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Deciphering Genetic Architecture, Cause-and-Effect Relationships for Yield and Micronutrient Related Attributes in Pearl Millet R-lines (Restorer Lines)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

The present study evaluated thirty restorer lines of pearl millet (*Pennisetum glaucum* (L.) R. Br.) to assess genetic variability, examine trait interrelationships through correlation analysis, and determine the direct and indirect effects of ten yield-contributing traits on grain yield through path coefficient analysis. Analysis of

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variance revealed highly significant differences among genotypes for all eleven traits, indicating substantial variability. High genotypic and phenotypic coefficients of variation, together with high broad-sense heritability [$h^2_{(b.s.)}$] and high genetic advance as a percentage of the mean, were recorded for grain yield per plant, grain zinc content, grain iron content, ear head length, number of effective tillers per plant, grain protein content, ear head girth, and 1000-grain weight. Grain yield per plant recorded 95.60% heritability and 103.52% genetic advance as a percentage of the mean. These estimates indicate that selection may be effective because inheritance is largely associated with additive gene action. Correlation analysis showed that ear head girth, 1000-grain weight, ear head length, and number of effective tillers per plant were significantly and positively associated with grain yield per plant. Genotypic path analysis further indicated that ear head girth, plant height, and number of effective tillers per plant had the largest positive direct effects on grain yield. Accordingly, simultaneous consideration of these traits may support the selection of higher-yielding pearl millet restorer lines.

Keywords: Pearl millet; restorer lines; genetic variability; broad-sense heritability; genetic advance; correlation analysis; path coefficient analysis; grain yield; grain iron; grain zinc.

1. Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is one of the oldest cultivated crops and originated in tropical Western Africa about 4000 years ago. It was domesticated along the southern margins of the Saharan central highlands at the onset of the present dry phase (Clark, 1962; Davies, 1968). It is well adapted to arid and semi-arid conditions because it uses soil moisture efficiently and has greater heat tolerance than sorghum and maize (Harinarayana *et al.*, 1999), enabling it to contribute to food security under poor growing conditions. It is a C_4 grass with high photosynthetic efficiency and grain-yield potential and is widely cultivated in China, India, Southeast Asia, Sudan, Pakistan, Arabia, Russia, and Nigeria. A key feature of millets is their remarkable resilience to both persistent and sporadic droughts caused by insufficient or unpredictable rainfall. Notably, millets can flourish in dry environments and require only 350-400 mm of rainfall annually (Gami *et al.*, 2026). Pearl millet is cultivated on more than 30 million ha worldwide, with the principal production areas in Africa (>18 million ha) and Asia (>10 million ha) (Satyavathi *et al.*, 2022). India accounts for 42% of global millet production (Sadh *et al.*, 2024). Recent meta-QTL evidence has identified consensus genomic regions associated with yield and nutritional traits, supporting the integration of phenotypic selection with genomic information in pearl millet improvement (Gupta *et al.*, 2024). A recent linkage-mapping study also identified stable QTL for flowering time, productive tiller number, ear head length, and test weight, indicating that these component traits have a measurable genetic basis relevant to selection (Subbulakshmi *et al.*, 2024).

However, grain yield in pearl millet is a complex quantitative trait governed by several interrelated morphological and physiological traits. Therefore, breeding efforts aimed at increasing yield require a clear understanding of the genetic constitution of yield and the traits that contribute to it in restorer lines used in hybrid breeding programmes. Estimates of genetic variability, including genotypic and phenotypic coefficients of variation, heritability, and genetic advance, provide information on the nature of gene action influencing important traits and the potential response to selection. Correlation analysis helps to identify the degree and direction of relationships among traits. However, correlation alone cannot distinguish direct from indirect effects; path coefficient analysis is therefore important because it partitions correlation coefficients into direct and indirect effects, allowing breeders to identify the traits that have the greatest influence on grain yield (Deewan *et al.*, 2023). Recent evaluations of pearl millet breeding material using variability, correlation, and path coefficient analyses have similarly demonstrated that yield and micronutrient traits can be examined jointly to identify useful selection criteria (Singh & Chaudhary, 2026). Multi-environment testing of pearl millet hybrids has further indicated that yield-related performance may vary across environments, emphasising the need to validate promising selections beyond an initial evaluation (Jat *et al.*, 2025).

Research gap: Despite these advances, evidence remains limited regarding the combined assessment of genetic variability, trait associations, direct and indirect effects, and grain micronutrient contents within a common set of pearl millet restorer lines. A focused analysis of these components is therefore required to identify traits that may guide the simultaneous improvement of grain yield and nutritional quality in the evaluated restorer material.

1.1 Objective

The objective of the present study was to assess genetic variability among thirty pearl millet restorer lines for eleven yield, yield-related, and micronutrient traits; determine the genotypic and phenotypic associations among these traits; and partition their direct and indirect effects on grain yield per plant through path coefficient analysis.

2. Materials and Methods

2.1 Experimental Material and Field Conditions

The experimental material comprised thirty different restorer lines of pearl millet. The experiment was conducted at the Centre for Millets Research, Sardarkrushinagar Dantiwada Agricultural University, Deesa, during summer 2024. The research site was located in North Gujarat Zone IV at 24°15' N latitude, 72°12' E longitude, and an elevation of 146 metres above mean sea level. The soil at the site was loamy, with a pH ranging from 7.5 to 9.3. The experimental material was sown in a four-metre row at an optimum spacing of 45 cm × 15 cm in a randomised block design (RBD) with three replications. The recommended agronomic and crop-protection practices were followed. Grain iron (Fe) and zinc (Zn) contents were estimated using the wet digestion procedure of Singh *et al.* (2005) with a di-acid mixture at the Department of Soil Science and Agricultural Chemistry, C. P. College of Agriculture, S. D. Agricultural University, Sardarkrushinagar, Gujarat.

Observations recorded: Data were recorded for days to flowering, days to maturity, plant height (cm), number of effective tillers per plant, ear head length (cm), ear head girth (mm), 1000-grain weight (g), grain yield per plant (g), grain protein content (%), grain iron (Fe) content (ppm), and grain zinc (Zn) content (ppm) from five randomly selected and tagged plants. Days to flowering and days to maturity were recorded on a plot basis.

Statistical analysis: The recorded data were analysed using established statistical methods. The genotypic and phenotypic coefficients of variation (GCV and PCV) for the various traits were calculated as suggested by Burton (1952). Broad-sense heritability ($h^2_{b.s.}$) and genetic advance were calculated using the formula proposed by Allard (1961). Genetic advance as a percentage of the mean was calculated using the formula suggested by Johnson *et al.* (1955). The genotypic (r_g) and phenotypic (r_p) correlation coefficients were calculated following the procedure described by Al-Jibouri *et al.* (1958). Path coefficient analysis was conducted using the method suggested by Wright (1921) and elaborated by Dewey and Lu (1959). The analyses were performed using SPAR software *version 1.0* and RStudio *version 2025.05.1*.

3. Results and Discussion

3.1 Analysis of Variance

The analysis of variance for the thirty pearl millet genotypes revealed highly significant mean squares for all eleven traits, indicating significant differences among the genotypes and substantial scope for exploiting variability through selection (Table 1).

The variance components, genotypic coefficient of variation, phenotypic coefficient of variation, broad-sense heritability, genetic advance, and genetic advance as a percentage of the mean are presented in Table 2. The highest genotypic and phenotypic variances were recorded for plant height (423.95, 594.72), followed by grain yield per plant (322.64, 337.48), grain iron content (315.93, 330.79), grain zinc content (122.08, 125.72), days to flowering (32.84, 44.57), and ear head length (22.49, 25.63). Phenotypic variance was higher than genotypic variance for all traits, as similarly reported by Lakshmana *et al.* (2010), Athoni *et al.* (2016), and Abubakar *et al.* (2019). The phenotypic and genotypic variances were close for the number of effective tillers per plant, ear head girth, 1000-grain weight, and grain protein content. The narrow differences between the phenotypic and genotypic coefficients of variation for these traits indicate strong genotypic control under the evaluated environmental conditions. However, because the trial was conducted in a single environment, multi-location or multi-year evaluations are required to validate the stability of these traits in relation to G × E interactions. These findings agree with the reports of Narasimhulu *et al.* (2021), Goswami *et al.* (2023), Rajpoot *et al.* (2023), and Jaiswal *et al.* (2025).

Table 1. Analysis of variance (MSS) for different characters in pearl millet

Sr. No.	Characters	Mean sum of squares (MSS)		
		Replication	Genotypes	Error
	Degree of freedom (df)	2	29	58
1	Days to flowering	3.41	110.24**	11.73
2	Days to maturity	25.01	39.63**	12.67
3	Plant height	201.93	1442.63**	170.77
4	Number of effective tillers per plant	0.01	1.52**	0.08
5	Ear head length	0.85	70.62**	3.14
6	Ear head girth	1.59	51.06**	0.50
7	1000 grain weight	2.27	9.29**	0.85
8	Grain yield per plant	10.06	982.75**	14.84
9	Grain protein content	0.09	18.21**	1.38
10	Grain zinc (Zn) content	4.64	369.89**	3.64
11	Grain iron (Fe) content	9.81	962.66**	14.86

**, ** Significant at 5 per cent and 1 per cent levels of significance, respectively*

3.2 Mean Performance of the Genotypes

The mean performance and distribution of the thirty pearl millet genotypes for the studied traits are shown by the violin plots in Fig. 1. The plots revealed distinct distribution patterns for the eleven traits, indicating differences in the mean performance and dispersion of the evaluated genotypes. Grain yield per plant, grain iron content, grain zinc content, plant height, and ear head length exhibited relatively wide violin plots, suggesting broader distributions around the mean and greater phenotypic diversity among the genotypes. These wider distributions were consistent with the comparatively high variability estimates for these traits, indicating that the differences in mean performance were accompanied by substantial genetic variation. In contrast, days to maturity showed the narrowest distribution, with most genotypes clustered closely around the mean, whereas days to flowering showed a relatively compact distribution with moderate dispersion. These patterns agreed with the lower to moderate variability estimates for these traits, suggesting greater uniformity among the genotypes. The distributions of the number of effective tillers per plant, ear head girth, 1000-grain weight, and grain protein content were intermediate, with most observations concentrated near the mean but extending over a moderate range.

Overall, the distribution patterns in the violin plots agreed with the genetic variability estimates, as traits with greater phenotypic spread generally exhibited higher genetic variability. However, the results also showed that mean performance and variability were independent characteristics. Traits with similar mean performance, such as grain iron and zinc contents, differed in the extent of their distributions, whereas traits with moderate mean values, particularly grain yield per plant, exhibited greater dispersion than several other traits. Likewise, ear head girth displayed a comparatively compact distribution despite its high genetic control, indicating that the observed variation was consistent rather than highly dispersed. Thus, the violin plots complemented the variability analysis by illustrating the distribution of each trait among the genotypes and confirmed that the scope for selection depends on both mean performance and the extent and pattern of variation within the population.

3.3 Variability Parameters

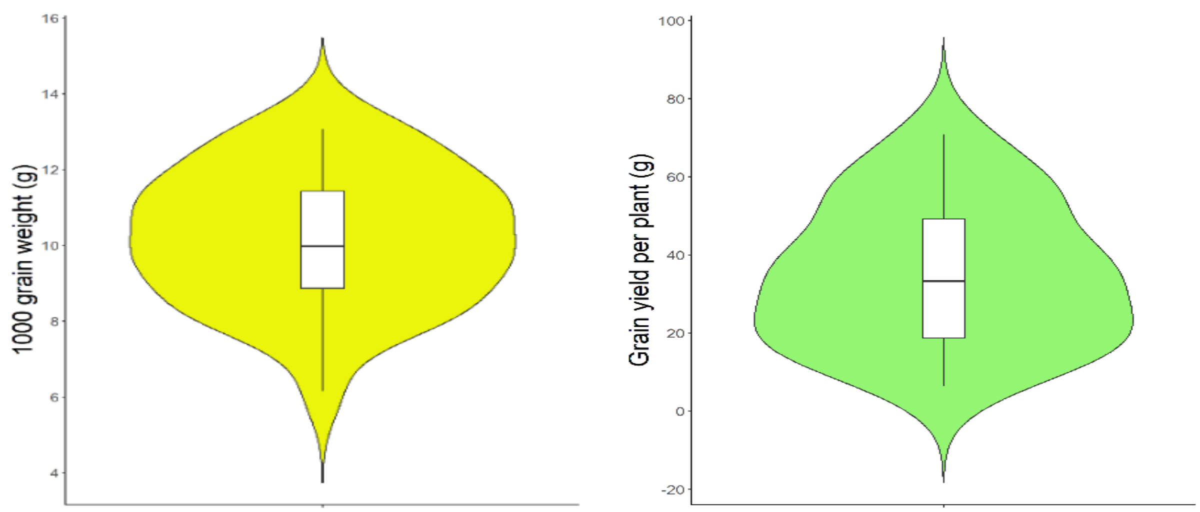
In the present study, the phenotypic coefficient of variation (PCV) was higher than the genotypic coefficient of variation (GCV) for all traits, with values ranging from 4.68% to 52.56% and from 3.02% to 51.39%, respectively. The highest GCV and PCV were observed for grain yield per plant (51.39%, 52.56%), followed by grain iron content (25.15%, 25.73%), grain zinc content (25.06%, 25.43%), ear head length (21.17%, 22.60%), and the number of effective tillers per plant (20.46%, 22.15%). The high GCV and PCV values for these traits indicate considerable variability and suggest scope for selection. These results agree with those reported by Yadav *et al.* (2020), Narasimhulu *et al.* (2021), Beniwal *et al.* (2023), Kahate *et al.* (2023), and Jaiswal *et al.* (2025). Moderate GCV and PCV were observed for 1000-grain weight (16.40%, 18.70%), ear head girth (15.32%, 15.54%), and plant height (13.83%, 16.39%). In contrast, days to maturity (3.02%, 4.68%) exhibited low GCV and PCV, whereas moderate PCV (11.19%) and low GCV (9.60%) were observed for days to flowering. Similar moderate GCV and PCV values have been reported by Narasimhulu *et al.* (2021), Goswami *et al.* (2023), Jaiswal *et al.* (2025), and Kumar *et al.* (2024).

Table 2. Variability parameters for different characters of pearl millet genotypes

Sr. No.	Characters	σ^2_g	σ^2_p	GCV (%)	PCV (%)	$h^2_{(b.s.)}$ (%)	GA	GAM (%)
1	Days to flowering	32.84	44.57	9.60	11.19	73.67	10.13	16.98
2	Days to maturity	8.99	21.65	3.02	4.68	41.51	3.97	4.00
3	Plant height	423.95	594.72	13.83	16.39	71.29	35.81	24.06
4	Number of effective tillers per plant	0.48	0.56	20.46	22.15	85.30	1.31	38.92
5	Ear head length	22.49	25.63	21.17	22.60	87.75	9.15	40.84
6	Ear head girth	16.85	17.35	15.32	15.54	97.09	8.33	31.09
7	1000 grain weight	2.81	3.66	16.40	18.70	76.85	3.02	29.61
8	Grain yield per plant	322.64	337.48	51.39	52.56	95.60	36.17	103.52
9	Grain protein content	5.61	6.99	19.66	21.95	80.19	4.36	36.26
10	Grain zinc (Zn) content	122.08	125.72	25.06	25.43	97.10	22.43	50.88
11	Grain iron (Fe) content	315.93	330.79	25.15	25.73	95.51	35.78	50.63

Where, $\sigma^2 g$ = Genotypic variance, $\sigma^2 p$ = Phenotypic variance, GCV (%) = Genotypic coefficient of variation, PCV (%) = Phenotypic coefficient of variation, $h^2_{(b.s.)}$ (%) = Broad sense heritability, GA = Genetic advance, GAM (%) = Genetic advance as per cent of mean

To predict the transmission of traits from one generation to the next, the total variation in a population should be partitioned into heritable and non-heritable components because only the heritable component is transmitted. Genetic advance alone does not express the expected gain relative to the *per se* performance of the experimental population; therefore, genetic advance as a percentage of the mean was also calculated. Heritability estimates considered together with genetic advance are more informative for predicting genetic gain under selection (Johnson *et al.*, 1955). In the present study, high heritability coupled with high genetic advance as a percentage of the mean was observed for grain yield per plant (95.60%, 103.52%), grain zinc content (97.10%, 50.88%), grain iron content (95.51%, 50.63%), ear head length (87.75%, 40.84%), the number of effective tillers per plant (85.30%, 38.92%), grain protein content (80.19%, 36.26%), ear head girth (97.09%, 31.09%), 1000-grain weight (76.85%, 29.61%), and plant height (71.29%, 24.06%). These patterns indicate the importance of additive gene action in the inheritance of these traits and suggest that selection may be effective. High heritability coupled with moderate genetic advance as a percentage of the mean was observed for days to flowering, indicating the involvement of both additive and non-additive gene effects. Although this trait was largely heritable, the scope for rapidly shifting mean flowering time through simple directional selection may be limited. Population improvement procedures or heterosis breeding may therefore be more appropriate for modifying maturity-related traits. These findings agree with Athoni *et al.* (2016), Kumawat *et al.* (2019), Narasimhulu *et al.* (2021), Goswami *et al.* (2023), and Jaiswal *et al.* (2025).



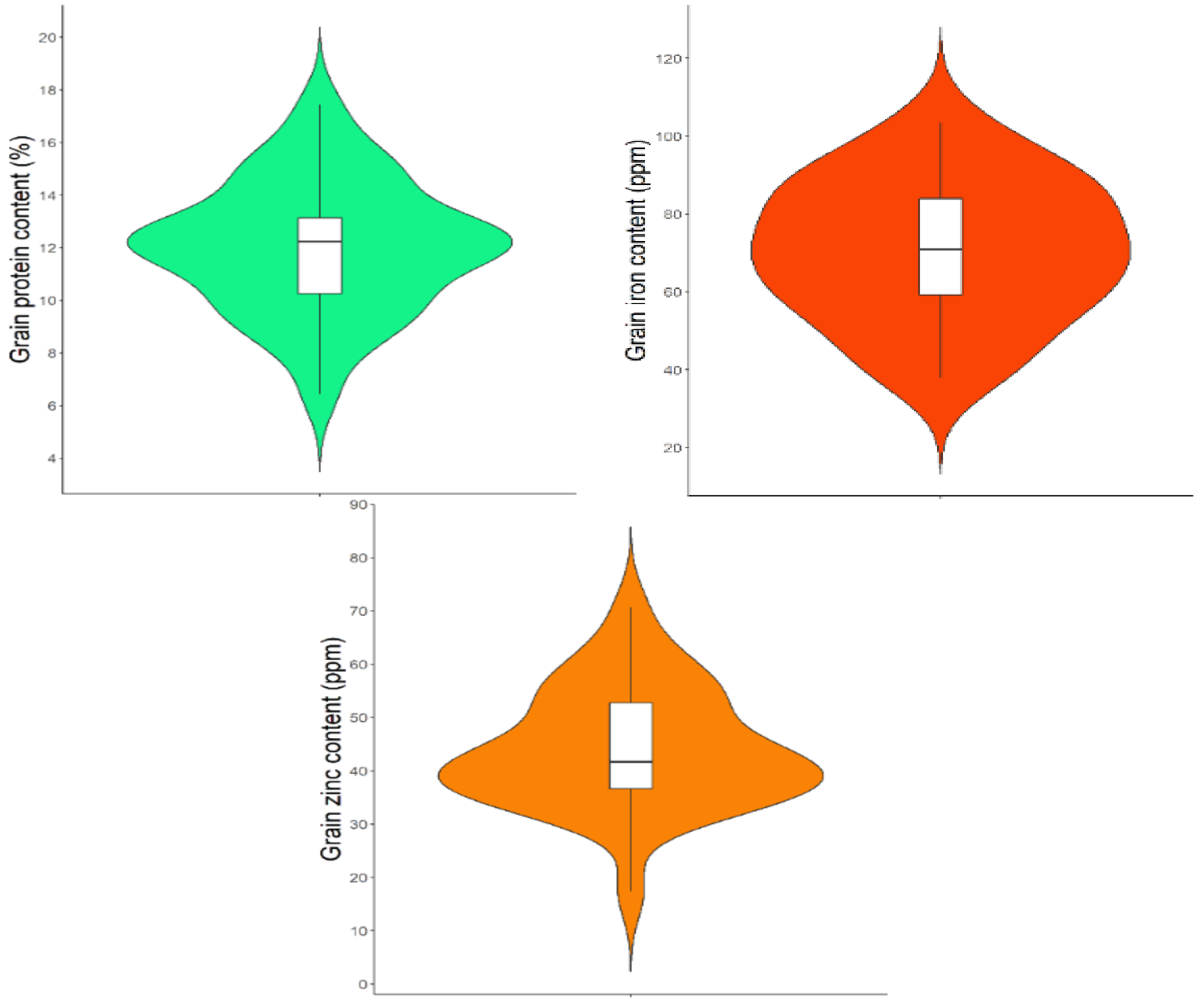


Fig. 1. Violin plots representing mean performance of thirty genotypes of pearl millet

3.4 Correlation Coefficients

Correlation analysis showed that the genotypic correlation coefficients were generally greater in magnitude than the phenotypic correlation coefficients, suggesting stronger heritable associations and lower environmental influence among the traits. The estimated genotypic and phenotypic correlation coefficients among the thirty genotypes revealed several significant relationships, emphasising the interdependence of traits and their combined association with yield performance (Table 3 and Fig. 2). Plant height (r_g = 0.392 and r_p = 0.321), number of effective tillers per plant (r_g = 0.419 and r_p = 0.445), ear head length (r_g = 0.486 and r_p = 0.456), ear head girth (r_g = 0.665 and r_p = 0.641), and 1000-grain weight (r_g = 0.541 and r_p = 0.469) were significantly and positively associated with grain yield per plant at both the genotypic and phenotypic levels. These traits may therefore assist breeders in selecting desirable genotypes for improved grain yield. Days to flowering (r_g = -0.194 and r_p = -0.160) and days to maturity (r_g = -0.317 and r_p = -0.186) showed negative but non-significant associations with grain yield per plant at both levels. Grain protein content (r_g = -0.513 and r_p = -0.457) and grain zinc content (r_g = -0.412 and r_p = -0.402) were significantly and negatively correlated with grain yield per plant at both levels. Grain iron content showed a significant negative phenotypic association with grain yield per plant (r_p = -0.277) but a non-significant genotypic association (r_g = -0.284).

The significant negative associations of grain zinc and iron contents with grain yield per plant may primarily be attributed to a dilution effect, whereby increased grain production distributes the available zinc and iron over a larger grain mass and reduces their concentrations in individual grains. The relationships may also reflect a physiological trade-off between biomass production and micronutrient accumulation, because high-yielding genotypes may allocate a greater proportion of assimilates towards grain formation rather than mineral enrichment. These findings suggest that the simultaneous improvement of grain yield and micronutrient concentration in pearl millet may require careful selection strategies and the utilisation of biofortified breeding material to address this trade-off. The results agree with those reported by Kanatti *et al.* (2014), Anuradha *et al.* (2018), Kumawat *et al.* (2019), Dadarwal *et al.* (2020), Patil *et al.* (2021), Kamble *et al.* (2022), Goswami *et al.* (2023), Andhale *et al.* (2024), and Pallavi *et al.* (2024).

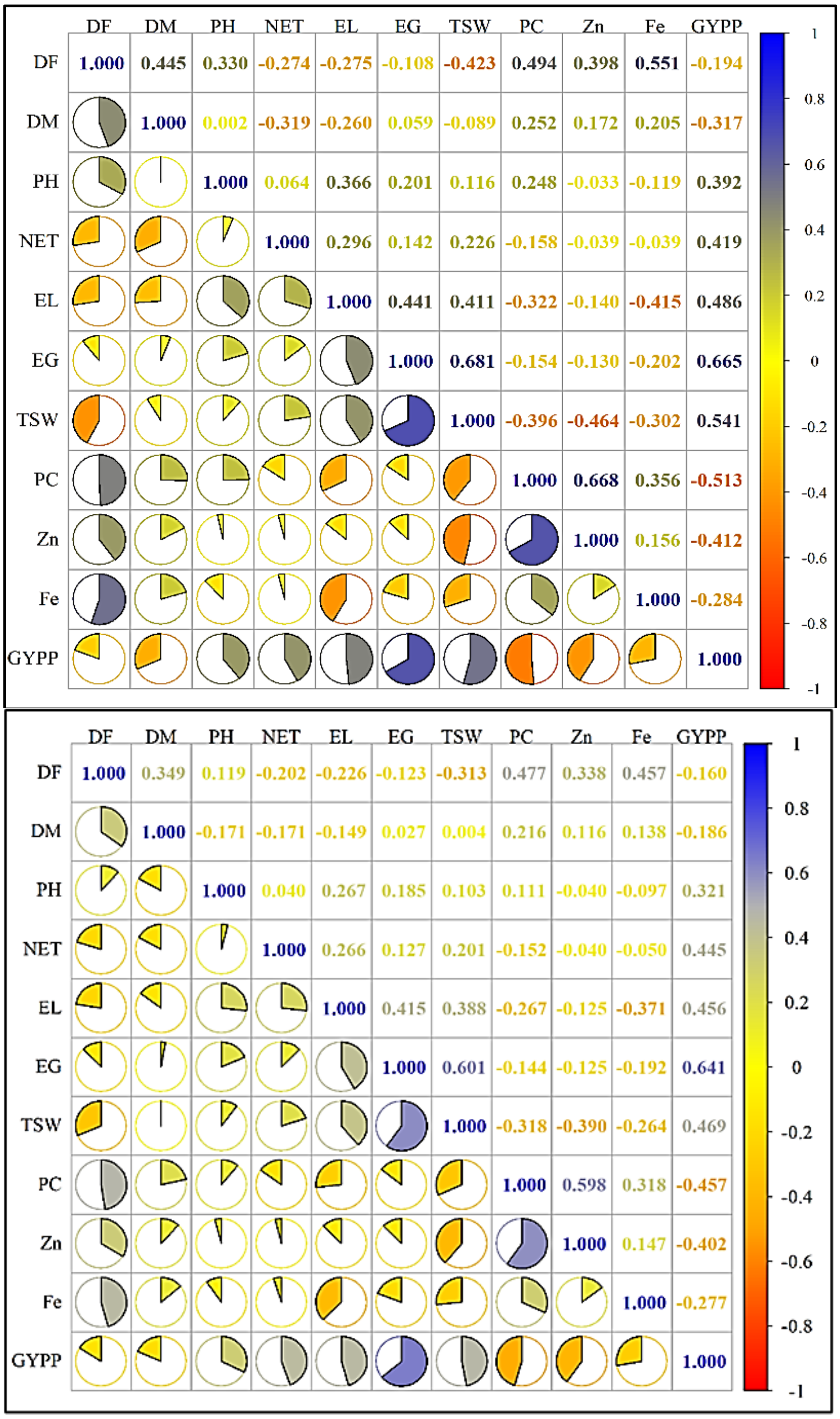


Fig. 2. Correlation plots representing genotypic and phenotypic correlation co-efficient among yield and its attributing traits

Table 3. Genotypic and phenotypic correlation co-efficient among yield and its related trait in thirty genotypes of pearl millet

Characters		DF	DM	PH	NET	EL	EG	TSW	PC	Zn	Fe	GYPP
DF	r_g	1.00	0.445*	0.330	-0.274	-0.275	-0.108	-0.423 *	0.494**	0.398*	0.551**	-0.194
	r_p	1.00	0.349**	0.119	-0.202	-0.226*	-0.123	-0.313**	0.477**	0.338**	0.457**	-0.160
DM	r_g		1.00	0.002	-0.319	-0.260	0.059	-0.089	0.252	0.172	0.205	-0.317
	r_p		1.00	-0.171	-0.171	-0.149	0.027	0.004	0.216*	0.116	0.138	-0.186
PH	r_g			1.00	0.064	0.366*	0.201	0.116	0.248	-0.033	-0.119	0.392*
	r_p			1.00	0.040	0.267*	0.185	0.103	0.111	-0.040	-0.097	0.321**
NET	r_g				1.00	0.296	0.142	0.226	-0.158	-0.039	-0.039	0.419*
	r_p				1.00	0.266*	0.127	0.201	-0.152	-0.040	-0.050	0.445**
EL	r_g					1.00	0.441*	0.411*	-0.322	-0.140	-0.415*	0.486**
	r_p					1.00	0.415**	0.388**	-0.267*	-0.125	-0.371**	0.456**
EG	r_g						1.00	0.681**	-0.154	-0.130	-0.202	0.665**
	r_p						1.00	0.601**	-0.144	-0.125	-0.192	0.641**
TSW	r_g							1.00	-0.396*	-0.464**	-0.302	0.541**
	r_p							1.00	-0.318**	-0.390**	-0.264*	0.469**
PC	r_g								1.00	0.668**	0.356	-0.513**
	r_p								1.00	0.598**	0.318**	-0.457**
Zn	r_g									1.00	0.156	-0.412*
	r_p									1.00	0.147	-0.402**
Fe	r_g										1.00	-0.284
	r_p										1.00	-0.277**
GYPP	r_g											1.00
	r_p											1.00

**, ** Significant at 5 per cent and 1 per cent levels of significance, respectively.*

Where, r_g = Genotypic correlation, r_p = Phenotypic correlation, DF = Days to flowering, DM = Days to maturity, NET = Number of effective tillers per plant, PH = Plant height, EL = Ear head length, EG = Ear head girth, TSW = 1000 grain weight, PC = Grain protein content, Zn = Grain zinc content, Fe = Grain iron content, GYPP = Grain yield per plant

3.5 Genotypic Path Coefficient Analysis

Genotypic path coefficient analysis (Table 4) showed that plant height (0.494) and ear head girth (0.681) had large positive direct effects, whereas the number of effective tillers per plant (0.241) had a smaller positive direct effect on grain yield per plant. These effects supported their positive associations with grain yield and indicated that selection based on these traits may be useful. The greatest positive indirect effect was exerted by 1000-grain weight through ear head girth (0.464). Days to maturity (-0.222) and grain protein content (-0.620) had negative direct effects, indicating inverse relationships with grain yield per plant. Ear head length and 1000-grain weight also exerted negative direct effects of -0.235 and -0.173, respectively, despite their significant positive total correlations with grain yield. This contrast indicates that their positive associations were largely attributable to indirect effects through ear head girth. Therefore, selection for ear head length and 1000-grain weight may be more effective when accompanied by simultaneous selection for ear head girth to offset these negative direct effects.

Path analysis showed that days to flowering, plant height, number of effective tillers per plant, ear head girth, grain zinc content, and grain iron content had positive direct effects on grain yield, indicating their contributions to yield variation. The residual effect of 0.31 suggested that the selected traits accounted for a substantial proportion of the variation in grain yield per plant in the present study. Similar results were reported by Kumari *et al.* (2018), Dadarwal *et al.* (2020), Kamble *et al.* (2022), Kumar *et al.* (2022), Goswami *et al.* (2023), Andhale *et al.* (2024), and Patil *et al.* (2024).

Table 4. Genotypic path matrix of direct (bold diagonal) and indirect effects of various traits on grain yield per plant in thirty genotypes of pearl millet

Characters	DF	DM	PH	NET	EL	EG	TSW	PC	Zn	Fe	Correlation with GYPP
DF	0.030	-0.099	0.163	-0.066	0.065	-0.074	0.073	-0.306	0.011	0.009	-0.194
DM	0.013	-0.222	0.001	-0.077	0.061	0.040	0.015	-0.156	0.005	0.003	-0.317
PH	0.010	-0.001	0.494	0.015	-0.086	0.137	-0.020	-0.154	-0.001	-0.002	0.392*
NET	-0.008	0.071	0.031	0.241	-0.070	0.097	-0.039	0.098	-0.001	-0.001	0.419*
EL	-0.008	0.058	0.181	0.072	-0.235	0.301	-0.071	0.200	-0.004	-0.007	0.486**
EG	-0.003	-0.013	0.099	0.034	-0.104	0.681	-0.118	0.095	-0.003	-0.003	0.665**
TSW	-0.013	0.020	0.057	0.055	-0.097	0.464	-0.173	0.246	-0.012	-0.005	0.541**
PC	0.015	-0.056	0.123	-0.038	0.076	-0.105	0.069	-0.620	0.018	0.006	-0.513**
Zn	0.012	-0.038	-0.016	-0.009	0.033	-0.089	0.080	-0.414	0.027	0.003	-0.412*
Fe	0.017	-0.046	-0.058	-0.009	0.097	-0.138	0.052	-0.221	0.004	0.017	-0.284

Residual effect = 0.31

Where, DF = Days to flowering, DM = Days to maturity, NET = Number of effective tillers per plant, PH = Plant height, EL = Ear head length,

EG = Ear head girth, TSW = 1000 grain weight, PC = Grain protein content, Zn = Grain zinc content, Fe = Grain iron content, GYPP = Grain yield per plant

4. Conclusion

The evaluated pearl millet restorer lines exhibited considerable variability for most yield, yield-related, and micronutrient traits, indicating useful scope for selection within the studied material. The violin plots supported the variability estimates by showing broad distributions for grain yield per plant, grain iron content, grain zinc content, plant height, and ear head length. Relatively small differences between the phenotypic and genotypic coefficients of variation for several traits indicated limited environmental influence under the conditions of this experiment. High heritability coupled with high genetic advance as a percentage of the mean for grain yield per plant, grain iron content, grain zinc content, ear head length, number of effective tillers per plant, grain protein content, ear head girth, 1000-grain weight, and plant height suggested that selection for these traits may be effective. Correlation analysis identified positive associations of plant height, ear head length, ear head girth, number of effective tillers per plant, and 1000-grain weight with grain yield per plant. Path analysis further identified ear head girth, plant height, and number of effective tillers per plant as traits with positive direct effects on grain yield. These traits may therefore be considered jointly when selecting promising restorer lines.

5. Limitation

The study evaluated thirty pearl millet restorer lines during one season at a single location. Consequently, the stability of trait expression and the effects of genotype × environment interaction could not be fully assessed. Multi-location and multi-year evaluations are required before the findings are applied more broadly in breeding programmes. Molecular or genomic analyses were not included and could provide additional evidence for interpreting the genetic architecture of the evaluated traits.

Declaration of AI Use

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Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abubakar, A., Falusi, O. A., Adebola, M. O., Olayemi, I. K., & Daudu, O. A. Y. (2019). Genetic diversity studies for morphological traits in pearl millet (*Pennisetum glaucum* L.) landraces of Northern Nigeria. *GSC Biological and Pharmaceutical Sciences, 7*(2), 60–70. https://doi.org/10.30574/gscbps.2019.7.2.0070

Al-Jibouri, H. A., Miller, P. A., & Robinson, H. F. (1958). Genotypic and environmental variances and covariances in an upland cotton cross of interspecific origin. *Agronomy Journal, 50*(10), 633–636. https://doi.org/10.2134/agronj1958.00021962005000100020x

Allard, R. W. (1961). Relationship between genetic diversity and consistency of performance in different environments. *Crop Science, 1*(2), 127–133. https://doi.org/10.2135/cropsci1961.0011183x000100020012x

Andhale, G. R., Bhavsar, V. V., Goykar, M. B., Pawar, V. Y., & Thorat, V. V. (2024). Study of correlation analysis and path analysis in different genotypes of pearl millet (*Pennisetum glaucum* L.). *International Journal of Environment and Climate Change, 14*(2), 30–44. https://doi.org/10.9734/ijecc/2024/v14i23917

Anuradha, N., Satyavathi, C. T., Bharadwaj, C., Sankar, M., Singh, S. P., & Pathy, T. L. (2018). Pearl millet genetic variability for grain yield and micronutrients in the arid zone of India. *Journal of Pharmacognosy and Phytochemistry, 7*(1), 875–878. https://www.phytojournal.com/archives/2018.v7.i1.2611/pearl-millet-genetic-variability-for-grain-yield-and-micronutrients-in-the-arid-zone-of-india

Athoni, B. K., Boodi, I., Pattanashetti, S. K., & Guggari, A. K. (2016). Genetic diversity for yield and its component traits in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *International Journal of Science and Nature, 7*(4), 795–798. https://oar.icrisat.org/10395/

Beniwal, R., Gupta, P. C., Sharma, A. K., Parihar, O. P., Phogat, B., & Rai, N. K. (2023). Assessment of genetic variability parameters in pearl millet [*Pennisetum glaucum* (L.) R. Br.] hybrids. *Biological Forum – An International Journal, 15*(2), 639–642. https://www.researchtrend.net/bfij/pdf/Assessment%20of%20Genetic%20Variability%20Parameters%20in%20Pearl%20Millet%20%5BPennisetum%20glaucum%20%28L%29.%20R.%20Br.%5D%20Hybrids-Ravina%20Beniwal-101.pdf

Burton, G. W. (1952). Quantitative inheritance in grasses. In *Proceedings of the Sixth International Grassland Congress* (Vol. 1, pp. 277–283). Pennsylvania State College.

Clark, J. D. (1962). The spread of food production in sub-Saharan Africa. *The Journal of African History, 3*(2), 211–228. https://doi.org/10.1017/S0021853700003042

Dadarwal, S. L., Rajput, S. S., & Yadav, G. L. (2020). Studies on correlation and path analysis for grain yield and its components in maintainer lines of pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *International*

Journal of Current Microbiology and Applied Sciences, 9(12), 1158–1164. https://doi.org/10.20546/ijcmas.2020.912.140

Davies, O. (1968). The origins of agriculture in West Africa. *Current Anthropology, 9*(5), 479–482. https://doi.org/10.1086/200945

Deewan, D. K., Jain, S. K., Prakash, O., & Sharma, L. D. (2023). Character associations and path coefficient analysis for grain yield and yield-contributing traits in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Annals of Arid Zone, 62*(2), 127–133. https://doi.org/10.59512/aaz.2023.62.2.5

Dewey, D. R., & Lu, K. H. (1959). A correlation and path-coefficient analysis of components of crested wheatgrass seed production. *Agronomy Journal, 51*(9), 515–518. https://doi.org/10.2134/agronj1959.00021962005100090002x

Gami, R. A., Kugashiya, K. G., Patil, J. V., Ganapathy, K. N., & Gnanesh, B. N. (2026). Millets: An emerging and promising climate-resilient nutri-cereals of the globe. In B. N. Gnanesh and C. Kole (Eds.), *Next generation crop improvement for agricultural sustainability and food security* (pp. 141–153). CRC Press. https://doi.org/10.1201/9781003584100-7

Goswami, P. A., Patel, P. R., Patel, H. S., & Chavda, H. R. (2023). Research of correlation and path coefficient analysis for grain yield and its attributes in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *The Pharma Innovation Journal, 12*(12), 2151–2154.

Gupta, S., Rangari, S. K., Sahu, A., Naik, Y. D., Satayavathi, C. T., Punnuri, S., & Thudi, M. (2024). Meta-QTL analysis reveals the important genomics regions for biotic stresses, nutritional quality and yield related traits in pearl millet. *CABI Agriculture and Bioscience, 5*, Article 36. https://doi.org/10.1186/s43170-024-00230-5

Harinarayana, G., Anand Kumar, A., & Andrews, D. J. (1999). Pearl millet in global agriculture. In I. S. Khairwal, K. N. Rai, D. J. Andrews, and G. Harinarayana (Eds.), *Pearl millet breeding* (pp. 479–506). Oxford & IBH Publishing.

Jaiswal, A., Kumhar, B. L., Singh, A. K., Choudhary, K., Gocher, K., Nayak, P. K., & Yadav, T. V. (2025). Analysis of variability parameters in restorer lines of pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Plant Archives, 25*(Supplement 1), 523–527. https://doi.org/10.51470/PLANTARCHIVES.2025.v25.supplement-1.069

Jat, G. P., Dhayal, L. S., Shekhawat, A. S., Sain, R. S., Yadav, I. R., & Jat, M. K. (2025). Assessment of genotype-environment interactions for identification of stable and high-performing pearl millet [*Pennisetum glaucum* (L.) R. Br.] hybrids. *Plant Cell Biotechnology and Molecular Biology, 26*(11-12), 10-19. https://doi.org/10.56557/pcbmb/2025/v26i11-129929

Johnson, H. W., Robinson, H. F., & Comstock, R. E. (1955). Estimates of genetic and environmental variability in soybeans. *Agronomy Journal, 47*(7), 314–318. https://doi.org/10.2134/agronj1955.00021962004700070009x

Kahate, D., Bagade, A. B., Pawar, S. B., Akhare, M., & Bhakad, V. (2023). Genetic variability analysis for yield and its contributing characters in pearl millet (*Pennisetum glaucum* L.). *The Pharma Innovation Journal, 12*(8), 1167–1170.

Kamble, P. S., Barhate, K. K., & Andhale, G. R. (2022). Correlation and path analysis for zinc, iron and yield-contributing characters in pearl millet [*Pennisetum glaucum* (L.) R. Br.] genotypes. *The Pharma Innovation Journal, 11*(6), 596–600.

Kanatti, A., Rai, K. N., Radhika, K., Govindaraj, M., Sahrawat, K. L., & Rao, A. S. (2014). Grain iron and zinc density in pearl millet: Combining ability, heterosis and association with grain yield and grain size. *SpringerPlus, 3*, Article 763. https://doi.org/10.1186/2193-1801-3-763

Kumar, A., Yadav, M. K., Barupal, H., Meena, M. B., Kumawat, R., & Mondal, K. (2022). Deciphering pearl millet grain yield under water stress using genotypic and phenotypic correlation and path coefficient analysis. *International Journal of Environment and Climate Change, 12*(10), 278–283. https://doi.org/10.9734/ijecc/2022/v12i1030796

Kumar, V., Kumar, K., Kumar, V., Dehinwal, A. K., Arya, R. K., Mandal, B. S., & Behl, R. K. (2024). Variability and inheritance among pearl millet genotypes under rainfed conditions: An overview. *Forage Research, 49*(4), 374–382. https://forageresearch.in/variability-and-inheritance-among-pearl-millet-genotypes-under-rainfed-condition-an-overview/

Kumari, N., Sharma, N. K., Kajla, S. L., & Sanadya, S. K. (2018). Studies on variability, character association and genetic diversity in R-lines of pearl millet. *International Journal of Chemical Studies, 6*(5), 700–704.

Kumawat, K., Sharma, N. K., & Sharma, N. (2019). Genetic variability and character association analysis in pearl millet single-cross hybrids under dry conditions of Rajasthan. *Electronic Journal of Plant Breeding, 10*(3), 1067–1070.

Lakshmana, D., Biradar, B. D., Madaiah, D., & Jolli, R. B. (2010). Genetic diversity for yield and its component traits in pearl millet germplasm. *Indian Journal of Plant Genetic Resources, 23*(2), 206–211.

Narasimhulu, R., Sahadeva Reddy, B., Satyavathi, C. T., & Ajay, B. C. (2021). Performance, genetic variability and association analysis of pearl millet yield-attributing traits in Andhra Pradesh's arid region. *Chemical Science Review and Letters, 10*(38), 177–182. https://doi.org/10.37273/chesci.cs205204317

Pallavi, M., Reddy, P. S., Ratnavathi, C. V., & Radha Krishna, K. V. (2024). Genetic variability and diversity for rancidity and associated characters in pearl millet (*Pennisetum glaucum* L.). *Journal of Experimental Agriculture International, 46*(7), 928–939. https://doi.org/10.9734/jeai/2024/v46i72647

Patil, P. B., Karad, S. R., Gajbhiye, P. N., & Mote, M. S. (2024). Genetic diversity in proso millet (*Panicum miliaceum* L.). *Biological Forum – An International Journal, 16*(1), 299–302. https://www.researchtrend.net/bfij/genetic-diversity-in-proso-millet-panicum-milliaceum-l-8298

Patil, S. H., Wadikar, P. B., Dhutraj, D. N., & Sargar, P. R. (2021). Correlation analysis for grain yield and its components in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Madras Agricultural Journal, 108*(1–3), 4–6. https://doi.org/10.29321/MAJ.10.000493

Rajpoot, P., Tripathi, M. K., Solanki, R. S., Tiwari, S., Tripathi, N., Chauhan, S., Pandya, R. K., & Khandelwal, V. (2023). Genetic variability and multivariate analysis in pearl millet [*Pennisetum glaucum* (L.) R. Br.] germplasm lines. *The Pharma Innovation Journal, 12*(4), 216–226.

Sadh, P. K., Kamboj, A., Kumar, S., Chawla, P., Kumar, R., Saharan, B. S., Kumar, D., Duhan, S., Nehra, M., Goyal, C., Brar, B., Joshi, S., & Duhan, J. S. (2024). Perspectives of millets for nutritional properties, health benefits and food of the future: A review. *Discover Food, 4*, Article 187. https://doi.org/10.1007/s44187-024-00266-6

Satyavathi, C. T., Sankar, S. M., Singh, S. P., Kapoor, C., Soumya, S. L., & Singhal, T. (2022). Pearl millet breeding. In D. K. Yadava, H. K. Dikshit, G. P. Mishra, and S. Tripathi (Eds.), *Fundamentals of field crop breeding* (pp. 309–366). Springer. https://doi.org/10.1007/978-981-16-9257-4_6

Singh, A. K., & Chaudhary, A. K. (2026). Genetic variability, character association, and path coefficient analysis for yield and micronutrients (zinc and iron) traits in pearl millet (*Pennisetum glaucum* L.). *Journal of Experimental Agriculture International, 48*(4), 452-460. https://doi.org/10.9734/jeai/2026/v48i44175

Singh, D., Chhonkar, P. K., & Dwivedi, B. S. (2005). *Manual on soil, plant and water analysis*. Westville Publishing House. https://catalog.princeton.edu/catalog/SCSB-9087463

Subbulakshmi, K., Karthikeyan, A., Murukarthick, J., Dhasarathan, M., Naveen, R., Sathya, M., Lavanya, B., Iyanar, K., Sivakumar, S., Ravikesavan, R., Sumathi, P., & Senthil, N. (2024). Consensus genetic linkage map and QTL mapping allow to capture the genomic regions associated with agronomic traits in pearl millet. *Planta, 260*, Article 57. https://doi.org/10.1007/s00425-024-04487-y

Wright, S. (1921). Correlation and causation. *Journal of Agricultural Research, 20*(7), 557–585. https://search.nal.usda.gov/discovery/fulldisplay/alma9916341892807426/01NAL_INST%3AMAIN

Yadav, S. L., Khandelwal, V., Rajpurohit, B. S., Satyavathi, C. T., & Kumari, M. (2020). Genetic variability for grain iron, zinc and yield-contributing traits in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *International Journal of Current Microbiology and Applied Sciences, 9*(10), 1927–1932. https://doi.org/10.20546/ijcmas.2020.910.235

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