2.70	-2.81	-2.26	-2.81	-18.62**	-17.07*	-17.52*
14.	MS 00888A x R 15348	5.71	1.83	0.00	2.84	2.26	1.69	-18.11**	-16.54*	-17.00*
15.	MS 00888A x R 15385	5.71	1.83	0.00	-3.83	-0.56	-1.12	-12.46	-10.79	-11.27
16.	MS 00888A x R 15535	-14.41**	-12.84**	-14.42**	-1.14	-1.69	-2.25	-8.71	-3.94	-4.47
17.	MS 97111A x R 16428	-12.15**	-13.76**	-15.32**	-10.87**	-7.34**	-7.87**	-14.91*	-13.68*	-14.15*
18.	MS 97111A x PS-4	0.00	-1.83	-3.60	-8.29**	-6.21**	-6.74**	-6.31	-4.97	-5.48
19.	MS 97111A x R 593	-3.64	-2.75	-4.50	-2.76	-0.56	-1.12	-6.41	-5.06	-5.58
20.	MS 97111A x AR-20	-12.60**	1.83	0.00	-2.21	0.00	-0.56	-8.41	-7.09	-7.59
21.	MS 97111A x R 15241	-0.93	-2.75	-4.50	-2.21	0.00	-0.56	1.58	3.04	2.48
22.	MS 97111A x R 15348	-15.89**	-17.43**	-18.92**	-8.29**	-6.21**	-6.74**	-5.44	-4.08	-4.60
23.	MS 97111A x R 15385	-2.80	-4.59	-6.31*	-4.37*	-1.13	-1.69	9.31	10.88	10.28
24.	MS 97111A x R 15535	0.90	2.75	0.90	1.10	3.39	2.81	0.49	5.74	5.17
25.	MS 88004A x R 16428	2.83	0.00	-1.80	-1.63	2.26	1.69	-2.63	-3.44	-3.97
26.	MS 88004A x PS-4	-10.28**	-11.93**	-13.51**	-3.39	-3.39	-3.93	-9.71	-9.12	-9.62
27.	MS 88004A x R 593	1.82	2.75	0.90	0.00	0.00	-0.56	18.46**	19.23**	18.59**
28.	MS 88004A x AR-20	-15.75**	-1.83	-3.60	4.02	2.26	1.69	-10.09	-10.84	-11.33
29.	MS 88004A x R 15241	-8.49**	-11.01**	-12.61**	-6.18**	-5.65**	-6.18**	-8.71	-9.47	-9.96
30.	MS 88004A x R 15348	0.94	-1.83	-3.60	4.55*	3.95	3.37	3.33	2.47	1.92
31.	MS 88004A x R 15385	0.00	-2.75	-4.50	-3.38	0.00	-0.56	-15.59*	-16.29*	-16.74*
32.	MS 88004A x R 15535	-1.80	0.00	-1.80	-3.45	-5.08*	-5.62**	-16.45*	-12.09	-12.57

Sr. No.	Crosses	No. of tillers per plant			Panicle length (cm)			Panicle girth (cm)		
		BPH	SH1	SH2	BPH	SH1	SH2	BPH	SH1	SH2
1.	MS 98222A x R 16428	41.70**	70.77**	77.60**	13.22**	19.53**	13.72**	-10.66**	0.00	3.81
2.	MS 98222A PS-4	44.47**	74.10**	81.07**	7.93	13.95**	8.41	-7.54*	3.49	7.43
3.	MS 98222A x R 593	-11.70*	6.41	10.67	-7.05	-1.86	-6.64	0.33	12.29**	16.57**
4.	MS 98222A x AR-20	5.53	27.18**	32.27**	-21.15**	-16.74**	-20.80**	3.28	15.60**	20.00**
5.	MS 98222A x R 15241	49.79**	80.51**	87.73**	14.10**	24.19**	18.14**	-10.16**	0.55	4.38
6.	MS 98222A x R 15348	-5.71	26.92**	32.00**	-29.96**	-26.05**	-29.65**	6.56	19.27**	23.81**
7.	MS 98222A x R 15385	-5.32	14.10*	18.67**	-7.93	-2.79	-7.52	-17.70**	-7.89	-4.38
8.	MS 98222A x R 15535	-5.00	21.79**	26.67**	-21.67**	-12.56*	-16.81**	-11.15**	-0.55	3.24
9.	MS 00888A x R 16428	18.29**	24.36**	29.33**	-22.50**	-13.49**	-17.70**	-13.68**	5.32	9.33*
10.	MS 00888A x PS-4	46.34**	53.85**	60.00**	12.50**	25.58**	19.47**	-14.29**	4.59	8.57*
11.	MS 00888A x R 593	53.41**	61.28**	67.73**	7.50	20.00**	14.16**	-10.08**	9.72*	13.90**
12.	MS 00888A x AR-20	-5.24	2.05	6.13	-7.08	3.72	-1.33	-10.38**	9.36*	13.52**
13.	MS 00888A x R 15241	25.12	31.54**	36.80**	-25.83**	-17.21**	-21.24**	-0.75	21.10**	25.71**
14.	MS 00888A x R 15348	-34.29**	-11.54	-8.00	-12.92**	-2.79	-7.52	-24.21**	-7.52	-4.00
15.	MS 00888A x R 15385	-17.07**	-12.82	-9.33	-10.83*	-0.47	-5.31	-18.20**	-0.18	3.62
16.	MS 00888A x R 15535	24.00**	58.97**	65.33**	13.44**	26.63**	20.46**	-21.80**	-4.59	-0.95
17.	MS 97111A x R 16428	38.75**	42.31**	48.00**	19.91**	31.07**	24.69**	-1.17	8.81*	12.95**
18.	MS 97111A x PS-4	-8.75	-6.41	-2.67	-11.49*	-3.26	-7.96	10.00**	21.10**	25.71**
19.	MS 97111A x R 593	10.00	12.82	17.33*	0.11	9.42	4.09	-10.33**	-1.28	2.48
20.	MS 97111A x AR-20	-10.71	-3.85	0.00	-14.89**	-6.98	-11.50*	10.00**	21.10**	25.71**
21.	MS 97111A x R 15241	-17.50**	-15.38*	-12.00	-0.85	8.37	3.10	-5.00	4.59	8.57*
22.	MS 97111A x R 15348	-10.48*	20.51**	25.33**	-7.66	0.93	-3.98	13.33**	24.77**	29.52**
23.	MS 97111A x R 15385	-15.00*	-12.82	-9.33	-23.40**	-16.28**	-20.35**	-12.67**	-3.85	-0.19
24.	MS 97111A x R 15535	-26.00**	-5.13	-1.33	1.25	13.02*	7.52	-7.33	2.02	5.90
25.	MS 88004A x R 16428	-14.10*	-14.10*	-10.67	8.89	1.40	-3.54	-8.56	-13.76**	-10.48*
26.	MS 88004A x PS-4	21.79**	21.79**	26.67**	31.12**	22.09**	16.15**	4.09	-1.83	1.90
27.	MS 88004A x R 593	-30.77**	-30.77**	-28.00**	-2.86	-5.12	-9.73*	8.14*	17.06**	21.52**
28.	MS 88004A x AR-20	11.90	20.51**	25.33**	-4.21	-4.65	-9.29	-11.19**	-11.19**	-7.81
29.	MS 88004A x R 15241	-12.82	-12.82	-9.33	-8.12	0.00	-4.87	14.01**	7.52	11.62**
30.	MS 88004A x R 15348	-42.86**	-23.08**	-20.00**	-17.78**	-13.95**	-18.14**	1.95	-3.85	-0.19
31.	MS 88004A x R 15385	5.13	5.13	9.33	-8.59	-14.88**	-19.03**	-4.71	-3.49	-0.19
32.	MS 88004A x R 15535	-4.00	23.08**	28.00**	17.50**	31.16**	24.78**	32.30**	24.77**	29.52**

Sr. No.	Crosses	Test weight (g)			Grain yield (g)			Fodder Yield (g)		
		BPH	SH1	SH2	BPH	SH1	SH2	BPH	SH1	SH2
1.	MS 98222A x R 16428	24.99**	8.89*	-0.23	28.75**	53.75**	44.14**	22.52*	3.30	18.63
2.	MS 98222A PS-4	21.89**	18.69**	8.75*	-5.09	13.33	6.25	20.80*	1.84	16.96
3.	MS 98222A x R 593	16.45**	6.39	-2.52	-20.45*	-5.00	-10.94	-4.71	-2.76	11.67
4.	MS 98222A x AR-20	-5.51	-15.20**	-22.30**	-2.30	16.67	9.38	-20.77*	-14.87	-2.24
5.	MS 98222A x R 15241	16.58**	-3.03	-11.15**	8.88	30.02**	21.89*	11.14	7.07	22.96*
6.	MS 98222A x R 15348	2.85	-14.44**	-21.61**	-41.38**	-30.00**	-34.38**	15.30	-2.79	11.63
7.	MS 98222A x R 15385	-1.20	-10.96*	-18.42**	-9.77	7.75	1.02	-2.14	-17.50*	-5.26
8.	MS 98222A x R 15535	43.23**	19.14**	9.16*	3.28	23.33*	15.63	13.56	2.57	17.79
9.	MS 00888A x R 16428	0.47	-8.48	-16.15**	-8.33	-8.33	-14.06	-5.31	-14.31	-1.59
10.	MS 00888A x PS-4	27.07**	23.74**	13.37**	32.79**	35.00**	26.56**	-6.58	-15.46	-2.91
11.	MS 00888A x R 593	5.86	-3.28	-11.38**	38.57**	51.67**	42.19**	-23.53**	-21.97*	-10.38
12.	MS 00888A x AR-20	26.37**	15.10**	5.46	-14.29	-20.00*	-25.00**	-18.36*	-12.28	0.75
13.	MS 00888A x R 15241	10.84*	0.96	-7.50	13.43	26.67**	18.75*	5.93	2.05	17.20
14.	MS 00888A x R 15348	27.47**	16.11**	6.39	20.00	10.00	3.13	-2.86	-12.09	0.95
15.	MS 00888A x R 15385	6.49	-3.01	-11.13**	5.89	9.42	2.58	-6.64	-15.52	-2.98
16.	MS 00888A x R 15535	10.90*	1.01	-7.45	44.83**	40.00**	31.25**	11.09	0.53	15.45
17.	MS 97111A x R 16428	47.83**	28.79**	18.00**	-22.73**	-15.00	-20.31*	-3.16	-4.66	9.49
18.	MS 97111A x PS-4	7.11	4.29	-4.44	-6.06	3.33	-3.13	6.72	5.07	20.67*
19.	MS 97111A x R 593	-4.48	-12.73**	-20.04**	36.36**	50.00**	40.63**	-12.68	-10.89	2.33
20.	MS 97111A x AR-20	3.88	-6.77	-14.58**	-10.61	-1.67	-7.81	-19.65*	-13.66	-0.84
21.	MS 97111A x R 15241	31.51**	8.33	-0.74	41.79**	58.33**	48.44**	-9.49	-10.89	2.33
22.	MS 97111A x R 15348	42.94**	18.69**	8.75*	15.15	26.67**	18.75*	5.24	3.61	18.99
23.	MS 97111A x R 15385	4.40	-5.91	-13.79**	-7.58	1.67	-4.69	-15.82	-17.12	-4.82
24.	MS 97111A x R 15535	50.21**	23.74**	13.37**	-33.33**	-26.67**	-31.25**	-0.18	-1.72	12.87
25.	MS 88004A x R 16428	15.03**	0.51	-7.91*	0.00	8.33	1.56	-24.26**	-19.53*	-7.59
26.	MS 88004A x PS-4	23.86**	20.61**	10.50*	41.54**	53.33**	43.75**	-10.94	-5.39	8.65
27.	MS 88004A x R 593	-2.27	-10.71*	-18.19**	-2.54	6.67	0.00	-20.05*	-15.06	-2.45
28.	MS 88004A x AR-20	26.62**	13.64**	4.12	0.00	8.33	1.56	-17.75*	-11.62	1.50
29.	MS 88004A x R 15241	10.69*	-3.28	-11.38**	-11.64	-1.33	-7.50	-8.53	-2.83	11.59
30.	MS 88004A x R 15348	2.60	-10.35*	-17.86**	-9.30	-1.67	-7.81	-13.36	-7.95	5.71
31.	MS 88004A x R 15385	-4.46	-13.89**	-21.10**	-7.69	0.00	-6.25	-26.55**	-21.97*	-10.38
32.	MS 88004A x R 15535	35.84**	18.69**	8.75*	29.23**	40.00**	31.25**	-4.23	1.74	16.84

Under the investigation, the negative heterosis for plant height was considered as desirable, and over better parents it range between (-18.62%) to (9.31%). The cross MS 00888A x R 15241 (-18.62%) showed significantly highest negative heterosis over better parents. The heterosis over standard hybrid check AHB 1200 Fe ranged from (-17.07%) to (19.23%) whereas, the cross MS 00888A x R 15241 (-17.07%) showed highest significant negative heterosis over standard check AHB 1200 Fe. The heterosis over standard check AHB 1269 ranged from (-17.52%) to (18.59%) The cross MS 00888A x R 15241 (-17.52%) recorded highest negative significant heterosis. These results were in according to Gajjar *et al*. (2023) [2] who reported -15.83% to 12.2% for heterobeltosis.

The heterosis over better parent ranged from (-42.86%) to (53.41%). The cross MS 00888A x R 593 (53.41%) showed highest positive heterosis over better parent, followed by MS 98222A x R 15241 (49.79%). The heterosis over standard hybrid check AHB 1200 Fe (80.51%) MS 98222A x R 15241 and second standard hybrid check AHB 1269 (87.73%) MS 98222A x R 15241 displayed highest positive heterosis over standard check. Similar finding for the significant and positive heterosis with Reshma *et al.* (2019) who reported range from -30.14% to 71.23% for heterobeltosis for the number of tillers per plant.

The heterosis over better parent ranged from (-0.85%) to (31.12%). The hybrid MS 88004A x PS-4 (31.12%) recorded highest positive significant heterosis over better parent, followed by MS 97111A x R 16428 (19.91%). The heterosis over standard hybrid check AHB 1200 Fe (31.16%), MS 88004A x R 15535 and second standard hybrid check AHB 1269 (24.78%) MS 88004A x R 15535 exihibited highest positive heterosis over standard check. Similar finding was reported by Moghariya *et al*. (2024) [6] who noticed that panicle length of plant contributed substantially towards the expression of heterosis for panicle length in pearl millet and range of better parent from -45.21 to 32.28% for panicle length.

The heterosis over better parent ranged from (-24.21%) to (32.30%). The hybrid MS 88004A x R 15535 (32.30%) showed highest positive significant heterosis over better parent, and hybrid MS 00888A x R 15348 (-24.21%) showed negative heterosis over better parent. The heterosis over standard hybrid check AHB 1200 Fe (24.77%) MS 97111A x R 15348 and second standard hybrid check AHB 1269 (29.52%) MS 88004A x R 15535 recorded highest positive significant heterosis over standard check. Similar heterotic range for standard heterosis for panicle girth was earlier reported by Suryavanshi *et al*. (2021) [11] who examined the cross DHLB-24 x S-19 and reported standard heterosis (21.49%) for panicle girth.

The heterosis over better parent ranged from (-5.51%) to (50.21%). The hybrid MS 97111A x R 15535 (50.21%) showed highest positive significant heterosis over better parent, and hybrid MS 98222A x AR-20 (-5.51%) showed negative heterosis over better parent. The heterosis over standard hybrid check AHB 1200 Fe (28.79%) MS 97111A x R 16428 and another standard hybrid check AHB 1269 Fe (44.83%) MS 00888A x R 15535 displayed highest positive significant heterosis over standard check. Under the investigation for the test weight trait, Mukesh *et al*. (2022) reported similar result showing highest standard heterosis for test weight (29.00%).

Conclusion

In this study, a comprehensive evaluation of heterosis across various hybrid crosses in pearl millet was carried out. The results showed significant variability in heterosis over better parent and standard hybrid checks for traits such as grain yield, days to 50% flowering, days to maturity, plant height, and panicle length. Positive heterosis was observed in several crosses for grain yield, fodder yield, and test weight, while negative heterosis was found to be desirable for days to 50% flowering and days to maturity. The findings are consistent with previous studies, highlighting the potential of hybridization to improve key traits in pearl millet, contributing to enhanced productivity and resilience in agricultural systems.

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