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Research article

Combining ability for yield, fodder traits, and grain micronutrient content in pearl millet (*Pennisetum glaucum* (L.) R. Br.) for arid zone farming systems

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Abstract

An experiment was conducted during two seasons (*summer* and *kharif* 2024) to evaluate general and specific combining ability and heterosis in pearl millet using a line × tester mating design comprising 15 female lines, 9 male testers, 135 hybrids, and one check. The study aimed to identify superior parental lines and cross combinations for grain and fodder yield, along with micronutrient traits (iron and zinc content). Significant genetic variation was observed among parents, indicating diverse genetic potential. The variance due to specific combining ability (SCA) was higher than that of general combining ability (GCA), highlighting the predominance of non-additive gene action for most traits. Among the parents, ICMB-04888 and ICMB-97111 (females) and RIB-13 and RIB-1501 (males) emerged as good general combiners for multiple traits. Crosses such as ICMA-04999 × RIB-3135-18, ICMA-97111 × RIB-494, ICMA-88004 × RIB-15S076, and ICMA-94333 × RIB-192 showed superior grain yield. For fodder yield, ICMA-05999 × RIB-15S076 and ICMA-05999 × RIB-20K86 were the most promising. Hybrids ICMA-99444 × RIB-1501, ICMA-02333 × RIB-13, and ICMA-94333 × RIB-15177 recorded high iron content, while ICMA-94333 × RIB-15177, ICMA-04888 × RIB-1501, and ICMA-96666 × RIB-192 showed high zinc content. Notably, ICMA-97111 × RIB-494 was best for both grain yield and plant height; ICMA-05999 × RIB-15S076 for plant height and fodder yield; and ICMA-94333 × RIB-15177 for dual micronutrient content. These superior hybrids hold significant potential for grain, fodder and biofortified pearl millet breeding programmes, especially under dryland and agroforestry-based farming systems.

Keywords: Fodder, GCA, Grain yield, Pearl millet, Micronutrients, SCA

Introduction

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is a highly climate-resilient cereal crop of India, ranking fourth after rice, wheat, and maize (Yadav *et al*., 2024). Its adaptability to low and erratic rainfall, high temperatures, and poor soil fertility makes it pivotal to dryland agriculture. In arid and semi-arid regions of north-western and central India, pearl millet serves as both a staple food and a major source of green fodder, contributing significantly to food, fodder, and livelihood security (Yadav and Manjit, 2012; Kumawat *et al*., 2016; Shrestha *et al*., 2023).

India continues to face severe micronutrient malnutrition or 'hidden hunger', particularly iron (Fe) and zinc (Zn) deficiencies. Iron-deficiency anaemia affects 67.1% of children, 57% of women (15–49 years), and nearly 59% of adolescent girls, while around 32% of adolescents are Zn-deficient. The situation is aggravated by the dominance of rice- and wheat-based diets with low bioavailable micronutrients and the fact that 49% of Indian soils are Zn-deficient (PIB, 2025). Consequently, India contributes disproportionately to global Fe and Zn malnutrition. Biofortification has emerged as a sustainable, cost-effective strategy to address this challenge. Pearl millet is an ideal candidate due to its higher baseline grain Fe and Zn levels and wide genetic variability for micronutrient content. Enhancing Fe and Zn concentration without compromising grain and fodder yield can significantly improve nutritional security in dryland regions (Satyavathi *et al*., 2021; Benjamin and Saunders, 2023).

Pearl millet is a predominantly cross-pollinated crop with strong protogyny and wind-mediated pollination, exhibiting natural outcrossing rates of 70-80%, often exceeding 85%, which makes it highly amenable to hybrid breeding and heterosis exploitation (Yadav *et al*., 2021). Hybrid breeding has therefore played a central role in productivity gains under rainfed conditions. Fodder value is another key attribute of pearl millet in mixed farming and agroforestry systems. Pearl millet fodder is considered safer than sorghum because it contains negligible levels of cyanogenic glycosides, whereas sorghum can accumulate dhurrin, which releases toxic hydrogen cyanide (HCN) under stress conditions such as drought, young growth or frost (McGee *et al*., 2013). Lower HCN content in pearl millet reduces the risk of prussic acid poisoning in livestock, thereby preventing respiratory distress, reduced feed intake and sudden mortality. Consequently, the absence of this major anti-nutritional factor improves fodder safety, supports better rumen function, and enhances overall animal health and productivity compared to sorghum-based forages (Rai *et al*., 2013; Kumar *et al*., 2020).

Given the multifaceted importance of pearl millet for efficient hybrid development, understanding the underlying genetic mechanisms, such as general and specific combining abilities and the nature of gene action, is essential (Jain and Nagar, 2007; Jain *et al*., 2025). Phenotypic selection alone is inadequate; thus, biometrical tools like the line × tester analysis (Kempthorne, 1957) are widely employed to assess parental performance and hybrid potential. In this context, the present study was conducted to evaluate combining ability and heterosis among diverse parental lines in pearl millet, with the objective of identifying promising hybrids for grain yield, fodder yield, and grain micronutrient content (Fe and Zn), suitable for dryland agriculture and integrated agroforestry systems.

Materials and Methods

Genotypes: The present study was conducted using experimental material consisting of 15 diverse A lines *viz* ICMB - 93333, ICMB - 88004, ICMB - 04888, ICMB - 02333, ICMB - 843-22, ICMB - 99444, ICMB - 96666, ICMB - 89111, ICMB - 94444, ICMB - 05999, ICMB - 97111, ICMB - 04999, ICMB - 92777, ICMB - 00444, ICMB - 94333 and 09 testers (R lines) namely RIB - 494, RIB - 3135-18, RIB - 192, RIB - 15176, RIB - 15177, RIB - 15S076, RIB - 20K86 RIB - 13 and RIB - 1501 along with 135 F_1s and one check RHB - 234.

In summer 2024, parental material was planted at 50 cm spacing in two rows with 4m row length at ICRISAT Hyderabad in an off-season nursery program and 135 F_1s were produced. In *kharif* 2024, these F_1s, along with parental lines and check (RHB - 234), were evaluated in line × testers mating design in randomized block design with three replications in 4.0 m row length spaced 50 x 15 cm distance at the research farm of Rajasthan Agricultural Research Institute (SKN Agriculture University), Durgapura, Jaipur. The recommended agronomic practices were adopted during the entire cropping period to ensure optimal crop performance in both seasons.

Trait observations: Observations were recorded on randomly selected five plants for 10 quantitative traits *viz* grain yield per plant (g), dry fodder yield per plant (g), days to 50% flowering, days to maturity, plant height (cm), productive tillers per plant, panicle length (cm), panicle diameter (cm), iron (ppm) and zinc (ppm). Iron (Fe) and Zinc (Zn) levels were measured using an atomic absorption spectrophotometer (AAS) following the tri-acid mixture method outlined by Sahrawat *et al*. (2002) at the Central Analytical Services Laboratory, ICRISAT, Patancheru, Hyderabad.

Statistical analysis: The replication-wise mean values of each genotype for various traits were used in statistical and genetic analyses. Analysis of variance (ANOVA) for the design was conducted following the fixed-effects model by Panse and Sukhatme (1954) and Singh and Chaudhary (1979). The line × tester design analysis for combining ability followed Kempthorne's (1957) method, partitioning the variance among hybrids into general combining ability (GCA) and specific combining ability (SCA) components. Heterosis was evaluated as a percentage change in the F_1 hybrid over the standard heterosis representing heterosis over the standard check (SC).

Results and Discussion

The analysis of variance (ANOVA) for line × tester mating design revealed highly significant differences among parents, crosses, and their interactions for most of the studied traits (Table 1). The significant variability among the parental lines and testers indicates substantial genetic diversity, which is a prerequisite for a successful hybrid breeding programme. Jain *et al*. (2025) also reported pronounced differences in performance among parental genotypes in pearl millet.

The line × tester interaction was highly significant for all traits, including grain yield, fodder yield, plant height, productive tillers, and micronutrient content (Fe and Zn), implying that the specific combinations between lines and testers had a strong influence on the expression of these traits. This significance suggests the presence of non-additive gene action, such as dominance and epistasis, governing trait expression. In contrast, the variance due to lines and testers individually was significant for all traits except grain yield and dry fodder yield, where they remained non-significant. This reflects that grain yield and biomass traits are predominantly influenced by interaction effects rather than main effects of the parents. The parent *vs.* sca and gca comparison showed highly significant differences across all traits,

Table 1. Analysis of variance (ANOVA) for various quantitative traits in line × tester mating design in pearl millet.

df	Source	Grain Yield (g/ plant)	Dry Fodder Yield (g/ plant)	Days to 50% flowering	Days to maturity	Plant Height (cm)	Productive tillers	Panicle Length (cm)	Panicle Diameter (cm)	Fe content (PPM)	Zn Content (PPM)
2	Rep	41.96	403.11	0.08	0.71	102.95	1.14 **	2.27	0.001	123.17 **	9.72
14	Line (l)	372.64	2121.13	170.58 **	167.14 **	4045.24 **	1.90 **	62.04 **	0.61**	1199.67 **	380.24 **
8	Tester (t)	60.52	895.90	227.34 **	116.46 **	1497.85 *	2.21 **	49.80 **	0.66 **	1822.92 **	357.98 **
112	L x t	227.09 **	1425.06 **	28.85 **	33.80 **	597.33 **	0.62 **	14.14 **	0.11**	232.95 **	82.95 **
23	Parents	85.94 **	439.47 **	74.01 **	102.94 **	2911.68 **	0.25 **	63.04 **	0.40**	997.81 **	296.48 **
	Var. sca	71.88	441.07	9.50	11.15	3.20	0.19	12.80	0.027	76.38	26.53
	Var. gca	0.04	0.31	0.20	0.14	3.20	0.01	0.05	0.001	1.51	0.36
316	Error	12.32	98.80	0.30	0.34	89.31	0.05	2.66	0.033	3.82	3.43

* and **, significant at the $p<0.05$ and 0.01 probability level, respectively.

suggesting that hybrid combinations outperformed their parental averages, confirming the presence of heterosis. This provides justification for the development of hybrids to harness hybrid vigour for yield and associated traits. Further, the variance component analysis revealed that the specific combining ability (SCA) variance exceeded the general combining ability (GCA) variance for all studied traits. The SCA/GCA ratio was also greater than unity, reaffirming the predominance of non-additive genetic variance. These results are supported by earlier reports (Singh and Sharma, 2014; Ashok *et al*., 2016 and Karvar *et al*., 2017), who also found that traits such as grain yield, plant height, and micronutrient content in pearl millet are governed primarily by dominance effects. This trend underlines the importance of developing hybrids rather than pure lines for achieving significant genetic gains in these traits.

The GCA estimates (Table 2) provide crucial insights into the potential of individual parents to contribute desirable alleles across combinations. Among the female lines, ICMB-88004 and ICMB-97111 recorded strong and positive GCA effects for grain yield, indicating their consistent contribution to superior hybrid performance. Moreover, the female lines, ICMB-97111, ICMB-05999, and ICMB-04888, exhibited strong and consistent combining ability for dual-purpose performance, contributing positively to both grain and fodder yield. Genotypes ICMB-02333, ICMB-94444, ICMB-94333, and ICMB-96666 emerged as superior for grain Fe–Zn enrichment, indicating their value in biofortification-oriented breeding. Additionally, ICMB-88004 demonstrated notable combining ability for high grain yield coupled with enhanced micronutrient density, making it a promising parent for developing nutritionally superior, high-yielding hybrids. Among male testers, RIB-494 and RIB-13 emerged as promising general combiners for grain yield. Overall, RIB-13 and RIB-1501 proved to be good general combiners across traits, suggesting their utility in future hybridization programmes. These observations align well with the findings of Bhardwaj *et al.* (2022) and Surendhar *et al.* (2023), who emphasized the importance of combining ability for yield improvement in pearl millet breeding. While GCA effects are crucial for identifying parents with additive genetic effects, SCA effects are equally important in identifying superior hybrid combinations arising from non-additive gene interactions. The SCA estimates and hybrid performance (Table 3) were used to identify the most promising crosses. Notably, no single cross combination was superior for all traits, highlighting the trait-specific nature of hybrid superiority.

The cross ICMA-97111 × RIB-494 stood out for its performance in both grain yield and plant height, while ICMA-05999 × RIB-15S076 showed superiority in plant height and fodder yield. For productive tillers and fodder yield, ICMA-05999 × RIB-20K86 was found superior. In terms of micronutrient enhancement, the

Table 2. Estimates of general combining ability (GCA) effects of parents for yield and related traits in pearl millet

Parents	Grain Yield	Dry Fodder Yield	Days to 50% flowering	Days to Maturity	Plant Height	Productive Tillers	Panicle Length (cm)	Panicle Diameter (cm)	Fe Content (PPM)	Zn Content (PPM)
Lines (Female)										
ICMB-93333	0.69ns	5.19**	-1.57**	-0.72**	-2.22ns	-0.28**	-1.00**	0.12**	-12.83**	-5.19**
ICMB-88004	5.97**	-9.81**	-2.98**	-2.95**	-3.26ns	-0.35**	-1.34**	0.05ns	8.02**	3.04**
ICMB-04888	1.86**	3.90*	1.99**	1.83**	-14.97**	-0.20**	-2.11**	0.09**	-3.83**	3.22**
ICMB-02333	-3.83**	-2.59ns	-1.38**	-1.91**	-4.71**	-0.26**	-0.74*	0.20**	7.02**	1.81**
ICMB-843-22	-3.96**	-9.44**	0.99**	0.83**	-8.41**	-0.37**	0.15ns	-0.06ns	-3.16**	-1.19**
ICMB-99444	-9.09**	-16.47**	3.91**	4.20**	-19.22**	-0.04ns	-0.67*	-0.16**	12.54**	2.30**
ICMB-96666	-1.55*	0.01ns	1.91**	1.20**	-20.08**	0.29**	-0.78*	-0.17**	6.02**	5.04**
ICMB-89111	-0.34ns	-1.84ns	3.25**	3.87**	0.52ns	0.31**	0.70*	-0.24**	-2.79**	-0.19ns
ICMB-94444	-0.11ns	-2.03ns	1.91**	1.61**	1.59ns	0.22**	-1.08**	-0.13**	-4.05**	-7.96**
ICMB-05999	2.20**	13.16**	0.73**	0.39**	18.00**	0.03ns	-0.19ns	-0.00ns	-2.64**	-0.56ns
ICMB-97111	4.71**	15.93**	0.77**	0.46**	15.29**	0.30**	1.07**	0.24**	-1.50**	-3.78**
ICMB-04999	2.86**	-3.23ns	0.28*	0.54**	2.26ns	0.17**	4.26**	0.05ns	-1.24**	1.33**
ICMB-92777	-0.71ns	0.01ns	-1.68**	-1.72**	10.59**	0.39**	-0.22ns	0.14**	-6.35**	-1.26**
ICMB-00444	1.49*	-4.24*	-4.01**	-4.24**	14.70**	0.02ns	1.40**	0.06ns	-2.01**	-2.07**
ICMB-94333	-0.19ns	11.47**	-4.12**	-3.39**	9.92**	-0.22**	0.55ns	-0.20**	6.80**	5.44**
SE/SED	0.9212	2.7466	0.1562	0.1584	2.4882	0.0628	0.4389	0.0477	0.5309	0.4983
CD 5%	1.8055	5.3833	0.3062	0.3105	4.8769	0.1231	0.8603	0.0935	1.0406	0.9767
CD 1%	2.3766	7.0862	0.4030	0.4087	6.4196	0.1621	1.1324	0.1231	1.3698	1.2856
Tester (Male)										
RIB-494	1.06*	-1.88ns	-0.96**	-1.62**	-3.57**	0.27**	-0.13ns	0.02ns	-6.21**	-2.89**
RIB-3135-18	0.87ns	4.12**	-2.72**	-1.73**	-7.41**	0.22**	-1.00**	0.05ns	-3.59**	1.44**
RIB-192	-0.14ns	5.90**	-1.12**	-0.26**	0.41ns	0.25**	0.89**	-0.23**	0.52ns	-0.20ns
RIB-15176	-0.60ns	-1.33ns	0.08ns	0.89**	3.55**	-0.18**	-0.35ns	0.07*	11.12**	4.71**
RIB-15177	-0.73ns	-3.10*	1.46**	-0.42**	2.03ns	-0.25**	0.20ns	-0.08**	2.23**	1.13**
RIB-15S076	-1.62**	-1.88ns	-1.96**	-1.71**	-5.12**	0.15**	-1.04**	0.04ns	-6.84**	-2.91**
RIB-20K86	-1.08*	-8.17**	-1.47**	0.78**	-5.54**	-0.03ns	-1.31**	-0.12**	-5.50**	-3.11**
RIB-13	2.04**	2.12ns	2.88**	3.09**	8.92**	-0.25**	1.80**	0.13**	0.12ns	-1.31**
RIB-1501	0.21ns	4.23**	3.80**	0.98**	6.72**	-0.17**	0.92**	0.13**	8.16**	3.13**
SE/SED	0.7135	2.1275	0.1210	0.1227	1.9274	0.0487	0.3400	0.0370	0.4112	0.3860
CD 5%	1.3985	4.1699	0.2372	0.2405	3.7776	0.0954	0.6664	0.0724	0.8060	0.7565
CD 1%	1.8409	5.4889	0.3122	0.3166	4.9726	0.1255	0.8772	0.0953	1.0610	0.9958

* and **, significant at the $p<0.05$ and 0.01 probability level, respectively.

Table 3. Top hybrid combinations identified based on specific combining ability (SCA) effects, per se performance, and trait superiority in pearl millet.

Characters	**Best crosses based on SCA Effect**		**Best crosses based on**			**Best crosses based on SCA effect, per se performance and economic heterosis**
				Per se performance	**Economic heterosis**	
Grain Yield	ICMA-94333 X RIB-192	17.20**	ICMA-04999 X RIB-3135-18	58.7	0.85	ICMA-04999 X RIB-3135-18
	ICMA-04999 X RIB-3135-18	30.30**	ICMA-97111 X RIB-494	55.0	0.74	ICMA-97111 X RIB-494
	ICMA-97111 X RIB-494	24.60**	ICMA-05999 X RIB-20K86	46.0	0.45	ICMA-88004 X RIB-15S076
	ICMA-93333 X RIB-20K86	15.92**	ICMA-88004 X RIB-15S076	42.5	0.34	ICMA-94333 X RIB-192
	ICMA-88004 X RIB-15S076	13.51**	ICMA-94333 X RIB-192	41.5	0.31	
Fodder Yield	ICMA-97111 X RIB-494	70.40**	ICMA-97111 X RIB-494	158.3	1.23	ICMA-05999 X RIB-15S076
	ICMA-88004 X RIB-15S076	41.14**	ICMA-94444 X RIB-192	123.3	0.74	ICMA-05999 X RIB-20K86
	ICMA-05999 X RIB-20K86	39.47**	ICMA-05999 X RIB-15S076	118.3	0.67	
	ICMA-02333 X RIB-13	39.92**	ICMA-05999 X RIB-20K86	118.3	0.67	
	ICMA-96666 X RIB-20K86	34.28**	ICMA-94333 X RIB-13	115.0	0.62	
Fe	ICMA-02333 X RIB-13	23.07**	ICMA-99444 X RIB-1501	85.6	0.023	ICMA-99444 X RIB-1501
	ICMA-97111 X RIB-3135-18	21.63**	ICMA-02333 X RIB-13	84.5	0.010	ICMA-02333 X RIB-13
	ICMA-94333 X RIB-15177	18.84**	ICMA-88004 X RIB-1501	83.7	-	ICMA-94333 X RIB-15177
	ICMA-94444 X RIB-1501	17.10**	ICMA-99444 X RIB-13	83.0	-	
	ICMA-04888 X RIB-1501	16.21**	ICMA-94333 X RIB-15177	82.4	-	
Zn	ICMA-04888 X RIB-1501	10.87**	ICMA-94333 X RIB-15177	61.7	0.54	ICMA-94333 X RIB-15177
	ICMA-94333 X RIB-15177	10.64**	ICMA-04888 X RIB-1501	61.6	0.54	ICMA-04888 X RIB-1501
	ICMA-96666 X RIB-192	10.05**	ICMA-96666 X RIB-192	59.3	0.48	ICMA-96666 X RIB-192
	ICMA-04888 X RIB-13	7.64**	ICMA-96666 X RIB-1501	58.9	0.47	
	ICMA-97111 X RIB-15176	7.29**	ICMA-88004 X RIB-1501	57.0	0.42	
Days to 50% Flowering	ICMA-04888 X RIB-13	-7.59**	ICMA-00444 X RIB-3135-18	40.0	-10.51	
	ICMA-99444 X RIB-494	-6.34**	ICMA-94333 X RIB-3135-18	40.0	-10.51	
	ICMA-04999 X RIB-494	-5.04**	ICMA-94333 X RIB-15S076	40.0	-10.51	
	ICMA-05999 X RIB-13	-5.00**	ICMA-00444 X RIB-494	40.3	-9.77	
	ICMA-04888 X RIB-15177	-4.17**	ICMA-93333 X RIB-3135-18	40.7	-9.02	
Plant Height	ICMA-04888 X RIB-494	46.79**	ICMA-05999 X RIB-15S076	230.0	0.33	ICMA-05999 X RIB-15S076
	ICMA-05999 X RIB-15S076	30.05**	ICMA-97111 X RIB-494	226.3	0.31	ICMA-97111 X RIB-494
	ICMA-843-22 X RIB-192	29.92**	ICMA-94333 X RIB-13	223.0	0.29	ICMA-93333 X RIB-13
	ICMA-93333 X RIB-13	28.89**	ICMA-93333 X RIB-13	222.7	0.28	
	ICMA-97111 X RIB-494	27.53**	ICMA-00444 X RIB-15176	221.0	0.28	
Productive tillers	ICMA-05999 X RIB-20K86	1.67**	ICMA-92777 X RIB-494	3.7	1.20	ICMA-92777 X RIB-494
	ICMA-92777 X RIB-494	1.55**	ICMA-05999 X RIB-20K86	3.2	0.88	ICMA-05999 X RIB-20K86
	ICMA-94333 X RIB-15S076	1.07**	ICMA-92777 X RIB-192	2.7	0.61	
	ICMA-99444 X RIB-192	0.79**	ICMA-97111 X RIB-3135-18	2.6	0.55	
	ICMA-00444 X RIB-15177	0.70**	ICMA-04999 X RIB-494	2.6	0.55	

Panicle Length (cm)	ICMA-843-22 X RIB-192	5.59**	ICMA-04999 X RIB-13	31.0	0.24	ICMA-843-22 X RIB-192
	ICMA-89111 X RIB-13	4.45**	ICMA-89111 X RIB-13	28.3	0.13	ICMA-89111 X RIB-13
	ICMA-02333 X RIB-13	4.23**	ICMA-00444 X RIB-13	28.3	0.13	
	ICMA-04888 X RIB-494	4.20**	ICMA-843-22 X RIB-192	28.0	0.12	
	ICMA-02333 X RIB-192	3.81**	ICMA-04999 X RIB-20K86	27.0	0.08	
Panicle Diameter (cm)	ICMA-00444 X RIB-15176	0.45**	ICMA-02333 X RIB-13	3.3	-	ICMA-00444 X RIB-15176
	ICMA-94333 X RIB-13	0.41**	ICMA-00444 X RIB-15176	3.3	-	
	ICMA-89111 X RIB-1501	0.38**	ICMA-97111 X RIB-494	3.2	-	
	ICMA-96666 X RIB-13	0.32**	ICMA-88004 X RIB-1501	3.1	-	
	ICMA-05999 X RIB-20K86	0.29**	ICMA-97111 X RIB-13	3.1	-	

* and **, significant at the $p<0.05$ and 0.01 probability level, respectively.

hybrids ICMA-99444 × RIB-1501, ICMA-02333 × RIB-13, and ICMA-94333 × RIB-15177 were promising for iron content, while ICMA-94333 × RIB-15177, ICMA-04888 × RIB-1501, and ICMA-96666 × RIB-192 were superior for zinc content. The dual enrichment observed in ICMA-94333 × RIB-15177 for both iron and zinc are particularly noteworthy from a nutritional security perspective. The findings reinforce the utility of line × tester analysis not only for hybrid identification but also for discerning the nature of gene action controlling key traits. While non-additive gene effects can be effectively exploited through hybrid breeding, crosses involving high × high and high × average general combiners may yield superior segregants with both additive and dominance effects. Such hybrids, after further multi-location evaluation and stability analysis, hold significant promise for commercial cultivation and biofortification goals in dryland ecosystems.

Conclusion

The line × tester analysis confirmed ample genetic variability and predominant non-additive gene action for grain yield, fodder yield and quality, and Fe–Zn enrichment, highlighting strong prospects for hybrid breeding. Key general combiners included ICMB 04999 and ICMB 00444 for grain yield; ICMB-97111, ICMB-05999, and ICMB-04888 for dual purpose; ICMB 02333, ICMB 94444, and ICMB 96666 for high Fe–Zn; and ICMB-88004 for grain yield with biofortification. Among restorers, RIB-13 was superior for grain yield; RIB-192 and RIB-3135-18 for fodder; RIB-1501 for dual purpose; and RIB-15176 and RIB-15177 for Fe–Zn enrichment. Promising hybrids included ICMA-04999 × RIB-3135-18 and ICMA-97111 × RIB-494 for grain yield; ICMA-97111 × RIB-494, ICMA-94444 × RIB-192, and ICMA-94333 × RIB-15177 for fodder; and ICMA-99444 × RIB-1501, ICMA-02333 × RIB-13, ICMA-04888 × RIB-1501, and ICMA-94333 × RIB-15177 for Fe–Zn biofortification. The convergence of high yield, fodder value, and micronutrient enhancement across these crosses supports their utility in developing multi-trait hybrids for future pearl millet improvement programmes.

References

Ashok, A., P. Sumathi, P. Veerabadhiran, J. Revathi and S. Poornimajency. 2016. Development of heterotic hybrids for quality, yield and its architectural traits in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Range Management and Agroforestry* 37: 181–184.

Benjamin, A. and J. Saunders. 2023. Malnutrition and undernutrition: causes, consequences, assessment and management. *Medicine* 51 (7): 461-468,

Bhardwaj, R., S. Singh, R.S. Sohu and H.K. Oberoi. 2022. Studies on combining ability and heterosis in three-way hybrids in forage pearl millet. *Range Management and Agroforestry* 44(2): 255–262.

Jain, R.K. and R. Nagar. 2007. Stability analysis in dual purpose bajra [*Pennisetum glaucum* (L.) R. Br.]. *Range Management and Agroforestry* 28: 311-313.

Jain, S.K., S.K. Sharma, D.K. Gupta, V. Khandelwal, R.K. Sharma, Anuradha, V. Sharma, B.L. Dhaka and S.K. Gupta. 2025. Combining ability and heterosis studies for yield, grain iron and zinc content in pearl millet (*Pennisetum glaucum*). *Indian Journal of Agricultural Sciences* 95(6): 611-616.

Karvar, S., V. Pawar and H. Patil. 2017. Heterosis and combining ability in pearl millet. *Electronic Journal of Plant Breeding* 8: 1197-1215.

Kempthorne, O. 1957. *An Introduction to Genetic Statistics*. John Wiley and Sons, Inc., New York.

Kumar, S., S. Arya, R. Kumar and R.S. Yadav. 2020. Anti-nutritional factors in forage crops and their management for improving livestock productivity. *Forage Research* 46(1):1–9.

Kumawat, S.M., M. Arif, S.S. Shekhawat and S.R. Kantwa 2016. Effect of nitrogen and cutting management on growth, yield and quality of fodder pearl millet (*Pennisetum glaucum* L.) cultivars. *Range Management and Agroforestry* 37: 207-213.

McGee, S.J., D.J. Undersander, C.R. Grau and J.G. Lauer.

2013. Prussic acid poisoning in livestock. University of Wisconsin–Extension, Cooperative Extension Service Bulletin A3859. Madison, WI, USA.

Panse, V.G. and P.V. Sukhatme. 1954. *Statistical Methods for Agricultural Workers*, 2nd edn. Indian Council of Agricultural Research (ICAR), New Delhi, pp. 381.

Press Information Bureau (PIB). 2025. India's fight against anaemia: NFHS-5 highlights continued burden among children, women and adolescents. Ministry of Health and Family Welfare, Government of India, New Delhi.

Rai, K.N., D.J. Andrews, B.H. Hare and F. Tegegne. 2013. Advances in pearl millet fodder yield and quality improvement through breeding and management practices. *Forage Research* 39(1): 1-14.

Sahrawat, K.L., Ravi Kumar and J.K. Rao. 2002. Evaluation of triacid and dry ashing procedures for determining potassium, calcium, magnesium, iron, zinc, manganese and copper in plant materials. *Communications in Soil Science and Plant Analysis* 33: 95-102.

Satyavathi, C.T., S. Ambawat, V. Khandelwal and R.K. Sriwastava. 2021. Pearl millet: A climate-resilient nutricereal for mitigating hidden hunger and provide nutritional security. *Frontiers in Plant Science* 12: 659938. https://doi.org/10.3389/fpls.2021.659938

Shrestha, N., H. Hu, K. Shrestha and A. Doust. 2023. Pearl millet response to drought: A review. *Frontiers in Plant Science* 14: 1059574. https://doi.org/10.3389/fpls.2023.1059574

Singh, J. and R. Sharma. 2014. Assessment of combining ability in pearl millet using line × tester analysis. *Advances in Crop Science and Technology* 2: 147. https://doi.org/10.4172/2329- 8863.1000147

Singh, R.K. and B.D. Choudhary. 1979. *Biometrical Methods in Quantitative Genetic Analysis*. Kalyani Publishers, New Delhi, India.

Surendhar, A., I. Kri, R. Ravikesavan and R.Veerasamy. 2023. Combining ability analysis in pearl millet [*Pennisetum glaucum* (L.) R. Br.] for yield and yield contributing traits. *Electronic Journal of Plant Breeding* 14: 584-590.

Yadav, O.P., S.K. Gupta, M. Govindaraj, R. Sharma, R.K. Varshney, R.K. Srivastava, A. Rathore and R.S. Mahala. 2021. Genetic gains in pearl millet in india: insights into historic breeding strategies and future perspective. *Frontiers in Plant Science* 12:645038. https://doi.org/10.3389/fpls.2021.645038

Yadav, O.P. and S. Manjit. 2012. Pearl millet stover productivity in crop-livestock farming system of arid zone: current status and opportunities for enhancement. *Range Management and Agroforestry* 33: 102-111.

Yadav, O.P., S.K. Gupta, M. Govindaraj, D.V. Singh, A. Verma, R. Sharma, R.S. Mahala, S.K. Srivastava and P.S. Birthal. 2024. Strategies for enhancing productivity, resilience, nutritional quality, and consumption of pearl millet [*Pennisetum glaucum* (L.) R. Br.] for food and nutritional security in India. *Crop Science* 64: 1-19.