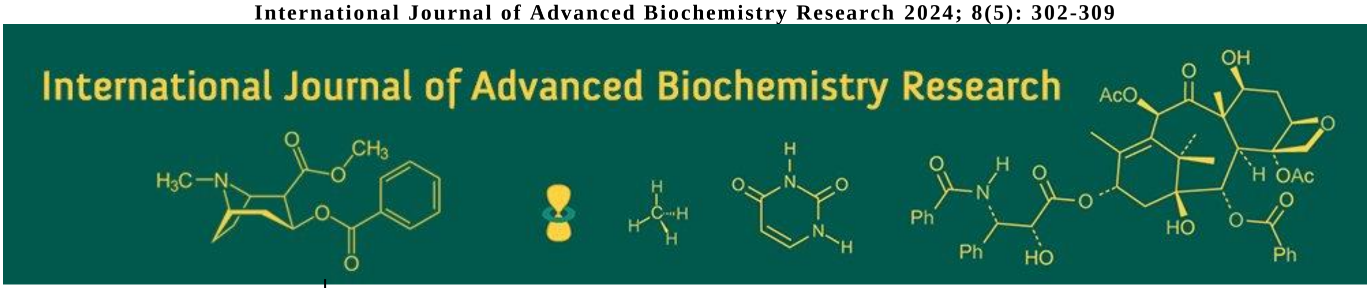

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Identification of heterotic effect and combining ability in the hybrids of male sterile and restorer pearl millet [*Pennisetum glaucum* (L.) R. Br.] Lines

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Abstract
Pearl millet, also known as *Pennisetum glaucum* L. R. Br., is regarded as a resilient Nutri-cereal that serves as the primary food staple for a large population within the country. A study was carried out to improve its grain mineral composition through the utilization of line × tester analysis, aiming to ascertain the levels of heterosis, gene action, and combining ability concerning grain yield potential, as well as the presence of grain mineral elements such as iron (Fe) and zinc (Zn). Seven CMS lines, in addition to 7 restorers (testers) of pearl millet, were employed for the current investigation. For ten agronomic and two micronutrient characters at 3 locations of the S.D.A.U.; during kharif 2021. All the genotypes were evaluated in RBD replicated thrice in three environments formed by different locations. In the case of most characteristics, notable discrepancies arose due to environmental factors, parental influences, and hybrid combinations, highlighting the considerable variability within the materials. Examination of genetic mechanisms revealed a predominance of non-additive and additive gene effects across different traits. The CMS lines SDMA 1 and pollen parents 15725 R and 16088 R had good general combiners for grain yield per plant and majority of its attributes. The hybrids ICMA 98444 x 16088 R (with an average x good rating), SDMA 1 x 15725 R (good x good), and ICMA 05888 x 15725 R (average x good) were derived from parental lines that exhibited high per se performance. These hybrids showed significant positive Relative heterosis, heterobeltiosis, and standard heterosis, along with a positive specific combining ability effect for both grain yield per plant and component characters.

Keywords: Pearl millet, L × T design, multi-locations, combining ability and Heterosis

Introduction

Pearl millet, scientifically known as *Pennisetum glaucum* L. R. Br., occupies a notable position as the sixth largest globally and the third largest in India among cereal food crops, after rice and wheat. Referred to by various names such as bajra, bajri, spiked millet, bulrush millet, or cat millet, pearl millet is distinguished for its ability to thrive in arid and semi-arid tropical areas of Asia and Africa. Pearl millet (2n = 14) is C4 plant species with excellent photosynthetic efficiency and enormous genetic variability. As a result of the cytoplasmic genetic male sterility mechanism, it is possible to create populations with heterozygous traits that can be effectively utilized for generating high-yielding hybrids with a rich mineral content. The initial and most commonly employed cytoplasmic male sterile strain, Tift 23A, was introduced by Burton in 1965, thereby enabling the creation of commercial hybrids in India through the cultivation and thorough evaluation of hybrids involving Tift 23A. The utilization of hybrid Vigor through the employment of cytoplasmic male sterile lines has demonstrated significant cost-effectiveness. Various sources of cytoplasmic genetic male sterility, such as A_1, A_2, A_3, A_v, A_4, A_{agp}, and A_5, are present in pearl millet. These sources have played a crucial role in enabling the development and introduction of numerous hybrid varieties. Rich in carbohydrates (70%), protein (14.0%), minerals (2 to 7%), fat (5.7%), and fiber (2.0%), pearl millet grain is highly nutritive, Recognizing its nutritional importance, pearl millet has been designated as a nutri-cereal, included in the Public Distribution System (PDS), and declared the "Year of Millets" in India in 2018 and the "International Year of Millets" by the FAO Committee on Agriculture (COAG) in 2023 (Anonymous, 2022) [2].

The investigation of combining ability in breeding studies offers valuable insights into the selection of appropriate parental candidates for efficient hybridization programs, while also shedding light on the characteristics and extent of gene action. Prior to initiating any breeding initiative, breeders must possess knowledge pertaining to gene action and the genetic framework of the population. Due to the fact that the manifestation of gene action varies in accordance with the genetic makeup of the population engaged in hybridization, it becomes imperative to assess the combining ability of the parental individuals. The assessment of breeding crosses and the identification of optimum cross combinations (combining ability) for yield and quality attributes are essential components for the proficient manipulation enabled by hybrid breeding strategies.

Materials and Methods

The materials consisted of seven CGMS lines utilized as female lines (SDMA 1, ICMA 04999, ICMA 05888, ICMA 08444, ICMA 98222, ICMA 98444 and JMSA 20101) and seven restorer lines utilized as testers (15298 R, 15725 R, 15990 R, 16088 R, 17548 R, 18196 R and 42299 HP) along with their 49 F_1 progenies. The hybrids were generated through the utilization of line × tester mating design in the Summer of 2021, following the methodology proposed by Kempthorne (1957) [15]. The assessment protocol was implemented utilizing a Randomized Block Design (RBD) with three replications in the *kharif* season of 2021 at three distinct sites, namely the Centre for Crop Improvement, Sardarkrushinagar Dantiwada Agricultural University in Banaskantha District (E_1), Wheat Research Station, Sardarkrushinagar Dantiwada Agricultural University in Mehsana District (E_2), and Regional Research Station, Sardarkrushinagar Dantiwada Agricultural University in Kachchh District (E_3). Agronomic observations encompassed monitoring 12 traits, including days to 50% flowering, days to maturity, plant height (cm), number of productive tillers per plant, panicle length (cm), panicle diameter (mm), total biomass yield per plant (g), grain yield per plant (g), test weight (g), harvest index (%), iron content, and zinc content (mg kg^{-1}). The collected data underwent analysis of variance, with each trait's data for both parents and hybrids being scrutinized separately for individual environments and collectively across environments. This analysis was conducted utilizing statistical methodologies outlined by Panse and Sukhatme (1978) [17] and Tai (1971) [25]. The hybrid performance was assessed by comparing it with the average value of the two parental lines, denoted as Relative heterosis/RH, the superior parent (heterobeltiosis/BP), and a standard control (Standard heterosis/SH) as proposed by Briggle (1963) [4], Fonseca and Patterson (1968) [10], and Meredith and Bridge (1972) [16] respectively. The prescribed agronomic techniques for promoting robust crop development were implemented.

Results and Discussion

The analysis of combining ability demonstrated the existence of genetic variability within both parents and hybrids with respect to the traits under investigation. Considerable variation was noted in the levels of Fe and Zn among the parental lines, a finding that has been previously documented by Govindraj *et al*. (2013) [11], Kanatti *et al*. (2014) [14], and Tribhuvan *et al*. (2022) [26]. Significance was prominently observed when comparing parents to hybrids across all traits, with the exception of the number of productive tillers per plant and iron content, suggesting the occurrence of heterosis (Table 1).

Table 2 illustrated the presence of diversity among the different environments for all characteristics. Significant variations in mean square values attributed to both testers and lines, as well as the interaction between lines and testers, for most traits, pointed towards their involvement in the broader concept of general combining ability (GCA) and specific combining ability (SCA), respectively. The impact of environments on the variance of GCA and SCA was found to be substantial. It is noteworthy that hybrids exhibited a higher level of interaction with environments compared to their interaction with lines and testers. Non-additive type of gene action (σ^2gca/σ^2sca < 1) was observed for traits such as days to maturity, number of productive tillers per plant, total biomass yield per plant, grain yield per plant, harvest index, iron content, and zinc content, suggesting the potential application of heterosis breeding for improving these characteristics. This finding is consistent with previous studies conducted by Jethva *et al*. in 2011 [13], Chavan and Nerkar in 1994 [6], Shelke and Chavan in 2010 [24], and Singh and Sharma in 2014. The prevalence of additive gene action (σ^2gca/σ^2sca > 1) for the remaining traits pointed towards the utilization of simplistic selection methods and recombination breeding, coupled with the pedigree selection approach. Corresponding observations were made in the study conducted by Shaikh *et al*. in 2020 [22] for traits such as days to flowering and plant height. Similar patterns were identified by Dhuppe *et al*. (2006) [9] for panicle length and panicle diameter. In contrast, Warrier *et al*. (2020) [27] documented dissimilar outcomes for test weight.

Different levels of performance, whether good, average, or poor, were associated with distinct outcomes in terms of gene actions. These outcomes were characterized by either significant positive, non-significant, or significant negative effects, as indicated in Table 3 & 4. Furthermore, graphical illustrations in Figure 1 and Figure 2 depict the general combining ability and specific combining ability effects for hybrids across various environments, specifically focusing on grain yield per plant in pearl millet. The understanding of both GCA and SCA is crucial for harnessing heterosis in breeding programs. Notably, the identification of suitable parents and hybrids for early flowering and maturity traits was based on their significantly negative GCA and SCA, respectively.

Among parents, SDMA 1, 15725 R and 16088 R were good general combiner for grain yield per plant, plant height, panicle diameter and total biomass yield per plant. Notably, the parental varieties ICMA 04999, ICMA 05888, ICMA 98222, JMSA 20101, 15990 R, and 17548 R demonstrated significant combiner effects for traits such as days to flowering and days to maturity, respectively. Furthermore, SDMA 1, ICMA 98444, 15725 R, 15990 R, 16088 R, 18196 R, and 42299 HP were identified as proficient combiners for plant height, whereas ICMA 04999 and 15990 R displayed notable combiner effects in relation to the number of productive tillers per plant. Among parents SDMA 1, ICMA 05888, JMSA 20101, 15725 R and 18196 R were good general combiner for panicle length. In terms of panicle diameter, SDMA 1, ICMA 98222, ICMA 98444, 15725 R, 16088 R, 18196 R, and 42299 HP were recognized as strong general combiners. Moreover, SDMA 1, ICMA 05888, 15725 R, 16088 R, 18196 R, and 42299 HP were identified as proficient combiners for total biomass yield per plant. Specifically, SDMA 1, ICMA 98444, 16088 R, and 18196 R were deemed as effective combiners for test weight. In the context of harvest index, SDMA 1, ICMA 08444, ICMA 98222, 15298 R, 15725 R, and 17548 R were acknowledged as valuable general combiners among parental lines. Conversely, ICMA 04999, ICMA 05888, 17548 R, and 42299 HP were noted for their substantial combiner effects on iron content. Lastly, among the parental lines ICMA 04999, JMSA 20101, 15298 R, and 16088 R were distinguished as noteworthy general combiners for zinc content (Table 3). This implies that parents could possibly be assumed to possess a larger quantity of advantageous alleles for the production of high-quality hybrids or varieties of pearl millet.

In general, all characters exhibit a cross that demonstrates positive and negative effects on combining ability, which encompasses combinations of good × good, average × good, good × poor, average × average, average × poor, and poor × poor general combiners. The crosses involving good × poor and poor × good combiners can be ascribed to the absence of co-adaptation between the favorable alleles of the parental lines. The crosses displaying high specific combining ability (sca) effects for grain yield per plant also manifest high, average, or poor sca effects for yield components (Table 4). This suggests that a yield is a intricate characteristic that relies on the number of component characters. Among 49 hybrids, fourteen hybrids displayed notable positive specific combining ability impacts on grain yield per plant. Previous significant GCA and SCA impacts in pearl millet for grain yield and component characteristics were also documented by Reshma Krishnan *et al*. (2017) [20], Davda and Dangaria (2018) [8], Sharma *et al*. (2019) [23], and Patel (2022) [18].

In reference to heterosis over mid parent, superior parent, and standard heterosis, a substantial level of heterosis was observed in the desired direction across all traits. The hybrids, namely SDMA 1 x 15725 R, ICMA 98444 x 16088 R, and ICMA 05888 x 15725 R, demonstrated remarkable individual performance alongside significant positive relative heterosis, heterobeltiosis, and standard heterosis for grain yield per plant (Table 4). The results of heterosis were in accordance with the studies conducted by that of Bachkar *et al.* (2014) [3] for days to flowering, days to maturity, plant height and total biomass yield per plant. The number of effective tillers per plant as documented by Patel *et al*. (2017) [19]. The findings associated with panicle length, panicle diameter, and test weight were consistent with the investigations conducted by Patel (2022) [18]. The results for the grain yield per plant corresponded with the discoveries of Salagarkar *et al*. (2016) [21] and Patel (2022) [18].

The hybrid SDMA 1 × 15725 R exhibited favorable parental combination with superior individual performance, noteworthy relative heterosis, heterobeltiosis, standard heterosis, and substantial positive specific combining ability effect along with significant SCA effects, encompassing a proficient general combiner. These findings suggest an interaction pattern of additive × dominance nature, capable of generating advantageous transgressive segregants in later breeding cycles, thus holding promise for the development of commercially viable hybrids.

The hybrid combination ICMA 98444 × 16088 R exhibited average to good combiner parents, high *per se* performance, notable positive relative heterosis, heterobeltiosis, and standard heterosis, along with a positive specific combining ability effect for grain yield per plant, plant height, and test weight. Similarly, the hybrid cross ICMA 05888 × 15725 R showcased average to good combiner parents, high intrinsic performance, significant positive relative heterosis, heterobeltiosis, and standard heterosis, as well as a positive specific combining ability effect for grain yield per plant. This suggests that acquiring favourable transgressive individuals in the F2 generation could be employed in the advancement of pollinated cytoplasmic male sterile (CMS) lines as the maternal progenitor and male parent pollen fertility restorer lines for forthcoming breeding initiatives focused on enhancing grain yield per plant, producing high-yielding hybrids, and targeting commercial applications.

Table 1: Analysis of variance for the various characteristics across multiple environments in pearl millet

Source of variation	**d.f.**	**Days to flowering**	**Days to maturity**	**Plant height**	**Number of productive tillers/plant**	**Panicle length**	**Panicle diameter**
		1	**2**	**3**	**4**	**5**	**6**
Environment	2	195.83**	313.62**	5314.94**	0.19**	8.95**	31.10**
Repli. within Environment	2	2.51*	0.30	5.73	0.11**	4.66**	3.72*
Genotypes	62	172.58**	65.91**	6455.58**	0.05**	30.45**	80.90**
Parents	13	171.26**	74.78**	10228.87**	0.07**	50.23**	139.38**
Lines	6	157.68**	21.99**	6635.36**	0.08**	94.62**	144.98**
Testers	6	123.28**	66.37**	2780.18**	0.07**	4.25**	128.66**
Lines *vs.* Testers	1	540.64**	442.03**	76482.06**	0.00	59.80**	170.10**
Hybrids	48	138.49**	54.48**	3648.03**	0.04**	13.95**	61.63**
Parents *vs.* Hybrids	1	1825.81**	498.88**	92165.13**	0.00	565.33**	245.66**
Genotypes × Environment	124	29.99**	12.14**	277.26**	0.03**	3.16**	9.43**
Parents × Environment	26	53.37**	11.83**	615.79**	0.04**	3.88**	11.97**
Lines × Environment	12	44.68**	10.19**	533.35**	0.04*	3.46**	12.93**
Testers × Environment	12	27.70**	8.16**	720.21**	0.04	1.34*	6.23**
Line *vs.* Tester × Environment	2	259.52**	43.72**	483.99**	0.13**	21.66**	40.48**
Hybrids × Environment	96	19.02**	10.95**	174.34**	0.03	2.40**	7.66**
Parents *vs.* Hybrids × Envi.	2	252.84**	73.12**	816.84**	0.11**	30.27**	61.24**
Error (Pooled)	372	0.70	0.27	12.57	0.02	0.71	1.01
Source of variation	**d.f.**	**Total biomass yield/plant**	**Grain yield/plant**	**Test weight**	**Harvest index**	**Iron content**	**Zinc content**

		7	8	9	10	11	12
Environment	2	798.95**	153.15**	149.62**	31.16**	7260.59**	356.51**
Repli. within Environment	2	65.69	11.96	0.33	6.26	64.93	12.21
Genotypes	62	2227.20**	262.56**	10.20**	783.91**	502.32**	275.56**
Parents	13	3940.92**	421.77**	11.32**	984.15**	1011.74**	399.86**
Lines	6	317.93**	174.78**	11.45**	571.15**	873.04**	74.46**
Testers	6	1635.31**	448.48**	9.10**	316.37**	167.62**	309.35**
Lines *vs.* Testers	1	39512.46**	1743.49**	23.76**	7468.87**	6908.64**	2895.37**
Hybrids	48	1508.18**	178.10**	10.09**	743.00**	374.37**	212.94**
Parents *vs.* Hybrids	1	14461.86**	2246.95**	0.95*	144.50**	21.28	1665.47**
Genotypes × Environment	124	80.40**	14.33**	2.86**	3.24	52.43	82.32**
Parents × Environment	26	87.88**	16.81**	4.11**	10.07**	80.29**	83.69**
Lines × Environment	12	20.08	9.05	3.39**	13.26**	94.21*	69.60**
Testers × Environment	12	165.57**	25.91**	5.50**	4.06	39.44	106.13**
Line *vs.* Tester × Environment	2	28.62	8.83	0.14	27.06**	241.88**	33.56*
Hybrids × Environment	96	80.00**	13.94**	2.57**	1.23	45.72	72.76**
Parents *vs.* Hybrids × Envi.	2	1.97	0.88	0.16	10.98*	12.60	523.60**
Error (Pooled)	372	34.02	5.45	0.24	2.68	43.85	9.61

*,** Significant at $p\leq 0.05$ and $p\leq 0.01$ levels of probability, respectively.

Table 2: Analysis of variance for combining ability and estimates of components of variance for various characters in pearl millet over pooled locations

Source of variation	d. f.	Days to flowering	Days to maturity	Plant height	Number of productive tillers/plant	Panicle length	Panicle diameter
		1	2	3	4	5	6
Environments	2	195.83**	313.62**	5314.94**	0.19**	8.95**	31.10**
Replications	2	2.51*	0.30	5.73	0.11**	4.66**	3.72*
Line (L)	6	157.68**	21.99**	6635.36**	0.08**	94.62**	144.98**
Tester (T)	6	123.28**	66.37**	2780.18**	0.07**	4.25**	128.66**
Line × Tester	1	540.64**	442.03**	76482.06**	0.00	59.80**	170.10**
Line × Environment	12	44.68**	10.19**	533.35**	0.04*	3.46**	12.93**
Tester × Environment	12	27.70**	8.16**	720.21**	0.04	1.34*	6.26**
L × T × Environment	2	259.52**	43.72**	483.99**	0.13**	21.66**	40.48**
σ^2gca		7.06	1.68	185.48	0.00	0.62	3.09
σ^2sca		3.94	4.12	105.80	0.00	0.51	1.80
σ^2gca/ σ^2sca		1.79	0.41	1.75	0.50	1.23	1.72
Pooled Error	372	0.70	0.27	12.57	0.02	0.71	1.01
Source of variation	**d. f.**	**Total biomass yield/plant**	**Grain yield/plant**	**Test weight**	**Harvest index**	**Iron content**	**Zinc content**
		7	8	9	10	11	12
Environments	2	798.95**	153.15**	149.62**	31.16**	7260.59**	356.51**
Replications	2	65.69	11.96	0.33	6.26	64.93	12.21
Line (L)	6	317.93**	174.78**	11.45**	571.15**	873.04**	74.46**
Tester (T)	6	1635.31**	448.48**	9.10**	316.37**	167.62**	309.35**
Line × Tester	1	39512.46**	1743.49**	23.76**	7468.87**	6908.64**	2895.37**
Line × Environment	12	20.08	9.05	3.39**	13.26**	94.21*	69.60**
Tester × Environment	12	165.57**	25.91**	5.50**	4.06	39.44	106.13**
L × T × Environment	2	28.62	8.83	0.14	27.06**	241.88**	33.56*
σ^2gca		55.50	6.26	0.46	20.09	14.58	3.05
σ^2sca		88.77	10.94	0.38	62.82	14.79	23.03
σ^2gca/ σ^2sca		0.63	0.57	1.22	0.32	0.99	0.13
Pooled Error	372	34.02	5.45	0.24	2.68	43.85	9.61

*,** Significant at $p\leq 0.05$ and $p\leq 0.01$ levels of probability, respectively.

Table 3: Estimation of general combining ability effects of parents for yield and yield attributing characters of pooled over the environments in pearl millet

Parents	Days to flowering	Days to maturity	Plant height	Number of productive tillers/plant	Panicle length	Panicle diameter
	1	2	3	4	5	6
Lines						
SDMA 1	4.82**	2.84**	17.94**	-0.03	0.44**	3.67**
ICMA 04999	-0.98**	-1.76**	-2.30**	0.05**	-0.22*	-1.15**
ICMA 05888	-0.98**	-0.22**	-2.00**	-0.01	1.10**	-2.01**
ICMA 08444	-2.49**	-0.09	-11.38**	0.02	-0.66**	0.03
ICMA 98222	-1.66**	-0.46**	-5.21**	-0.01	-1.05**	0.34**
ICMA 98444	1.79**	0.13*	7.02**	0.00	-0.76**	0.54**
JMSA 20101	-0.50**	-0.44**	-4.07**	-0.01	1.15**	-1.42**

S. Em. ±	0.96	0.60	3.31	0.01	0.45	0.68
Testers						
15298 R	2.50**	0.26**	-36.54**	-0.05**	-0.43**	-2.14**
15725 R	2.32**	1.10**	9.78**	0.01	1.11**	1.07**
15990 R	-4.03**	-1.35**	3.80**	0.07**	-0.29**	-2.44**
16088 R	1.42**	1.65**	8.05**	0.00	-0.19	0.88**
17548 R	-3.18**	-1.65**	-0.99*	-0.02	-0.58**	0.11
18196 R	-1.37**	-0.08	3.62**	-0.02	0.81**	1.63**
42299 HP	2.34**	0.07	12.27**	0.01	-0.43**	0.90**
S. Em. ±	1.03	0.65	7.04	0.01	0.37	0.51
Parents	**Total biomass yield/plant**	**Grain yield/plant**	**Test weight**	**Harvest index**	**Iron content**	**Zinc content**
	7	**8**	**9**	**10**	**11**	**12**
Lines						
SDMA 1	9.00**	5.16**	0.62**	2.29**	-2.35**	-1.91**
ICMA 04999	-3.43**	-1.85**	-0.45**	-0.42*	7.19**	0.98*
ICMA 05888	2.46**	-0.03	-0.81**	-1.99**	6.47**	-1.69**
ICMA 08444	-7.21**	-0.61*	0.02	3.05**	-6.49**	-1.91**
ICMA 98222	-0.89	-0.09	0.01	0.84**	-2.38**	0.31
ICMA 98444	-0.19	-0.28	1.09**	0.37	-2.56**	0.52
JMSA 20101	0.26	-2.30**	-0.49**	-4.14**	0.13	3.69**
S. Em. ±	2.12	1.10	1.10	0.92	2.22	1.24
Testers						
15298 R	-10.99**	-2.57**	-0.83**	4.00**	0.19	2.50**
15725 R	2.06**	3.99**	-0.17**	4.21**	-4.11**	-2.21**
15990 R	0.15	-3.15**	-0.28**	-6.01**	0.51	-0.26
16088 R	8.39**	2.52**	1.38**	-2.16**	-0.53	1.12**
17548 R	-14.33**	-1.22**	-0.28**	9.14**	1.87*	0.09
18196 R	4.92**	0.40	0.37**	-3.00**	-0.81	-0.47
42299 HP	9.80**	0.04	-0.19**	-6.17**	2.89**	-0.78*
S. Em. ±	3.90	1.20	0.34	2.18	0.77	0.42

Table 4: The top three ranking parents in terms of per se performance and general combining ability effects were identified, along with three top ranking hybrids in terms of per se performance, specific combining ability effects, and heterosis over mid-parent, better parent, and a standard check (GHB 1129) in pearl millet

Sr. No.	Trait	Best performing Parent (*per se performing*)	Best General Combiner	Best performing Hybrid (*per se performing*)	Status of parents	SCA effect	Heterosis		
							RH	HB	SH
1	Days to flowering	ICMA 98222	17548 R	ICMA 98222 × 15990 R	G × G	-0.61*	-9.32**	-11.39**	-2.75**
		ICMA 08444	15990 R	ICMA 08444 × 15990 R	G × G	0.77**	-9.32**	-10.25**	-1.50
		15990 R	ICMA 08444	ICMA 08444 × 17548 R	G × G	-0.18	-15.30**	-21.08**	-1.75
2	Days to maturity	ICMA 04999	17548 R	ICMA 98222 × 17548 R	G × G	-1.32**	-6.99**	-8.58**	-1.63**
		ICMA 08444	15990 R	ICMA 04999 × 15990 R	G × G	-0.32	-3.14**	-3.33**	-1.63**
		15990 R	ICMA 04999	ICMA 98444 × 17548 R	P × G	-0.91**	-7.09**	-7.44**	-0.41
3	Plant height	42299 HP	42299 HP	SDMA 1 × 42299 HP	G × G	6.45**	54.90**	16.26**	20.62**
		18196 R	SDMA 1	SDMA 1 × 16088 R	G × G	7.24**	53.83**	16.01**	18.64**
		16088 R	15725 R	ICMA 98444 × 16088 R	G × G	14.31**	48.79**	13.84**	16.42**
4	Number of productive tillers per plant	ICMA 08444	15990 R	ICMA 04999 × 15990 R	G × G	0.11**	15.79**	10.00*	8.20
		ICMA 98222	ICMA 04999	ICMA 08444 × 15990 R	A × G	0.08	4.13	3.28	3.28
		15298 R	42299 HP	ICMA 04999 × 18196 R	G × A	0.06	9.09*	7.14	-1.64
5	Panicle length	JMSA 20101	15725 R	JMSA 20101 × 15725 R	G × G	0.70*	20.07**	11.21**	16.51**
		SDMA 1	ICMA 05888	JMSA 20101 × 18196 R	G × G	0.95**	16.48**	11.01**	16.30**
		17548 R	JMSA 20101	ICMA 05888 × 15725 R	G × G	-0.10	20.32**	15.17**	12.49**
6	Panicle diameter	18196 R	SDMA 1	SDMA 1 × 18196 R	G × G	0.75*	11.79**	4.81**	28.84**
		16088 R	18196 R	SDMA 1 × 16088 R	G × G	0.80**	12.63**	8.46**	26.00**
		JMSA 20101	15725 R	SDMA 1 × 42299 HP	G × G	0.64*	20.07**	16.62**	25.45**
7	Total biomass yield per plant	18196 R	SDMA 1	SDMA 1 × 16088 R	G × G	8.24**	56.60**	10.10**	44.50**
		16088 R	42299 HP	SDMA 1 × 42299 HP	G × G	4.77*	86.70**	44.26**	40.97**
		15298 R	16088 R	ICMA 98444 × 42299 HP	A × G	9.61**	90.85**	36.64**	33.53**
8	Grain yield per plant	18196 R	SDMA 1	SDMA 1 × 15725 R	G × G	5.82**	131.34**	97.35**	74.06**
		15298 R	15725 R	ICMA 98444 × 16088 R	A × G	9.47**	117.98**	63.94**	59.10**
		17548 R	16088 R	ICMA 05888 × 15725 R	A × G	2.74**	130.66**	119.87**	36.22**
9	Test weight	16088 R	16088 R	ICMA 98444 × 16088 R	G × G	0.87**	34.87**	7.94**	58.06**
		ICMA 98222	SDMA 1	ICMA 98444 × 18196 R	G × G	1.35**	44.51**	24.84**	50.89**
		15298 R	ICMA 98444	SDMA 1 × 16088 R	G × G	0.50**	11.43**	0.04	46.49**
10	Harvest index	SDMA 1	17548 R	SDMA 1 × 15725 R	G × G	18.00**	35.21**	5.17**	73.87**
		ICMA 98222	15725 R	ICMA 98222 × 17548 R	G × G	13.24**	34.02**	6.62**	70.44**
		JMSA 20101	15298 R	ICMA 98444 × 15298 R	A × G	13.60**	55.17**	36.54**	56.37**
11	Iron content	ICMA 05888	ICMA 05888	ICMA 04999 × 17548 R	G × G	5.03*	13.28**	-1.20	-10.98**

		SDMA 1	ICMA 04999	ICMA 05888 × 42299 HP	G × G	3.62	2.61	-8.54*	-12.18**
		ICMA 04999	42299 HP	ICMA 04999 × 42299 HP	G × G	2.35	5.55	-3.21	-12.79**
12	Zinc content	ICMA 04999	JMSA 20101	JMSA 20101 × 16088 R	G × G	4.53**	12.95**	-5.78	-2.34
		JMSA 20101	ICMA 98444	JMSA 20101 × 17548 R	G × A	5.34**	21.70**	-6.28	-2.86
		ICMA 98444	15298 R	ICMA 98444 × 17548 R	A × A	7.96**	24.53**	-2.13	-4.17

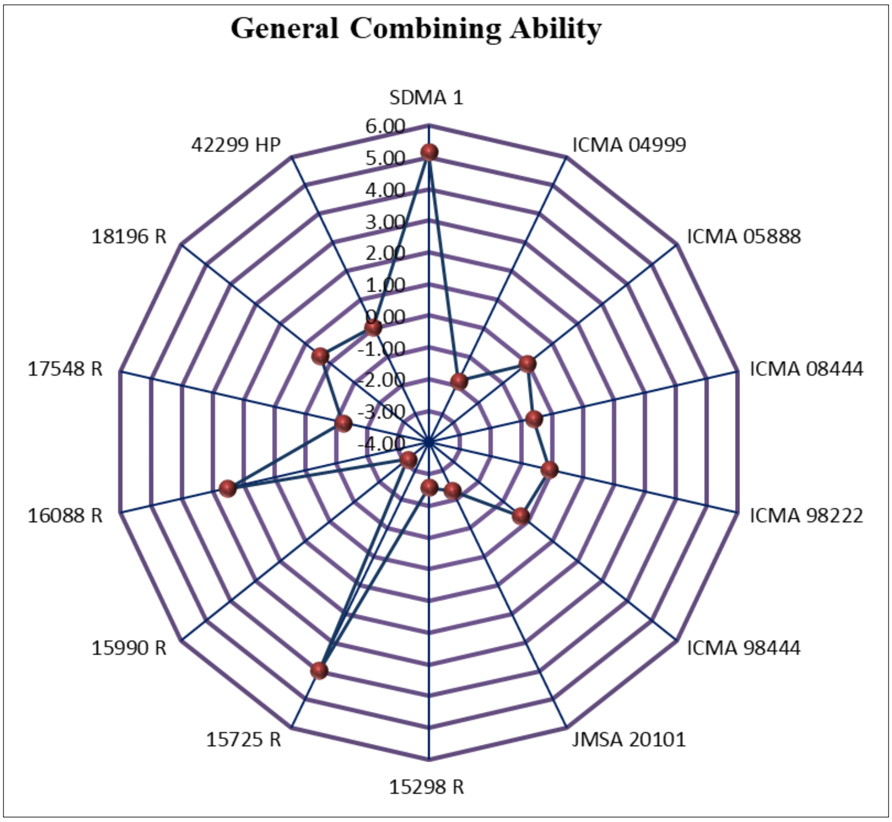

Fig 1: Graphical representation of general combining ability effects of parents based on pooled over environments for grain yield per plant

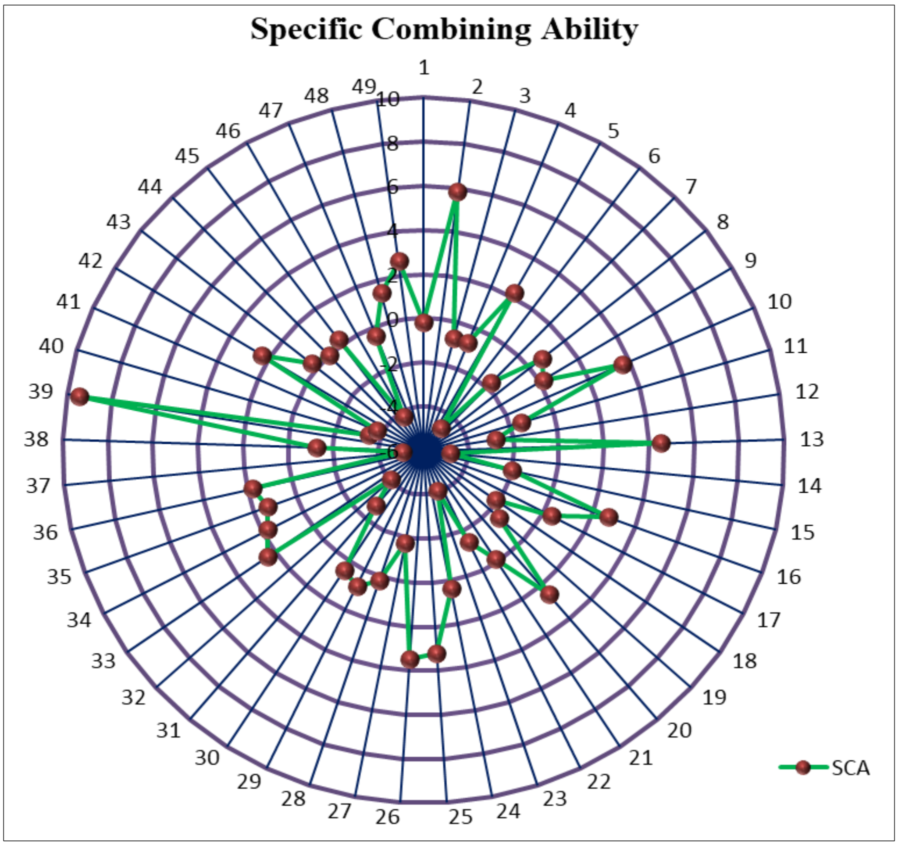

Fig 2: Graphical representation of specific combining ability effects for hybrids based on pooled over environments for grain yield per plant

Table 5: Checkerboard of 1 to 49 hybrids developed through L × T mating

Lines Testers	SDMA 1	ICMA 04999	ICMA 05888	ICMA 08444	ICMA 98222	ICMA 98444	JMSA 20101
15298 R	1	8	15	22	29	36	43
15725 R	2	9	16	23	30	37	44
15990 R	3	10	17	24	31	38	45
16088 R	4	11	18	25	32	39	46
17548 R	5	12	19	26	33	40	47
18196 R	6	13	20	27	34	41	48
42299 HP	7	14	21	28	35	42	49

Conclusion
According to the comprehensive evaluation of the genotypes in various environmental conditions, the most proficient combiners (GCA) identified for grain yield among CMS lines SDMA 1 and pollen parents 15725 R and 16088 R have the potential to be employed in the creation of hybrids, synthetic varieties and open-pollinated varieties. The germplasm utilized in the present investigation could be optimally utilized within a hybrid breeding scheme. The crosses, namely 'SDMA 1 × 15725 R', 'ICMA 98444 × 16088 R', and 'ICMA 05888 × 15725 R', were observed as the preferred crosses for traits such as grain yield per plant and various other characteristics. In addition, the best general combiners may not always create the best specific combinations for all the characters. Although, in some cases, good × good combinations showed a high specific combining ability effect. An instance of such a blend in aggregated evaluation for yield per plant is 'SDMA 1 × 15725 R'. It yielded significant and desirable effects on specific combining ability and heterosis for the majority of the characteristics examined, suggesting the potential for capitalizing on hybrid Vigor in breeding schemes.

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