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MULTI-ENVIRONMENT ASSESSMENT OF HETEROSIS AND COMBINING ABILITY IN PEARL MILLET (PENNISETUM GLAUCUM (L.) R. BR.) ACROSS TESTING LOCATIONS IN RAJASTHAN AND HARYANA

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ABSTRACT
Abundant in protein, balanced amino acids, CHO, fat, iron, and zinc, pearl millet *Pennisetum glaucum* (L.) R. Br.] is a vital part of the average person's diet, which is free from gluten as well, and it is additionally known as a great source of nutrition for poultry and dairy animals. It is typically produced in marginal and submarginal soils under rainfed circumstances with low fertilizer inputs and is also capable of surviving at temperatures and drought conditions, resulting in poor and variable productivity. Despite high-yield hybrids, the pearl millet crop's productivity is erratic because of a number of environmental conditions that affect yield. Consequently, it is necessary to assess the availability of limited, basic, effective old germplasm in various parts of India and replace it with new-era germplasm; hence, the need to regularly assess heterosis and combining ability among germplasm created utilizing stability of various male sterility sources by mixing new and old germplasm from various sources and geographical locations. This work, therefore, conducted a genetic study on heterosis and combining ability in diverse agro-climatic zones of North-West India, including four locations: Jaipur & Alwar in Rajasthan and Rewari & Hisar in Haryana, for six female lines and five male testers, which will be mated using the line x tester design to produce thirty crosses. The experiment was carried out in the Kharif 2025–26 season using a Randomized Block Design (RBD) across four different environments, to test thirty F_1 hybrids that were produced through a Line × Tester mating arrangement along with parents. The findings pointed toward meaningful heterosis, along with higher and steadier performance for grain yield for several associated characters. Overall, the results clearly suggested that both additive as well as non-additive gene effects were involved and there was quite a lot of genetic diversity among the genotypes. Finally, the study shortlisted early maturing, high yielding, more stable, and broadly adapted hybrids, having real promise for pearl millet improvement programmes.

KEYWORDS: Randomized Block Design, *Pennisetum glaucum* (L.) R. Br., heterosis, combining ability, F_1 hybrids

1. INTRODUCTION

Pearl millet, or [*Pennisetum glaucum (L.)* R.Br.] commonly known as bulrush millet, spiked millet, or cat tail millet, is an annual tetraploid (2n=2x=14) of the genus Pennisetum and a significant species of the Poaceae (Graminae). Pearl millet is believed to have originated in Africa. In dry and semi-arid regions of South Asia, India, and part of sub-Saharan Africa. It is grown in a number of states, including Rajasthan, Maharashtra, Gujarat, Madhya Pradesh, Karnataka, and Andhra Pradesh. Tamil Nadu and Uttar Pradesh have a productivity of 1,436 kg/ha, cover 6.7 million hectares, and produce 9.62 million tonnes. It has also grown to be one of the most popular millets in the world and is becoming an increasingly important nutri-grain (Ramya et al., 2018). It is used in food and feed, fodder, forage, building materials, brewing, and biofuel, hence a valuable crop that supports the food and livelihood security of approximately 500 million poor and nutritionally vulnerable people worldwide.

Pearl millet yields are impacted by high temperatures and heat stress caused by drought, which eventually lowers crop productivity. It is essential to develop stable, high-yielding cultivars and hybrids that produce sustainable production in such an uncertain region and are more adaptable to the numerous climate change-related difficulties. (Burton's,1958) Tift 23A CMS line and its use in the hybrid development program have contributed to the remarkable success of pearl millet hybrid growth. In 1965, India saw the introduction of HB-1 of pearl millet utilizing cytoplasmic male sterile line Tift 23A (Athwal,1965). Since then, several promising hybrids have been developed and made accessible for general cultivation, improving the yield of pearl millet. However, most hybrids died rapidly due to the downy mildew disease, which was common in all hybrids (Safeeulla, 1977). Tift 23A cytoplasm was later found to be associated with susceptibility to downy mildew. After continued research on the genetic diversification of cytoplasms, several more sources, such as A2, A3, A4, A5, and PT732A (Bellary) cytoplasm, have been found in pearl millet. The hybrids' varied cytoplasmic backgrounds not only give pearl millet breeding programs flexibility and nuclear diversity, but they also shield the crop against cytoplasmic hazards. Since then, pearl millet hybrids developed in India have mostly been based on the A1 CMS system, except for two hybrids (GHB 316 on A3 and HHB 216 on A4 CMS systems). A2 and A3 sources were thoroughly analyzed by several researchers, but none of them performed better than the A1 CMS system. The exceptionally stable A4 and A5 sources that were found have limited utility due to the lack of effective fertility restorers (Rai et al., 1997). Therefore, strong hybridization breeding has always required the identification and cultivation of a diversity of parental lines. Therefore, research in this field is necessary to identify the restorative genes in the various sources and find the best combination restorer for the commercial use of heterosis on the various sources of cytoplasmic male sterile lines. This work, therefore, conducted a genetic study on heterosis and combining ability in diverse agro-climatic zones of Northwest India. Previously, various researchers have worked in the same domain, and the present paper analyzed their work in the next section.

1.1 Heterosis in Pearl Millet

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is a genetically diverse, predominantly cross-pollinated cereal in which heterosis breeding plays an important role in improving productivity, nutritional quality, and adaptation. The exploitation of heterosis through CMS-based hybrid breeding has resulted in substantial improvement in grain yield and associated traits. Recent studies using line × tester designs have reported significant heterosis for grain yield, panicle length, panicle girth, panicle weight, productive tillers, harvest index, and 1000-grain weight (Khandelwal et al., 2025; Boratkar et al., 2025; Thorat et al., 2025). Heterosis is also relevant to nutritional improvement in pearl millet. Significant positive heterosis has been reported for iron (Fe) and zinc (Zn) concentrations, with a strong positive association between these two micronutrients. This indicates the potential for developing nutritionally superior hybrids without substantial compromise in grain yield (Thribhuvan et al., 2023). Considerable variation in heterobeltiosis and standard heterosis for grain yield has been reported among hybrids, with some combinations showing exceptionally high heterotic responses (Moghariya et al., 2024; Barhate et al., 2023). Heterotic effects for biomass and fodder yield further support the development of dual-purpose hybrids combining grain production with livestock-feed value (Thorat et al., 2025). The magnitude of heterosis largely depends on parental diversity and combining ability. GCA and SCA analysis can therefore be used to identify promising parents and superior cross combinations. Papanna et al. (2024) demonstrated the usefulness of combining-ability information for assigning new pearl millet germplasm to established heterotic groups, thereby facilitating systematic selection of parental lines. Overall, heterosis breeding, supported by combining-ability analysis and heterotic-group classification, provides an effective strategy for developing high-yielding, nutritionally enriched, and climate-resilient pearl millet hybrids.

1.2 Combining Ability and Gene Action in Pearl Millet

Combining ability analysis is an important tool for understanding the genetic control of quantitative traits and identifying suitable parents for pearl millet hybrid breeding. Studies using line × tester designs have shown that both additive and non-additive gene actions contribute to the inheritance of agronomic, yield, nutritional, and stress-related traits. Kapse et al. (2026) evaluated 32 hybrids and reported predominantly additive inheritance for grain yield and days to 50% flowering, with high narrow-sense heritability for grain yield (83.02%). In contrast, plant height, ear-head length, and grain zinc content were mainly governed by non-additive dominance effects, while days to maturity, productive tillers, ear-head traits, thousand-seed weight, fodder yield, and grain iron content showed intermediate inheritance. Several other studies have similarly reported significant GCA and SCA effects for yield and its component traits, indicating the combined contribution of additive and non-additive gene action (Damor et al., 2024; Athoni et al., 2022; Siddique et al., 2022; Balasaheb, 2021). Additive effects were generally more important for traits such as flowering and maturity, whereas non-additive effects predominated for grain yield, panicle weight, productive tillers, and other yield-related characters. These findings emphasize the importance of selecting superior general combiners for developing improved breeding populations and exploiting specific cross combinations for hybrid development. Combining ability analysis has also been extended to nutritional and stress-related traits. Gaoh et al. (2023) identified promising general combiners for iron and zinc concentration, supporting the use of hybrid breeding for micronutrient biofortification. Similarly, Rouamba et al. (2024) demonstrated that both GCA and SCA contributed to yield and *Striga hermonthica* resistance, with specific parental lines consistently contributing to resistance. Overall, these studies indicate that understanding the relative contribution of additive and non-additive gene effects is essential for designing effective selection strategies and developing high-yielding, nutritionally enriched, and stress-resilient pearl millet hybrids.

2. MATERIALS AND METHODS

The current study was conducted under irrigation during the Kharif 2025-26 season in four locations: Jaipur & Alwar in Rajasthan and Rewari & Hisar in Haryana.

2.1 Material: The experiment started in the Kharif season (July, 2025-26). For hybrid seeds, the author performed the crossing farming. In general, conventional hybrid seed production used manual pollination, using the Line × Tester mating approach. But here in the present work, in the Kharif 2025–26 season, all 30 F_1 hybrids along with the parent original seeds and also three standard checks were sown at four sites. The four locations selected for the testing are Jaipur and Alwar in Rajasthan, and Rewari and Hisar in Haryana. The parents used in this investigation include six female (CMS) lines, that is, ICMA 94555, ICMA 97111, HMS 7A, ICMA 04888, ICMA 02333 and HMS 37A. On the other side, there are five male tester (restorer) lines, namely H 77/833-2-202, G 73-107, HTP 94/54, RIB 155076 and RIB 151761-1(Table 1).

2.2 Experimental layout

For the present work, 44 experimental entries were considered using Randomized Block Design (RBD) with 3 distinct replications, across four different experimental environments (Table 2). The experimental material had 30 F_1 hybrids and 11 parental lines, which included 6 CMS lines and 5 restorer lines, and also three standard check hybrids. The multi-location screening was done at E_1 Jaipur (Rajasthan), E_2 Alwar (Rajasthan), E_3 Rewari (Haryana), and E_4 Hisar (Haryana). These varied testing setups were chosen so that the genotype × environment interaction could be looked at, along with heterosis and combining ability, for grain yield and also for related component characters in pearl millet [*Pennisetum glaucum* (L.) R. Br.].

The experimental plots were set up with experimental entries that were planted in 4 rows; each row had a 4 m length, while the spacing was kept at 50 cm between rows and 15 cm between plants. Sowing was done manually, by dropping seeds at the given recommended depth. Further, the thinning was performed after 10 DAS to keep only the vigorous plant in each hill. Standard agronomic practices, including irrigation, fertilizer input, intercultural tasks, weed control, and plant protection measures, were uniformly applied across every location as per recommendations by local SAU's. All this included for better growth of the crop under environmental variation.

Table 1: Detailed description of Genotypes (Parents) used in the study

Sr. No.	CMS (A) Lines	Maintainer (B) Lines	Restorer (R) Lines
1	ICMA 94555	ICMB 94555	H 77/833-2-202
2	ICMA 97111	ICMB 97111	G 73-107
3	HMS 7A	HMS 7B	HTP 94/54
4	ICMA 04888	ICMB 04888	RIB 155076
5	ICMA 02333	ICMB 02333	RIB 151761-1
6	HMS 37A	HMS 37B	

Table 2: Experimental layout

Category	Particular	Details
Experimental Material	Total entries	44
	F_1 hybrids	30
	Parent lines	11
	Standard checks	3
Parental Material	CMS (A) lines	6
	Restorer (R) lines	5
Experimental Design	Mating design	Line × Tester
	Field design	Randomized Block Design (RBD)
	Replications	3
Crop Geometry	Spacing	50 cm (Row × Row) × 15 cm (Plant × Plant)
	Number of rows per entry	4
	Row length	4 m
Experimental Period	Crossing	Kharif 2024–25
	Evaluation	Kharif 2025–26
Experimental Environments	$\mathbf{E_1}$	Jaipur, Rajasthan (26°59′28.8″N, 75°37′40.3″E)
	$\mathbf{E_2}$	Alwar, Rajasthan (28°03′23.3″N, 76°08′16.4″E)
	$\mathbf{E_3}$	Rewari, Haryana (28°29′22.5″N, 76°36′74.7″E)
	$\mathbf{E_4}$	Hisar, Haryana (29°07′51.4″N, 75°37′23.7″E)

2.3 Statistical analysis

The recorded observations for all the characters have been analyzed first using the analysis of variance (ANOVA) based on the procedure outlined by Panse and Sukhatme (1967) to identify the significant differences among genotypes, environments, and the interaction between them. For Heterosis (mid-parent, better-parent, and standard heterosis) and combining ability analyses, the general combining ability (GCA) and specific combining ability (SCA) effects were evaluated to find the Line × Tester mating design and also the superior parents as well as the most promising hybrid combinations.

3. RESULTS

3.1 Variance analysis

The variance analysis for the ten quantitative traits including days to 50 per cent flowering, number of productive tillers per plant, days to maturity, panicle length, plant height, panicle weight, grain yield, dry fodder yield, and 1000-grain weight as well as harvest index was performed for each environment separately (E_1: Jaipur, E_2: Alwar, E_3: Rewari and E_4: Hisar). The experimental material utilized in this research was obtained from the Head of the Millet Section, Chaudhary Charan Singh Haryana Agricultural University, Hisar, and Rajasthan Agricultural Research Institute (RARI), Durgapura. The hybridization process that produced the hybrid material took place in 2024 through a crossing program at a farmer's field in Gangapur Nehari, Aurangabad, Maharashtra-431133 (latitude 19.80° N and longitude 75.27° E). The mean sum of squares of different sources of variation among the environments is given in Table 3.

The analysis of variance across four environments, namely Hisar (E1), Rewari (E2), Jaipur (E3), and Alwar (E4), demonstrated that all genotypes showed significant variation for each trait that researchers investigated. The study found that plant height showed high genetic heritability across all sites, with Hisar recording 2531.07, Rewari recording 2586.18, Jaipur recording 2760.64, and Alwar recording 2616.61. The genetic material under study showed distinct variations in plant characteristics because the two traits of flowering time and maturity time displayed particular differences among plant types. The parental lines showed moderate trait variation, which existed across most observed characteristics. Female lines demonstrated a higher tendency to vary their panicle length measurements, which reached 7.99 in Hisar and 9.98 in Rewari. Males who acted as testers showed greater day-to-50%-flowering time variability, which reached 19.38 in Rewari and 15.53 in Jaipur because they affected flowering patterns. The hybrid crossings demonstrated extensive differences in multiple yield-related characteristics. The study established that Hisar (0.1702), Rewari (0.1248), Jaipur (0.1461), and Alwar (0.1610) showed different grain yield results because hybrid plants produced different output levels in various environmental conditions (Table 4). The study found that dry fodder yield exhibited significant differences across hybrid combinations between Jaipur (1.1695) and Alwar (1.2851), which demonstrated how hybrid combinations affected biomass output. The study found that variance measurements for parental lines and their hybrid offspring produced results that matched those of genotypes. The findings demonstrate that hybrid breeding programs show potential to generate better results because they exhibit heterotic effects. The study found that all three tested groups, which included genotypes, parents, and crosses, showed different results in all tested environments. The study showed that hybrid breeding programs at work currently produce higher yield results because they can access hidden genetic variation found in different hybrids. The study found that environmental factors affected the results because various locations produced different variance results, which demonstrated how genotype and environment interaction affected trait development.

As per the variance, ANOVA across the four environments-Hisar E_1, Rewari E_2, Jaipur E_3, and Alwar E_4 showed a significant difference among genotypes for every trait. Overall genetic variability is high; i.e., plant height has high variability, and days to 50% flowering and days to maturity are also significantly different among genotypes. However, this is not true for parental lines. In particular, the female lines give more input for panicle length; however, other male testers are affected by the flowering time. For the F_1 hybrids, there is significant variation for grain yield and dry fodder yield across environments; hence, hybrid constitution and the location situation are important. Overall, significant variation among both parents and hybrids also suggested exploitable genetic diversity is present, plus there may be heterotic effects at play. And since different genotypes performed differently in each location, it points to a strong genotype × environment interaction. Further in the pooled ANOVA, there is also a significant difference among genotype parents and F_1 hybrids for almost all the traits under study. The mean squares for the lines, the testers, and also for the line × tester interaction were significant, which basically supports that both the female and male parents play a real role in how traits work. The fact that the parents' vs hybrids differed significantly tells us heterosis is present, and the very strong variation across crosses also suggests broad genetic diversity for growth, yield, and those yield-related traits too. Overall, such results give more detailed work on heterosis, combining ability, and genotype × environment interaction, so we can pick superior and stable pearl millet hybrids.

3.2 Estimation of heterosis

Heterosis was estimated for all the traits involved using thirty F_1 hybrids created through a line × tester mating design, which included six female lines and five male testers. This evaluation included the hybrids, eleven parents, and three standard check hybrids (Pro 9001, HHB 67 Improved, and HHB 299), and they were tested in four environments during Kharif under a randomized block design. Heterosis was calculated as the percentage difference or increase of F_1 hybrids over:

(i) mid-parent (Relative heterosis, H_1),

(ii) better parent (Heterobeltiosis, H_2), and

(iii) standard check hybrid (Standard heterosis, H_3).

Standard heterosis was calculated referring to the best commercial check among Pro 9001, HHB 67 Improved and HHB 299 for each trait. The estimates of heterosis against mid-parent, better parent and standard checks for all characters are given in Table 5. The heterosis analysis across the four environments showed significant variation among the 30 F_1 hybrids for all traits. For days to 50% flowering and for days to maturity, it has been observed that there is desirable negative heterosis, with standard heterosis values ranging from −17.83% to −9.48%, respectively, hence indicating that several hybrids could be useful for developing early-flowering and early maturing cultivars (Table 5). Productive tillers per plant, panicle length, panicle weight, grain yield, dry fodder yield, 1000-grain weight, and harvest index all showed desirable positive heterosis, and the highest heterosis was 21.43%, 22.34%, 27.26%, 48.78%, 22.90%, 30.52%, and 34.33%, respectively. Such results suggested that those hybrids are doing better than the parents and also the standard checks. Further, plant height showed both positive heterosis (29.83%) and negative heterosis (−41.12%), which gives breeders an opportunity to pick either high biomass types or more lodging-resistant genotypes. The broad range of heterotic responses that are under observation across traits and environments points to genotype × environment interaction playing a key role, and it also confirms there is substantial genetic variability available. Overall, this supports the idea of developing high-yielding, stable, and widely adapted pearl millet hybrids. Relative heterosis (H_1) for grain yield ranged from −5.77% to 42.82%, with the hybrid HMS 7A × RIB 151761-1 exhibiting the highest positive heterosis (42.82%). Plant height showed both positive and negative heterotic responses ranging from −25.35% to 29.83%, indicating the possibility of selecting either high biomass or comparatively dwarf genotypes. For dry fodder yield, heterosis reached as high as 27.31% in ICMA 02333 × RIB 151761-1. Heterobeltiosis (H_2) for grain yield was highest in HMS 7A × RIB 151761-1

Table 3: Analysis of variation for all traits in all three environments

Source	Env	Days to 50% Flowering	Productive tillers (No. plant-1)	Days to Maturity	Panicle length (cm)	Plant Height (cm)	Panicle weight (kg plot-1)	Grain yield (kg plot-1)	Dry fodder yield (kg plot-1)	1000 grain weight (g)	Harvest Index
Genotypes	Hisar	15.13**	0.09*	14.16**	1.68*	2531.07**	0.26*	0.16*	1.22**	1.86*	20.66**
Parents	Hisar	6.90*	0.05	11.13**	5.43**	422.62*	0.26*	0.08	0.19	2.08**	16.09**
Females	Hisar	6.11*	0.05	7.98*	7.99**	435.01*	0.10	0.06	0.28*	1.26*	7.12*
Males	Hisar	9.62	0.05	15.56**	3.17*	285.85**	0.48*	0.07	0.12	3.58**	20.90**
Crosses	Hisar	13.43**	0.10*	14.92**	0.45	640.98**	0.25*	0.17*	1.24**	1.30*	20.37**
Parents vs Crosses	Hisar	15.13**	0.09*	14.16**	1.68	2531.07**	0.26*	0.16*	1.22**	1.86*	20.66**
Error	Hisar	15.13**	0.09*	14.16**	1.68	2531.07**	0.26*	0.16*	1.22**	1.86*	20.66**
Genotypes	Rewari	10.88**	0.09*	8.35*	4.68*	2586.18**	0.22*	0.17*	0.88*	1.74*	14.40*
Parents	Rewari	14.67**	0.06	4.41	7.41**	347.97**	0.13	0.08	0.18	2.46**	10.24
Females	Rewari	12.42**	0.06	4.13	9.96**	408.98**	0.15	0.09	0.14	4.23**	10.59*
Males	Rewari	19.39**	0.06	5.77*	2.80	229.47**	0.14	0.09	0.03	0.58*	8.45
Crosses	Rewari	8.86*	0.11**	9.86	3.18	910.67**	0.24*	0.12*	0.78*	1.62**	15.16**
Parents vs Crosses	Rewari	10.88**	0.09*	8.35	4.68*	2586.18**	0.22*	0.17*	0.88*	1.74**	14.40**
Error	Rewari	10.88**	0.09*	8.35*	4.68*	2586.18**	0.22**	0.17*	0.88**	1.74**	14.40**
Genotypes	Jaipur	9.79*	0.11*	12.60*	7.99**	2760.64**	0.27**	0.12*	0.97**	1.08**	24.07**
Parents	Jaipur	11.11**	0.03	3.45*	4.25*	435.33*	0.14*	0.07	0.13	1.95**	9.54*
Females	Jaipur	4.44	0.05	2.62*	4.51*	545.65*	0.22**	0.11	0.10	1.55**	10.86*
Males	Jaipur	15.54**	0.01	5.17*	3.08	167.61*	0.08	0.04	0.03	2.77**	7.90*
Crosses	Jaipur	10.09*	0.15**	15.02**	9.70**	925.36*	0.31**	0.15*	1.17**	0.80	28.69**
Parents vs Crosses	Jaipur	9.79*	0.11*	12.60**	7.99**	2760.64**	0.27**	0.12	0.97**	1.08**	24.07**
Error	Jaipur	9.79	0.11*	12.60**	7.99**	2760.64**	0.27**	0.12	0.97**	1.08**	24.07**
Genotypes	Alwar	17.18**	0.04	9.24**	4.50*	2616.61**	0.38**	0.16*	0.97**	1.47**	26.98**
Parents	Alwar	8.42*	0.06	4.36**	5.87*	327.09*	0.42**	0.16*	0.35*	1.95**	22.04*
Females	Alwar	9.10*	0.02	2.67*	6.64**	398.38*	0.29**	0.10	0.67**	1.55**	17.48**
Males	Alwar	7.70*	0.11*	0.50	6.38**	153.19	0.48**	0.23**	0.02	2.77**	30.78**
Crosses	Alwar	15.58**	0.03	10.70**	3.21*	655.76**	0.37**	0.16*	1.29**	1.34**	24.94**
Parents vs Crosses	Alwar	17.18**	0.04	9.24**	4.50**	2616.61**	0.38**	0.16*	0.97**	1.47**	26.98**
Error	Alwar	17.18**	0.04	9.24**	4.50**	2616.61**	0.38**	0.16*	0.97**	1.47**	26.98**

**Significant at 5 per cent and 1 per cent level, respectively

Table 4: Pooled analysis of variance for the experimental setup across different environments for various pearl millet features

Source	Days to 50% Flowering	Productive tillers (No. plant⁻¹)	Days to Maturity	Panicle length (cm)	Plant Height (cm)	Panicle weight (kg plot⁻¹)	Grain yield (kg plot⁻¹)	Dry fodder yield (kg plot⁻¹)	1000 grain weight (g)	Harvest Index
Replication	205.44**	0.33**	470.09**	150.42**	366.43**	0.96*	1.51**	16.20**	3.07**	50.64**
Genotypes	41.81**	0.11*	33.33*	9.91*	10404.05**	0.46	0.35*	1.78*	3.83**	40.10**
Parents	30.09*	0.09	19.60*	13.95*	9380.35**	0.61**	0.25*	0.99	5.77**	28.64*
Crosses	40.29**	0.12*	39.45*	7.79*	3038.38**	0.40	0.34*	2.02*	2.95**	44.63**
Lines	51.47**	0.17**	72.79**	1.85	5278.04**	0.41*	0.89*	1.00*	11.93**	126.01**
Testers	38.43*	0.06	30.92*	4.20	6091.02**	0.27	0.04	1.59*	1.36	12.91
Parents vs Crosses	10.20	0.03	19.86*	6.16*	6341.97**	0.21*	0.10	1.03*	2.82**	15.99
L × T	4.66	0.00	12.40*	4.76	2646.15**	0.06	0.12	0.73*	3.70**	24.83*
Error	163.62**	0.23*	436.76**	140.51**	10037.62**	0.50*	1.17**	14.42**	0.76	10.54

(48.78%), followed by HMS 7A × RIB 155076 (35.54%) and HMS 7A × G 73-107 (34.93%), indicating substantial exploitation of non-additive gene action for yield improvement (Table 6). Standard heterosis (H_3) for grain yield was highest in HMS 7A × RIB 151761-1 (18.49%), followed by HMS 7A × RIB 155076 (7.95%) and HMS 7A × G 73-107 (7.46%), demonstrating their superiority over the commercial check (Table 7).

3.4 Combine ability analysis

The pooled analysis of variance for combining ability represents the significant differences among parents, crosses, lines, testers, and the line × tester interaction for each and every traits under study. The lines had higher mean squares for grain yield (0.89), harvest index (126.01), and 1000-grain weight (11.93). Additionally, significant line × tester interactions for days to 50% flowering (4.66), days to maturity (12.40), plant height

(2646.15), grain yield (0.12), and harvest index (24.83) demonstrated that specific combining ability, or SCA, plays a vital role in the performance of hybrids (Table 8). Further, in the case of GCA work, HMS 7A and ICMA 02333 give better general combiners for plant height (38.23 and 45.88), panicle weight (0.266), grain yield (0.44), and harvest index (4.35); on the other hand, H 77/833-2-202 and RIB 155076 give promising testers, showing positive GCA impacts for yield and closely linked traits. Then the SCA analysis gives the number of top cross combinations, each with significant positive effects for grain yield, panicle weight, dry fodder yield, and harvest index. Such results suggest these crosses could be used for further exploitation in hybrid breeding programs (Table 9, 10). Overall, the outcomes from ANOVA, heterosis, and combining ability studies indicate that there is some major genetic variability among the parental lines as well as the F_1 hybrids for each trait under study. The observed significant differences between genotypes, parents, crosses, lines, testers, and especially line × tester interactions really point out that both additive and non-additive gene effects matter a lot in how growth, yield, and yield-attributing traits get inherited. In the heterosis analysis, several top hybrids came up, with useful positive but also a few negative heterotic responses for traits that are economically important, and then the combining ability part showed which general combiners and specific combiners look promising, for use in hybrid development. Also, the fact that significant variation stayed consistent across the four test environments stressed the importance of genotype × environment interaction.

Table 5: Percent heterosis H1 for all traits in all three environments

Name	Days to 50% Flowering	Productive tillers (No. plant⁻¹)	Days to Maturity	Panicle length (cm)	Plant Height (cm)	Panicle weight (kg plot-1)	Grain yield (kg plot⁻¹)	Dry fodder yield (kg plot⁻¹)	1000 grain weight (g)	Harvest Index
HMS 37 AxH 77/833-2-202	5.94**	0.93*	4.43**	4.26*	-6.01	3.60*	13.59**	-2.37	7.27**	15.96**
HMS 37 AxG 73-107	5.45**	-9.26	5.38**	14.89**	-5.07	-7.46	0.10	0.24*	15.70**	0.11*
HMS 37 AxHTP 94/54	0.50*	-11.11	1.90*	2.13*	7.31**	-4.54	30.01**	16.03**	14.83**	12.25**
HMS 37 AxRIB 155076	-0.50	0.65*	2.22*	5.32**	11.67**	8.01**	18.87**	9.14**	9.88**	10.12**
HMS 37 AxRIB 151761-1	0.50*	-10.19	1.58*	7.45**	1.30*	3.81*	13.49**	9.16**	12.79**	3.28*
HMS 7 AxH 77/833-2-202	13.37**	-12.96	10.76**	3.19*	22.88**	4.72*	15.74**	-1.51	2.62*	16.42**
HMS 7 AxG 73-107	11.88**	-14.81	8.54**	9.57**	6.49**	-1.85	29.52**	5.28**	7.56**	21.81**
HMS 7 AxHTP 94/54	-2.48	-14.81	1.27*	10.64**	20.52**	11.75**	20.82**	18.62**	13.95**	1.48*
HMS 7 AxRIB 155076	3.47*	-13.89	3.80*	9.57**	20.87**	6.74**	30.11**	5.18**	0.58*	23.20**
HMS 7 AxRIB 151761-1	6.93**	-4.63	7.28**	7.45**	20.99**	6.66**	42.82**	19.81**	22.38**	18.62**
ICMA 02333xH 77/833-2-202	12.38**	-12.96	8.23**	22.34**	27.36**	-2.47	5.57**	-1.42	6.69**	6.41**
ICMA 02333xG 73-107	11.39**	-10.19	9.49**	9.57**	1.89*	9.01**	17.89**	16.18**	11.05**	2.74*
ICMA 02333xHTP 94/54	3.47*	-11.11	8.54**	2.13*	25.71**	-6.39	2.15*	-7.43	13.37**	9.19**
ICMA 02333xRIB 155076	14.36**	-3.70	11.71**	18.09**	29.83**	-5.96	4.40*	22.00**	18.60**	-15.73
ICMA 02333xRIB 151761-1	4.95*	-2.78	6.65**	-1.06	25.00**	6.48**	17.69**	27.31**	12.79**	-8.27
ICMA 04888xH 77/833-2-202	0.99*	-11.11	1.58*	8.51**	22.64**	-7.21	1.47*	2.31*	11.92**	-1.60
ICMA 04888xG 73-107	9.41**	-11.11	6.65**	14.89**	-3.07	-9.60	25.32**	20.98**	30.52**	2.34*
ICMA 04888xHTP 94/54	1.98*	10.19	3.48*	1.06*	4.72*	1.47*	9.78**	18.22**	11.34**	-7.18
ICMA 04888xRIB 155076	-1.49	-7.41	1.27*	4.26*	6.72**	1.72*	8.41**	4.72*	20.64**	3.65*
ICMA 04888xRIB 151761-1	-3.47	-11.11	0.63*	5.32**	10.97**	-1.57	21.11**	6.13**	20.64**	15.63**
ICMA 94555xH 77/833-2-202	-1.98	8.33**	0.32*	10.64**	16.27**	6.06**	17.11**	9.81**	10.17**	6.74**
ICMA 94555xG 73-107	14.85**	-5.56	12.97**	8.51**	10.85**	5.82**	12.41**	4.70*	6.69**	6.60**
ICMA 94555xHTP 94/54	9.41**	-7.41	9.18**	12.77**	17.22**	-2.05	5.96**	-0.33	22.67**	6.60**
ICMA 94555xRIB 155076	0.99*	-5.56	2.53*	7.45**	15.45**	11.69**	20.92**	14.77**	17.73**	5.30**
ICMA 94555xRIB 151761-1	7.92**	-6.48	6.33**	-1.06	-25.35	-22.75	-5.77	-11.46	9.30**	6.45**
ICMA 97111xH 77/833-2-202	4.46*	-12.04	5.70**	3.19*	13.33**	5.07**	13.59**	11.52**	-8.14	1.82*
ICMA 97111xG 73-107	-6.44	-14.81	0.63*	3.19*	-8.14	-14.28	-2.35	6.99**	-5.23	-9.29
ICMA 97111xHTP 94/54	-2.48	-6.48	-0.32	6.38**	28.07**	-7.47	2.93*	3.65*	-6.69	2.08*
ICMA 97111xRIB 155076	-1.98	-8.33	0.63*	9.57**	24.69**	-1.99	0.10*	18.04**	-9.01	-15.53
ICMA 97111xRIB 151761-1	16.34**	-14.81	11.71**	21.28**	19.34**	-5.96	1.76*	4.34*	-7.56	-1.28

**-Significant at 5 per cent and 1 per cent level, respectively

Table 6: Heterobeltiosis (H2) for all traits in all three environments

Name	Days to 50% Flowering	Productive tillers (No. plan⁻¹)	Days to Maturity	Panicle length (cm)	Plant Height (cm)	Panicle weight (kg plot⁻¹)	Grain yield (kg plot⁻¹)	Dry fodder yield (kg plot⁻¹)	1000 grain weight (g)	Harvest Index
HMS 37 AxH 77/833-2-202	-1.38	11.22**	-1.79	-8.41	-16.89	17.97**	18.33**	-8.76	3.36*	26.43**
HMS 37 AxG 73-107	-1.84	0.00	-0.89	0.93*	-16.06	5.38**	4.28*	-6.32	11.48**	9.15**
HMS 37 AxHTP 94/54	-6.45	-2.04	-4.17	-10.28	-5.11	8.70**	35.44**	8.43**	10.64**	22.40**
HMS 37 AxRIB 155076	-7.37	10.92**	-3.87	-7.48	-1.25	22.99**	23.83**	1.99*	5.88**	20.07**
HMS 37 AxRIB 151761-1	-6.45	-1.02	-4.46	-5.61	-10.43	18.22**	18.23**	2.02*	8.66**	12.61**
HMS 7 AxH 77/833-2-202	5.53**	-4.08	4.17*	-9.35	8.65**	19.25**	20.57**	-7.96	-1.12	26.94**
HMS 7 AxG 73-107	4.15*	-6.12	2.08*	-3.74	-5.84	11.77**	34.93**	-1.61	3.64*	32.82**
HMS 7 AxHTP 94/54	-9.22	-6.12	-4.76	-2.80	6.57**	27.26**	25.87**	10.86**	9.80**	10.65**
HMS 7 AxRIB 155076	-3.69	-5.10	-2.38	-3.74	6.88**	21.55**	35.54**	-1.71	-3.08	34.33**
HMS 7 AxRIB 151761-1	-0.46	5.10**	0.89*	-5.61	6.99**	21.46**	48.78**	11.97**	17.93**	29.34**
ICMA 02333xH 77/833-2-202	4.61*	-4.08	1.79*	7.48**	12.62**	11.06**	9.98**	-7.87	2.80*	16.02**
ICMA 02333xG 73-107	3.69*	-1.02	2.98*	-3.74	-9.91	24.13**	22.81**	8.57**	7.00**	12.02**
ICMA 02333xHTP 94/54	-3.69	-2.04	2.08*	-10.28	11.16**	6.60**	6.42**	-13.49	9.24**	19.05**
ICMA 02333xRIB 155076	6.45**	6.12**	5.06**	3.74*	14.81**	7.08**	8.76**	14.86**	14.29**	-8.12
ICMA 02333xRIB 151761-1	-2.30	7.14**	0.30*	-13.08	10.51**	21.25**	22.61**	18.98**	8.69**	0.02*
ICMA 04888xH 77/833-2-202	-5.99	-2.04	-4.46	-4.67	8.45**	5.66**	5.70**	-4.39	7.84**	7.29**
ICMA 04888xG 73-107	1.84*	-2.04	0.30*	0.93*	-14.29	2.95*	30.55**	13.06**	25.77**	11.59**
ICMA 04888xHTP 94/54	-5.07	21.43**	-2.68	-11.22	-7.40	15.55**	14.36**	10.48**	7.28**	1.20*
ICMA 04888xRIB 155076	-8.29	2.04*	-4.76	-8.41	-5.63	15.83**	12.93**	-2.14	16.25**	13.02*
ICMA 04888xRIB 151761-1	-10.14	-2.04	-5.36	-7.48	-1.88	12.09**	26.17**	-0.92	16.25**	26.07**
ICMA 94555xH 77/833-2-202	-8.76	19.39**	-5.65	-2.80	2.82*	20.78**	22.00**	2.62*	6.16**	16.38**
ICMA 94555xG 73-107	6.91**	4.08*	6.25**	-4.67	-1.98	20.50**	17.11**	-2.16	2.80*	16.23**
ICMA 94555xHTP 94/54	1.84*	2.04*	2.68*	-0.93	3.65*	11.54**	10.39**	-6.85	18.21**	16.23**
ICMA 94555xRIB 155076	-5.99	4.08*	-3.57	-5.61	2.09*	27.19**	25.97**	7.26**	13.45**	14.81**
ICMA 94555xRIB 151761-1	0.46*	3.06*	0.00	-13.08	-33.99	-12.03	-1.83	-17.26	5.32**	16.07**
ICMA 97111xH 77/833-2-202	-2.76	-3.06	-0.60	-9.35	0.21*	19.64**	18.33**	4.22**	-11.48	11.02**
ICMA 97111xG 73-107	-12.90	-6.12	-5.36	-9.35	-18.77	-2.38	1.73*	-0.02	-8.68	-1.09
ICMA 97111xHTP 94/54	-9.22	3.06*	-6.25	-6.54	13.24**	5.37**	7.23**	-3.13	-10.08	11.30**
ICMA 97111xRIB 155076	-8.76	1.02*	-5.36	-3.74	10.22**	11.60**	4.28*	10.31**	-12.32	-7.89
ICMA 97111xRIB 151761-1	8.29**	-6.12	5.06**	6.54**	5.53**	7.09**	6.01**	-2.49	-10.92	7.64

**-Significant at 5 per cent and 1 per cent level, respectively

Table 7. Standard heterosis (H3) for all traits in all three environments

Name	Days to 50% Flowering	Productive tillers (No. plant^{-1})	Days to Maturity	Panicle length (cm)	Plant Height (cm)	Panicle weight (kg plot-1)	Grain yield (kg plot^{-1})	Dry fodder yield (kg plot^{-1})	1000 grain weight (g)	Harvest Index
HMS 37 AxH 77/833-2-202	-6.96	7.92**	-5.17	0.00	-25.86	-7.78	-5.76	-20.02	1.37*	17.23**
HMS 37 AxG 73-107	-7.39	-2.97	-4.31	10.20**	-25.12	-17.62	-16.95	-17.88	9.34**	1.21*
HMS 37 AxHTP 94/54	-11.74	-4.95	-7.47	-2.04	-15.35	-15.03	7.87**	-4.95	8.52**	13.49**
HMS 37 AxRIB 155076	-12.61	7.62**	-7.18	1.02*	-11.91	-3.86	-1.38	-10.59	3.85*	11.34**
HMS 37 AxRIB 151761-1	-11.74	-3.96	-7.76	3.06*	-20.09	-7.59	-5.84	-10.57	6.59**	4.41**
HMS 7 AxH 77/833-2-202	-0.43	-6.93	0.57*	-1.02	-3.07	-6.78	-3.97	-19.32	-3.02	17.71**
HMS 7 AxG 73-107	-1.74	-8.91	-1.44	5.10**	-16.00	-12.63	7.46**	-13.75	1.65*	23.15**
HMS 7 AxHTP 94/54	-14.35	-8.91	-8.05**	6.12**	-4.93	-0.52	0.24	-2.82	7.69**	2.59*
HMS 7 AxRIB 155076	-9.13	-7.92	-5.75	5.10**	-4.65	-4.98	7.95**	-13.84	-4.95	24.55**
HMS 7 AxRIB 151761-1	-6.09	1.98*	-2.59	3.06*	-4.56	-5.05	18.49**	-1.85	15.66**	19.93**
ICMA 02333xH 77/833-2-202	-1.30	-6.93	-1.72	17.35**	0.47	-13.18	-12.41	-19.24	0.82**	7.58**
ICMA 02333xG 73-107	-2.17	-3.96	-0.57	5.10**	-19.63	-2.96	-2.19	-4.83	4.95*	3.87*
ICMA 02333xHTP 94/54	-9.13	-4.95	-1.44	-2.04	-0.84	-16.67	-15.25	-24.16	7.14**	10.39**
ICMA 02333xRIB 155076	0.43**	2.97**	1.44*	13.27**	2.42*	-16.29**	-13.38	0.68*	12.09**	-14.80
ICMA 02333xRIB 151761-1	-7.83	3.96*	-3.16	-5.10	-1.40	-5.22	-2.35	4.29**	6.59**	-7.26
ICMA 04888xH 77/833-2-202	-11.30	-4.95	-7.76	4.08*	-3.26	-17.40	-15.82	-16.19	5.77**	-0.52
ICMA 04888xG 73-107	-3.91	-4.95	-3.16	10.20**	-23.53**	-19.53	3.97*	-0.89	23.35**	3.47*
ICMA 04888xHTP 94/54	-10.43	17.82**	-6.03	-3.06	-17.40	-9.67	-8.92	-3.15	5.22**	-6.16
ICMA 04888xRIB 155076	-13.48	-0.99	-8.05	0.00	-15.81	-9.45	-10.06	-14.21	14.01**	4.80**
ICMA 04888xRIB 151761-1	-15.22	-4.95	-8.62	1.02*	-12.47	-12.38	0.49*	-13.06	14.01**	16.90**
ICMA 94555xH 77/833-2-202	-13.91	15.84**	-8.91	6.12**	-8.28	-5.59	-2.84	-10.04	4.12*	7.91**
ICMA 94555xG 73-107	0.87*	0.99*	2.59*	4.08**	-12.56	-5.80	-6.73	-14.23	0.82*	7.77**
ICMA 94555xHTP 94/54	-3.91	-0.99	-0.86	8.16**	-7.53	-12.80	-12.08	-18.35	15.93**	7.77**
ICMA 94555xRIB 155076	-11.30	0.99*	-6.90	3.06*	-8.93	-0.58	0.32*	-5.98	11.26**	6.45**
ICMA 94555xRIB 151761-1	-5.22	0.00	-3.45	-5.10	-41.12	-31.24	-21.82	-27.47	3.30*	7.63**
ICMA 97111xH 77/833-2-202	-8.26	-5.94	-4.02	-1.02	-10.60	-6.47	-5.76	-8.64	-13.19	2.94*
ICMA 97111xG 73-107	-17.83	-8.91	-8.62	-1.02	-27.53	-23.69	-18.98	-12.35*	-10.44	-8.29
ICMA 97111xHTP 94/54	-14.35	0.00*	-9.48	2.04*	1.02*	-17.63	-14.60	-15.08	-11.81	3.20*
ICMA 97111xRIB 155076	-13.91	-1.98	-8.62	5.10**	-1.67	-12.76	-16.95	-3.30	-14.01	-14.60
ICMA 97111xRIB 151761-1	2.17*	-8.91	1.44*	16.33**	-5.86	-16.29	-15.57	-14.52	-12.64	-0.20

Table 8: Pooled analysis of variance for parents and crosses for combining ability

	Days to 50% Flowering	Productive tillers (No. plant^{-1})	Days to Maturity	Panicle length (cm)	Plant Height (cm)	Panicle weight (kg plot^{-1})	Grain yield (kg plot^{-1})	Dry fodder yield (kg plot^{-1})	1000 grain weight (g)	Harvest Index
Replication	205.44**	0.33*	470.09**	150.42**	366.43**	0.96*	1.51*	16.20**	3.07*	50.64**
Genotypes	41.81**	0.11*	33.33**	9.91**	10404.05**	0.46*	0.35*	1.78*	3.83*	40.10**
Parents	30.09**	0.09*	19.60**	13.95**	9380.35**	0.61*	0.25*	0.99*	5.77**	28.64**
Crosses	40.29**	0.12*	39.45**	7.79**	3038.38**	0.40*	0.34*	2.02*	2.95**	44.63**
Lines	51.47**	0.17*	72.79**	1.85*	5278.04**	0.41*	0.89*	1.00*	11.93**	126.01**
Testers	38.43**	0.06*	30.92**	4.20*	6091.02**	0.27*	0.04*	1.59*	1.36*	12.91**
Parents vs Crosses	10.20**	0.03*	19.66**	6.16**	6341.97**	0.21*	0.10*	1.03*	2.82*	15.99**
L×T	4.60*	0.00*	12.40**	4.76*	2646.15**	0.06*	0.12*	0.73*	3.70*	24.83**
Error	163.62**	0.23*	436.76**	140.51**	10037.62**	0.50*	1.17*	14.42**	0.76*	10.54**

**-Significant at 5 per cent and 1 per cent level, respectively

Table 9: Pooled estimates of parents' GCA effects across three different environments

	Days to 50% Flowering	Productive tillers (No. plant^{-1})	Days to Maturity	Panicle length (cm)	Plant Height (cm)	Panicle weight (kg plot^{-1})	Grain yield (kg plot^{-1})	Dry fodder yield (kg plot^{-1})	1000 grain weight (g)	Harvest Index
HMS 37A	-1.95	0.06*	-1.93	-0.07	3.23*	0.073*	0.12*	-0.03	0.09*	1.64*
HMS 7A	0.20*	-0.12	0.62*	0.23*	38.23**	0.266*	0.44*	0.20*	-0.14	4.35*
ICMA 02333	1.55*	-0.01	2.67*	0.73*	45.88**	0.050*	-0.03	0.35*	0.12*	-1.58
ICMA 04888	-2.40	0.05*	-2.23	-0.07	17.13**	-0.075	0.07*	0.27*	0.68*	-0.32
ICMA 94555	0.00	0.12*	0.57*	0.13*	13.93**	0.035*	-0.01	-0.26	0.19*	0.96*
ICMA 97111	-2.15	-0.09	-1.48	0.38*	32.08**	-0.150	-0.19	0.16*	-1.58	-2.70
H 77/833-2-202	-0.20	0.03*	-0.30	0.37*	33.42**	0.110*	0.02*	-0.29	-0.51	1.40*
G 73-107	0.76*	-0.08	1.37*	0.71*	0.38	-0.076	0.08*	0.17*	0.00	0.18*
HTP 94/54	-2.28	0.03*	-1.22	-0.29	35.92**	-0.002	0.04*	0.10*	0.04*	0.19*
RIB 155076	-1.90	0.04*	-1.47	0.46*	37.92**	0.178*	0.08*	0.42*	-0.11	-0.57
RIB 151761-1	-0.36	-0.01	0.12*	-0.13	17.79**	-0.043	0.12*	0.18*	0.06*	0.70*

**-Significant at 5 per cent and 1 per cent level, respectively

Table 10: Pooled analysis of SCA impacts across all environments

Line	Tester	Days to 50% Flowering	Productive tillers (No. plant^{-1})	Days to Maturity	Panicle length (cm)	Plant Height (cm)	Panicle weight (kg plot^{-1})	Grain yield (kg plot^{-1})	Dry fodder yield (kg plot^{-1})	1000 grain weight (g)	Harvest Index
HMS 37A	**H 77/833-2-202**	2.00*	0.15*	1.35*	-0.97	-50.07	0.01*	-0.06	-0.38	0.10*	1.19*
	G 73-107	0.79*	-0.01	0.43*	1.19*	-15.03	-0.25	-0.47	-0.64	0.31*	-2.98
	HTP 94/54	1.33*	-0.17	0.27*	-0.81	-24.32	-0.20	0.34*	0.63*	0.19*	1.14*
	RIB 155076	0.45*	0.13*	0.77*	-0.81	-17.07	0.11*	0.01*	-0.22	-0.08	1.17*
	RIB 151761-1	-0.59	-0.11	-1.32	0.28*	-18.94	0.17*	-0.16	0.03*	0.00*	-2.48
HMS 7A	**H 77/833-2-202**	3.60*	-0.05	3.80*	-1.52	-23.82	-0.15	-0.32	-0.54	-0.07	-1.36
	G 73-107	1.89*	0.01*	0.38*	-0.36	-25.53	-0.22	-0.04	-0.48	-0.16	1.69*
	HTP 94/54	-2.32	-0.10	-2.78	0.89*	-31.32	0.24*	-0.21	0.60*	0.35*	-5.23
	RIB 155076	0.30*	-0.08	-0.53	-0.11	-32.57	-0.13	-0.02	-0.75	-0.65	2.91*
	RIB 151761-1	0.51*	0.22	0.63*	-0.02	-12.19	0.09*	0.27*	0.61*	1.06*	0.03*
ICMA 02333	**H 77/833-2-202**	1.75*	-0.16	-0.25	2.48*	-21.97	-0.21	-0.12	-0.69	0.01*	1.17*
	G 73-107	0.29*	0.03*	-0.92	-0.86	-42.93	0.43*	0.13*	0.19*	-0.12	1.13*
	HTP 94/54	-0.67	-0.11	0.92*	-1.61	-27.97	-0.25	-0.22	-1.53	0.03*	3.32*
	RIB 155076	4.45*	0.08*	3.67**	1.39**	-21.22	-0.42	-0.21	0.44*	0.64*	-4.39
	RIB 151761-1	-1.84	0.16*	-1.92	-2.52	-11.34	0.29*	0.09*	1.02*	-0.03	-3.18
ICMA 04888	**H 77/833-2-202**	-0.05	-0.17	-0.60	0.03*	-3.22	-0.28	-0.32	-0.33	-0.10	-2.81
	G 73-107	3.24*	-0.05	1.73*	1.19*	-24.68	-0.18	0.23*	0.63*	0.99*	-0.26
	HTP 94/54	2.53*	0.41*	1.82*	-1.06	-43.72	0.18*	-0.12	0.49*	-0.70	-3.50
	RIB 155076	0.40*	-0.07	0.32*	-1.06	-41.47	0.01*	-0.21	-0.86	0.25*	0.94*
	RIB 151761-1	-2.14	-0.12	-1.77	-0.22	-12.34	0.10*	0.08*	-0.51	0.08*	3.68*
ICMA 94555	**H 77/833-2-202**	-3.95	0.28*	-4.40	0.33*	-13.52	0.14*	0.16*	0.77*	0.24*	-1.26
	G 73-107	3.59*	0.02*	3.93**	-0.51	8.02*	0.32*	-0.02	-0.08	-0.57	-0.09
	HTP 94/54	3.88*	-0.14	3.52**	1.49*	-14.02	-0.07	-0.14	-0.39	0.76*	-0.10
	RIB 155076	-0.75	-0.10	-1.48	-0.51	-19.77	0.29*	0.19	0.43	0.49	0.22
	RIB 151761-1	1.21*	-0.07	-0.07	-1.92	-86.14	-0.85	-0.52	-1.31	-0.40	-0.72
ICMA 97111	**H 77/833-2-202**	1.45*	-0.05	1.90*	-1.67	-37.92	0.29*	0.25	0.49	0.44	0.73
	G 73-107	-5.01	-0.01	-3.77	-2.01	-50.38	-0.30	-0.23	-0.31	0.18	-1.83
	HTP 94/54	0.03*	0.10*	-1.93	-0.26	-9.17	-0.10	-0.04	-0.49	0.01	2.03
	RIB 155076	-0.10	0.04*	-0.93	-0.26	-18.42	-0.06	-0.16	0.27	-0.03	-3.20
	RIB 151761-1	7.61**	-0.08	6.23**	3.08*	-9.54	0.00	-0.16	-0.52	-0.08	0.32

**Significant at 5 per cent and 1 percent level, respectively

Overall, these findings suggest the experimental material has a wide genetic base and decent breeding potential, so it can provide valuable parental lines and hybrid combinations aimed at stable, high-yielding, and broadly adapted pearl millet cultivars.

4. CONCLUSIONS

Pearl millet is an important cereal crop usually grown under rainfed and drought-prone conditions; hence, high yields along with stable hybrids are main breeding goals. The present study has used 30 F_1 hybrids from 6 CMS lines and 5 testers, of which 11 are parents, plus 3 standard checks. The testing has been performed in four different environments. For this, the ANOVA indicated very significant differences among genotypes, parents, crosses, lines, testers, and also for the line × tester interaction for every trait. For heterosis under study, some hybrids showed promising results, i.e., grain yield went as high as 48.78%, 1000-grain weight reached 30.52%, dry fodder yield was 22.90%, and harvest index recorded 34.33%. The combining ability analysis shows significant GCA and SCA effects, meaning both additive and non-additive gene actions are involved. In this context, HMS 7A, ICMA 02333, H 77/833-2-202, and RIB 155076 appeared as strong general combiners for yield plus related traits. Overall, the study basically showed there is substantial genetic variability, heterosis that can be utilized, and favorable combining-ability patterns. Hence, it gives useful parental lines and also better hybrid choices for developing high-yielding, early-maturing, stable, and widely adapted pearl millet hybrids that can perform well across various agroclimatic conditions. Hybrids like H 77/833-2-202, HMS 7A x G 73-107 and ICMA 94555 x RIB 155076 were more responsive when the conditions were favorable, so they appear better suited for high-input management too. As for locations, Rewari and Alwar were more favorable for grain yield expression, while Jaipur gave comparatively weaker productivity, in a more straightforward way. The hybrids HMS 7A × RIB 155076, HMS 7A × RIB 151761-1, ICMA 04888 × G 73-107, ICMA 04888 × RIB 151761-1, ICMA 94555 × RIB 155076, and HHB-299 consistently recorded higher grain yield, plus a favorable expression of yield-contributing traits, pretty steady across the environments. From the combining ability analysis, it seems like both additive and non-additive genetic effects were present in the inheritance of traits, but overall, the non-additive gene action was the one that showed up more, especially for grain yield and many of the related characters.

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