



Multivariate Analysis in Pearl Millet Parental Lines for Diversity Estimation and Association Study of Yield Contributing Traits for Genetic Improvement of Hybrids

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Abstract: Sixty parental lines of pearl millet containing Restorers (R) and Maintainers (B) lines were evaluated at ICAR-AICRP on Pearl Millet, Mandor, Rajasthan during *Kharif*-2020 to determine the extent of genetic diversity and association among yield and yield contributing traits. Multivariate analysis was carried out. The results of PCA revealed four principal components with eigen values greater than one, explaining 33.53%, 18.51%, 14.06% and 8.49% of the total variability, respectively, with a cumulative effect of 74.59%. The study identified the traits such as number of productive tillers, dry fodder yield and plant height as excellent selection indicators which exhibited positive loading toward genetic diversity. Cluster analysis sorted all the parental lines into six distinct clusters, with cluster VI having the highest number of lines (42) followed by cluster III due to similar ancestry of parental lines. The parental lines J-2591, PPMI-1267 and RIB-109-120-S/19, RIB 3135-18, ICMB 95222, ICMB 94555, ICMB 04999, ICMB 93333 and ICMB 97111 displayed diversity in both cluster and PCA analyses, indicating utility of these lines for hybridization program to harness heterosis and to select superior segregants in pearl millet.

Key words: Pearl Millet, Cluster analysis, Trait Association, Grain yield

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is a major cereal crop of arid and semi-arid regions of India and around the world owing to its aptitude to grow under uncharitable environmental conditions. It is a highly cross-pollinated, diploid (2n=14), C4 crop with a high photosynthetic efficiency. In India, pearl millet hybrids cover a significant portion (70-75%) of the total land area, with open-pollinated varieties (OPVs) or landraces accounting for the remaining area (Patil et

al., 2020). Pearl millet is the predominant crop of the western arid region thus it is necessary to develop its high yielding varieties though the genetic gain noticed in past seven decades for enhancing the productivity levels, (Mann *et al.*, 1976; Yadav *et al.*, 2021). Breeding of highly adaptive varieties is also very much needed to cope with the climate change. Success of hybrid development programs relies on selecting diverse seed and pollen parents to develop high-yielding hybrids (Sharma *et al.*, 2020). Therefore, evaluating the available parental lines for their genetic diversity is crucial for identifying superior genotypes for further breeding programs.

Apart from genetic divergence, correlation coefficients indicate the direct impact of specific traits on seed yield and provide a background for selecting and developing new genetically diverse inbred lines. Multivariate statistical techniques such as cluster analysis reveal the type of link between samples specified by different descriptors. It can be used as a preliminary step in selecting parental types that will produce better hybrids. Previous studies have extensively employed multivariate analysis for genetic diversity analysis in pearl millet (Rasitha *et al.*, 2020; Sanjana Reddy *et al.*, 2021; Narasimhulu *et al.*, 2022).

In this study, the aim was to comprehensively analyse the genetic diversity and correlation of yield-related traits in a large collection of parental lines using recent statistical methods (Govindaraj *et al.*, 2021; Singh *et al.*, 2021; Yadav *et al.*, 2022). The goal is to group parental lines into distinct clusters based on morpho-physiological characteristics and establish an acceptable selection criterion for selecting the best parental lines for trait-specific line/hybrid development programs. The findings will provide valuable insights into the genetic diversity and selection of optimal parental lines for pearl millet hybrid development programs.

Materials and Methods

The present investigation was conducted at Experimental Research Farm of ICAR-AICRP on Pearl Millet, PC Unit, Mandor, Jodhpur (26°15' N to 26°45' North latitude: 73°00' E to 73°29' East longitude and 231 meters above mean sea level) in Rajasthan. The region falls under Agro Climatic Zone IA (Arid Western Plains Zone) of Rajasthan, India. Average

rainfall received is approximately 367 mm during the cropping season as and the region is characterized by low and erratic rainfalls. Sixty diverse parental lines comprising of 50 Restorers (R) and 10 Maintainer (B) lines were grown in randomized block design with three replications during *Kharif*-2020. The experiment unit was a single row plot of 4.0m length, spaced 0.60 m apart. The standard agronomic practices were followed throughout the period of crop growth. The observations were recorded on the five randomly selected competitive plants from each genotype and replication for the observed traits *viz.*, plant height (cm), number of productive tillers per plant, panicle length (cm), panicle girth (cm), leaf area (cm²), flag leaf area (cm²), stem girth (cm), grain yield per plant (g) and dry fodder yield per plant (g), 1000-grain weight (g) while observations on days to 50% flowering and days to maturity were recorded on plot basis. Genetic diversity among the genotypes was assessed through a cluster diagram, principal component analysis (PCA) following Davis (1986) and with a correlation matrix in the R program (R Core team, 2018). The PCs with eigen value >1.0 were considered for determining the agromorphological variability in the genotypes (Kaiser, 1960). Before PCA analysis, data was normalized using square root transformation, and PC-1 and PC-2 scores were used to create a scatter plot of traits. To determine the association among yield and its contributing traits Pearson's correlation coefficients were computed for the twelve individual traits using R-software (R Core team, 2020).

Results and Discussion

The results indicated that there is a significant diversity among the lines, providing opportunities for further selection to develop superior genotypes. The mean and range for yield-related traits varied significantly among the breeding material, highlighting the potential for genetic enhancement through hybridization and selection.

Among the breeding material, RIB-109-120-S/19 was identified as the best line with a medium maturity period, as it showed superior performance across multiple traits, including for highest grain yield (43.7 g plant⁻¹). RIB 3135-18 (38.5 g plant⁻¹) and PPMI-1267(35.3 g plant⁻¹) also exhibited good performance, suggesting

Table 1. Pearl millet parental germplasm lines analysed

S. No.	Name of Material	Source	S. No.	Name of Material	Source
1	MIR 606	AICRP-PM, Jodhpur	31	MIR 503	AICRP-PM, Jodhpur
2	MIR 612	AICRP-PM, Jodhpur	32	MIR 507	AICRP-PM, Jodhpur
3	MIR 705-1	AICRP-PM, Jodhpur	33	MIR 514	AICRP-PM, Jodhpur
4	MIR 710	AICRP-PM, Jodhpur	34	MIR 519	AICRP-PM, Jodhpur
5	MIR 714	AICRP-PM, Jodhpur	35	MIR 519-2	AICRP-PM, Jodhpur
6	MIR 901	AICRP-PM, Jodhpur	36	MIR 522	AICRP-PM, Jodhpur
7	MIR 915	AICRP-PM, Jodhpur	37	MIR 525-2	AICRP-PM, Jodhpur
8	MIR 916	AICRP-PM, Jodhpur	38	MIR 1112	AICRP-PM, Jodhpur
9	MIR 920-1	AICRP-PM, Jodhpur	39	MIR 1114	AICRP-PM, Jodhpur
10	MIR 1106	AICRP-PM, Jodhpur	40	MIR 1116	AICRP-PM, Jodhpur
11	MIR 1255	AICRP-PM, Jodhpur	41	MIR 1252	AICRP-PM, Jodhpur
12	MIR 1259	AICRP-PM, Jodhpur	42	MIR 1253	AICRP-PM, Jodhpur
13	MIR 1261	AICRP-PM, Jodhpur	43	MIR 1254	AICRP-PM, Jodhpur
14	PPMI-732	IARI, New Delhi	44	MIR 1714	AICRP-PM, Jodhpur
15	PPMI-1239	IARI, New Delhi	45	MIR 1801	AICRP-PM, Jodhpur
16	PPMI-1267	IARI, New Delhi	46	PPMI-85	IARI, New Delhi
17	RIB-102-108-S/19	RARI, Durgapura	47	PPMI-952	IARI, New Delhi
18	RIB-109-120-S/19	RARI, Durgapura	48	RIB 335/74	RARI, Durgapura
19	RIB-121-127-S/19	RARI, Durgapura	49	RIB 494	RARI, Durgapura
20	G 73-107	CCS HAU, Hisar	50	RIB 3135-18	RARI, Durgapura
21	H 77/29-2	CCS HAU, Hisar	51	H 77/833-2-202	CCS HAU, Hisar
22	H 77/833-2	CCS HAU, Hisar	52	H 90/4-5	CCS HAU, Hisar
23	J-2290	JAU, Jamnagar	53	HBL 11	CCS HAU, Hisar
24	J-2565	JAU, Jamnagar	54	J 2340	JAU, Jamnagar
25	J-2591	JAU, Jamnagar	55	J 2467	JAU, Jamnagar
26	ICMB 88004	ICRISAT, Hyderabad	56	ICMB 843-22	ICRISAT, Hyderabad
27	ICMB 92777	ICRISAT, Hyderabad	57	ICMB 93333	ICRISAT, Hyderabad
28	ICMB 95222	ICRISAT, Hyderabad	58	ICMB 94555	ICRISAT, Hyderabad
29	ICMB 97444	ICRISAT, Hyderabad	59	ICMB 97111	ICRISAT, Hyderabad
30	ICMB 02333	ICRISAT, Hyderabad	60	ICMB 04999	ICRISAT, Hyderabad

that these lines could also be used as parental lines in hybridization programs to improve the pearl millet crop.

The mean and range for yield-related traits (Table 1) revealed that the mean values for the majority of the traits varied significantly. The trait grain yield ranged from 8.5 to 43.7 g plant⁻¹, the days to 50% flowering ranged from 40 to 66, the days to maturity ranged from 66 to 87, the leaf area ranged from 60.5 to 199.8 cm, the flag leaf area ranged from 44.9 to 160.9 cm, the plant height ranged from 96.2 to 200.3 cm, the panicle length ranged from 14.0 to 25.4 cm, the panicle diameter ranged from 1.5 to 3.5 cm, the stem girth ranged from 0.7 to 1.3 cm, the No. of effective tillers ranged from

1.0 to 3.7, the dry fodder yield ranged from 19.3 to 81.3 g plant⁻¹ and 1000-grain weight from 3.9 to 10.1 g. High range of variation for majority of the traits highlighted the potential for genetic enhancement of pearl millet through hybridization and selection using these identified superior lines as parental material. The findings also support the need for further research to explore the genetic variability and heritability of pearl millet genotypes to develop more productive and sustainable crop varieties.

Cluster analysis

Cluster analysis was employed to investigate the genetic diversity among the 60 pearl millet parental lines based on different traits. The method classified the entities into six main

Table 2. Mean performance of pearl millet parental lines for traits studied

S. No.	Means	DF	DM	LA	FLA	PH	PL	PG	SG	ET	DFY	TW	GY
1	RIB-109-120-S/19	50	75	110.1	87.3	157.7	20.1	2.2	0.8	3.6	70.0	6.5	43.7
2	RIB 3135-18	49	72	82.9	85.9	141.1	14.0	2.6	0.8	3.0	66.0	7.3	38.5
3	PPMI-1267	58	83	199.8	129.0	178.7	20.4	3.0	1.1	1.5	81.3	9.2	35.3
4	ICMB 92777	52	76	84.0	94.7	182.1	20.0	3.0	1.1	1.8	57.3	7.6	33.2
5	J-2290	57	81	176.4	118.3	185.8	19.2	3.5	1.2	1.8	74.7	7.5	32.4
6	RIB-102-108-S/19	56	81	103.2	77.8	161.1	20.0	2.1	0.9	2.2	50.7	7.0	30.1
7	MIR 705-1	57	82	92.4	70.1	163.0	19.2	2.4	0.9	2.3	75.3	6.0	29.1
8	MIR 503	49	75	159.0	154.2	158.4	23.9	2.8	1.0	2.2	71.0	6.9	28.2
9	H 77/833-2-202	48	73	78.1	130.1	134.1	18.9	2.7	0.7	1.7	24.0	6.0	26.6
10	MIR 1259	52	78	92.1	76.1	154.8	19.5	2.2	0.8	2.6	68.0	6.2	26.1
11	MIR 514	48	74	103.1	132.1	157.0	15.6	1.9	0.8	2.6	73.3	6.8	25.9
12	MIR 1255	52	72	87.4	58.1	171.3	18.5	1.7	0.8	3.7	67.3	5.6	25.9
13	ICMB 97111	52	82	147.1	127.0	181.2	21.8	2.9	1.0	1.6	46.0	9.5	25.8
14	ICMB 93333	57	85	168.4	126.4	153.3	20.2	1.8	0.9	1.8	57.3	7.6	25.5
15	MIR 1801	51	78	181.2	69.2	161.7	23.5	2.3	0.9	1.7	58.0	6.3	23.9
16	MIR 1114	46	77	130.3	98.6	151.7	17.6	2.5	0.9	2.0	67.3	7.3	23.7
17	MIR 710	49	74	66.8	44.9	155.3	16.9	2.1	0.8	2.8	60.7	6.6	23.7
18	H 77/29-2	51	76	123.3	87.3	143.2	18.4	1.9	0.7	2.0	70.0	5.2	23.1
19	MIR 1254	50	80	99.5	67.0	149.7	20.2	2.1	1.0	2.0	64.0	7.6	23.0
20	MIR 1116	53	81	165.4	102.0	147.0	25.4	2.6	1.0	1.5	63.7	8.8	22.9
21	MIR 507	40	66	101.3	72.5	121.6	15.8	2.2	0.8	2.8	35.3	6.4	22.8
22	MIR 522	48	76	128.8	86.5	141.1	23.5	2.5	1.0	1.3	43.7	9.2	22.5
23	ICMB 04999	55	84	138.5	105.0	115.6	19.9	2.1	0.9	1.5	44.3	7.9	22.5
24	J 2340	52	78	165.6	98.1	168.5	18.5	2.3	0.9	2.2	53.3	8.6	22.4
25	MIR 1112	48	78	133.2	98.8	143.7	18.6	2.0	0.9	2.1	50.3	8.2	22.1
26	ICMB 94555	55	83	199.2	124.0	96.2	20.7	1.7	1.1	1.4	32.3	7.9	22.0
27	MIR 1261	54	80	91.0	67.1	146.3	17.8	2.3	0.9	2.4	42.0	5.3	22.0
28	J 2467	49	79	162.1	160.9	110.8	17.0	2.3	0.9	1.0	19.3	9.0	21.0
29	MIR 1252	46	74	83.7	116.0	141.2	18.7	2.0	0.7	2.2	30.7	6.8	20.8
30	ICMB 95222	56	80	98.9	99.1	158.1	17.5	2.2	1.0	2.0	49.3	6.6	19.7
31	H 90/4-5	54	82	92.1	65.1	152.1	16.1	2.2	0.9	2.2	70.7	7.0	19.4
32	MIR 606	47	72	79.7	60.3	138.4	16.1	1.9	0.7	3.0	38.7	5.9	19.2
33	MIR 525-2	52	80	157.0	112.6	129.2	18.1	2.5	0.9	1.8	40.3	6.2	18.1
34	MIR 1253	58	84	108.1	68.8	160.4	19.1	2.2	1.0	1.5	27.3	7.6	18.0
35	PPMI-952	60	86	117.4	91.6	158.0	17.3	2.4	1.0	1.3	52.7	10.1	18.0
36	MIR 920-1	50	76	110.4	84.2	168.3	19.9	2.1	0.9	2.5	27.3	6.6	17.8
37	PPMI-85	47	77	138.1	110.7	123.6	18.4	1.7	0.9	1.5	27.3	5.9	17.5
38	MIR 901	47	72	119.8	86.0	123.3	17.7	2.0	0.9	2.3	46.7	6.9	17.3
39	G 73-107	55	83	93.9	86.3	150.5	19.7	2.2	0.9	2.6	75.3	8.1	17.3
40	MIR 519-2	47	76	148.9	105.8	155.4	20.2	2.4	0.9	1.4	41.3	5.9	17.1
41	MIR 714	48	74	103.7	80.0	141.7	14.4	1.7	0.8	2.1	41.3	6.6	17.1
42	MIR 1106	50	80	111.6	85.4	120.7	20.6	2.2	1.0	1.7	52.0	5.6	17.0
43	HBL 11	48	72	116.5	85.7	125.1	15.6	2.3	0.7	2.1	40.0	6.2	16.4
44	ICMB 843-22	51	75	115.3	62.8	108.3	17.1	2.7	0.8	1.4	22.7	8.3	16.0
45	MIR 916	48	73	120.9	81.1	134.8	16.5	2.2	0.8	1.3	33.3	7.4	15.7

Table 2. Contd...

S. No.	Means	DF	DM	LA	FLA	PH	PL	PG	SG	ET	DFY	TW	GY
46	J-2591	66	87	143.4	97.8	200.3	23.4	2.4	1.3	1.0	55.3	6.9	15.5
47	MIR 1714	50	79	152.9	98.3	143.8	18.9	1.9	0.8	1.4	24.7	6.2	15.3
48	J-2565	58	84	84.6	53.2	153.5	16.3	2.1	1.1	1.1	80.7	7.0	15.2
49	ICMB 97444	51	77	108.7	101.5	120.2	17.8	2.4	0.9	1.7	24.0	5.6	14.7
50	MIR 519	44	71	132.0	60.8	131.8	21.3	2.5	0.8	1.5	31.3	3.9	14.7
51	ICMB 88004	53	77	60.5	46.1	167.2	15.5	2.5	0.8	1.6	42.7	8.8	13.9
52	MIR 915	52	77	139.8	93.7	156.0	20.7	1.8	0.8	1.7	52.7	6.0	13.8
53	RIB 335/74	55	81	72.3	55.8	161.9	17.9	1.7	0.9	1.3	35.7	6.6	13.4
54	RIB 494	49	73	137.6	54.1	144.6	18.8	1.9	0.7	1.7	25.3	6.9	13.1
55	PPMI-1239	61	84	130.5	83.1	140.6	17.4	3.2	1.2	1.0	70.7	7.7	12.4
56	H 77/833-2	47	72	80.6	51.6	140.2	17.1	1.5	0.7	2.7	44.7	5.4	12.4
57	RIB-121-127-S/19	54	78	126.4	103.1	146.5	23.5	1.9	0.9	1.3	50.0	6.4	11.5
58	PPMI-732	64	85	117.2	73.5	103.3	20.9	2.7	1.2	1.1	50.0	5.7	10.6
59	ICMB 02333	57	82	119.9	95.6	143.7	14.9	3.2	0.9	1.1	27.3	5.4	9.8
60	MIR 612	47	73	108.8	77.1	157.6	20.8	2.0	0.9	1.2	26.0	5.8	8.5
	Mean	52	78	120.0	89.6	147.2	18.9	2.3	0.9	1.9	49.1	6.9	20.7
	Max	66	87	199.8	160.9	200.3	25.4	3.5	1.3	3.7	81.3	10.1	43.7
	Min	40	66	60.5	44.9	96.2	14.0	1.5	0.7	1.0	19.3	3.9	8.5

DF: Days to 50 % flowering, DM: Days to maturity, LA: Leaf Area (cm), FLA: Flag Leaf Area (cm), PH: Plant Height (cm), PL: Panicle Length (cm), PG: Panicle Girth (cm), SG: Stem Girth (cm), ET: Effective tillers (no. plant⁻¹), DFY: Dry Fodder Yield (gPlant⁻¹), TW: 1000 - grain weight (g), GY: Grain Yield (g Plant⁻¹)

groups (Table 3) and further divided into sub-clusters (Fig. 1). Cluster VI was the largest with 42 parental lines, followed by cluster III with eight lines, and cluster V with four accessions. The study suggests that selection of parents from cluster I, V, and VI could serve as potential breeding material to improve yield attributing traits in hybridization programs. The results are consistent with studies by Kaushik *et al.*, (2018), Kumar *et al.*, (2020), and Narasimhulu *et al.*, (2022), who also used quantitative data to identify prospective parents for heterotic expression of yield components.

Singh *et al.*, (2017) and Kumari *et al.*, (2016) also reported similar results where clustering was used to identify diverse parental lines for developing high-yielding hybrids in pearl millet. Furthermore, Sankar *et al.*, (2014) identified early flowering genotypes that are suitable for cultivation in drought-prone areas. Accordingly, individuals belonging to cluster VI and IV were used to develop early-flowering lines with higher yield. The grouping of most of the lines of AICRP, Mandor origin having series codes as MIR (Mandor Inbred Restores) grouped in cluster VI; hence genetic diversity

Table 3. Grouping of pearl millet parental lines into different clusters

S. No	Cluster No	Number of genotypes	Parental Lines
1	I	1	J-2591
2	II	3	ICMB 02333,PPMI-1239, PPMI-732
3	III	8	J-2290, PPMI-1267, ICMB 92777, MIR 503, MIR 1801,ICMB 97111, MIR 1116,MIR 522
4	IV	2	RIB-109-120-S/19,RIB 3135-18
5	V	4	J 2467,ICMB 94555, ICMB 04999, ICMB 93333
6	VI	42	PPMI-952,J-2565, ICMB 88004,MIR 1253,RIB 335/74, MIR 606, MIR 612, MIR 705-1, MIR 710, MIR 714, MIR 901, MIR 915, MIR 916, MIR 920-1, MIR 1106, MIR 1255, MIR 1259, MIR 1261, RIB-102-108-S/19, RIB-121-127-S/19, G 73-107, H 77/29-2, H 77/833-2, ICMB 95222, ICMB 97444, MIR 507, MIR 514, MIR 519, MIR 519-2,MIR 525-2, MIR 1112, MIR 1114, MIR 1252, MIR 1254, MIR 1714, PPMI-85, RIB 494, H 77/833-2-202, H 90/4-5, HBL 11, J 2340, ICMB 843-22

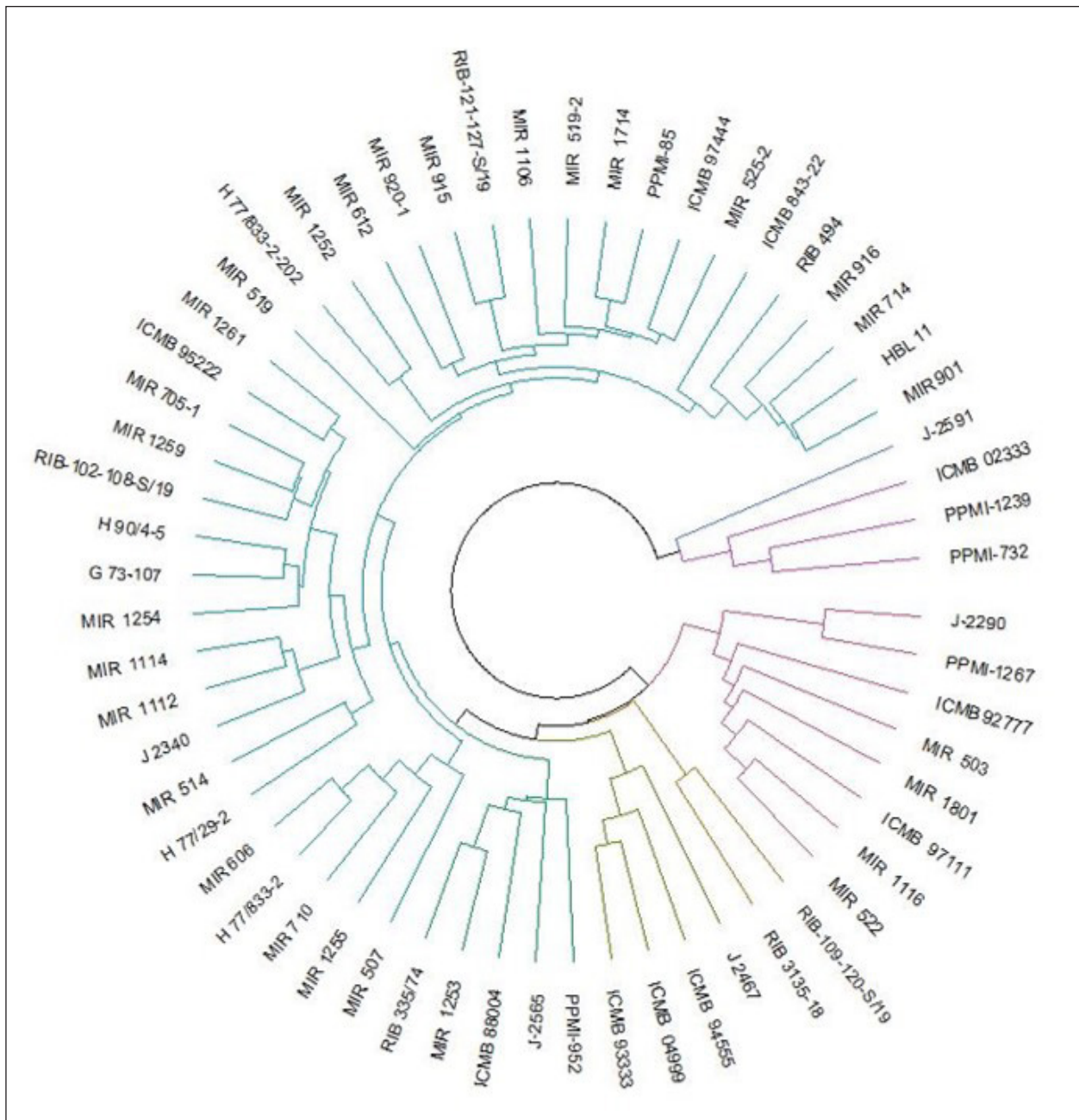


Fig. 1. Dendrogram depicting clustering pattern of 60 parental lines analysed in pearl millet.

showed correlation with respect to source as they have been bred at single location hence forth selection pressure may have led to narrow down of genetic base.

Recent studies have continued to use clustering analysis to understand the genetic diversity of pearl millet germplasm. For example, a study by Singh *et al.*, (2021) identified 118 diverse germplasm accessions that were clustered into six groups based on 18 yield and quality traits. Hence clustering

analysis was useful for identifying diverse parental lines and improving the yield potential of pearl millet.

Principal Component Analysis (PCA)

The results of the Principal Component Analysis (PCA) showed that the first four components had eigen values greater than one and accounted for approximately 74.59% of the cumulative variability among the twelve different morphological traits evaluated in 60

Table 4. Principal components, eigen values, proportion of variation and total variation across axis

Principal component axis	1	2	3	4	5	6	7	8	9	10	11
Eigenvalues	4.02	2.22	1.69	1.02	0.77	0.68	0.49	0.37	0.28	0.21	0.15
Proportion of Variance (%)	33.53	18.51	14.06	8.49	6.44	5.68	4.06	3.10	2.36	1.96	1.80
Cumulative variation (%)	33.53	52.03	66.10	74.59	81.03	86.71	90.77	93.87	96.24	98.20	100.00

Table 5. Factor loading of four important principal components for the traits studied

Particulars	PC1	PC2	PC3	PC4
Days to 50 % flowering	0.76	-0.01	-0.53	-0.01
Days to maturity	0.83	-0.12	-0.35	-0.01
Leaf Area(cm)	0.59	-0.22	0.58	0.21
Flag Leaf Area(cm)	0.44	-0.04	0.74	-0.09
Plant Height (cm)	0.34	0.60	-0.24	0.21
Panicle Length (cm)	0.52	-0.03	0.26	0.69
Panicle Girth (cm)	0.58	0.13	0.10	-0.43
Stem Girth (cm)	0.87	-0.05	-0.18	0.02
Effective tillers (no plant ⁻¹)	-0.56	0.73	0.04	0.08
Dry Fodder Yield (g plant ⁻¹)	0.35	0.75	-0.19	0.10
1000 - grain weight (g)	0.53	0.13	0.20	-0.48
Grain Yield (g plant ⁻¹)	0.14	0.81	0.40	-0.10

parental lines. PC1 was the greatest contributor to variability, accounting for 33.53% of the overall variation, followed by PC2, PC3, and PC4, which contributed 18.51%, 14.06%, and

8.49% of the total variability, respectively. The study suggested considering traits with high PC1 scores to capture the variability of particular traits.

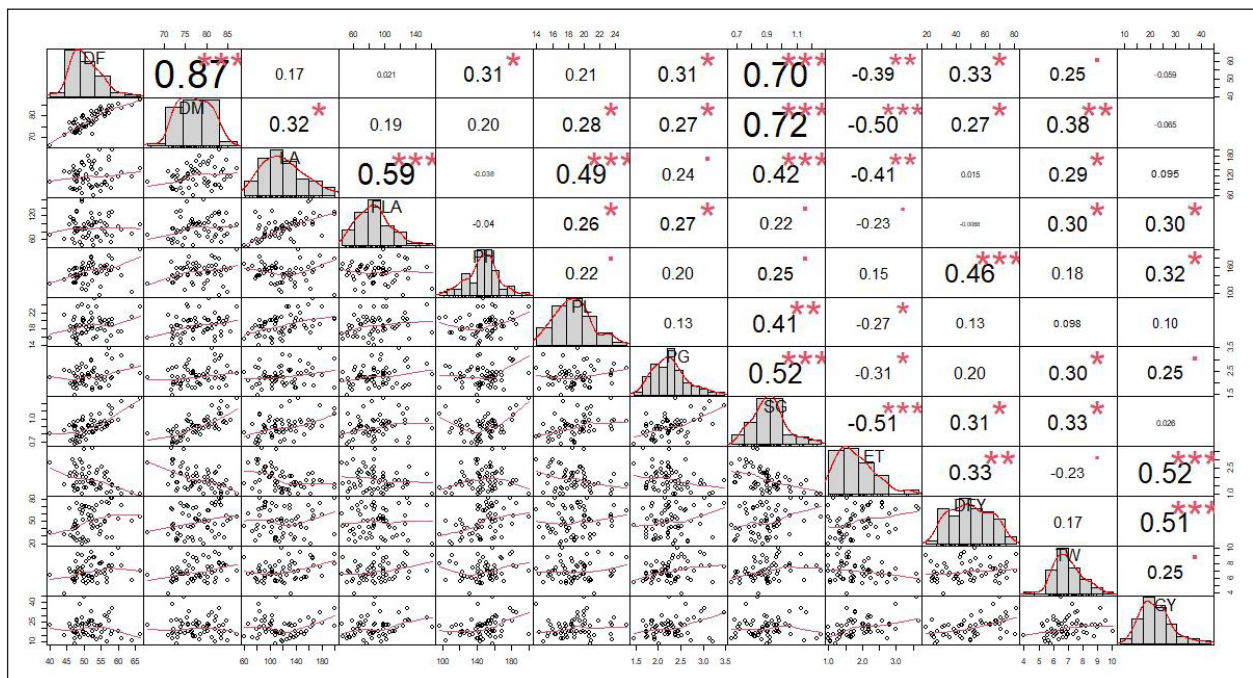


Fig. 2. Correlation for yield and yield contributing traits in pearl millet.

DF: Days to 50 % flowering, DM: Days to maturity, LA: Leaf Area (cm), FLA: Flag Leaf Area (cm), PH: Plant Height (cm), PL: Panicle Length (cm), PG: Panicle Girth (cm), SG: stem girth (cm), ET: Effective tillers (no. plant⁻¹), DFY: Dry Fodder Yield (g Plant⁻¹), TW: 1000 - grain weight (g), GY: Grain Yield (g Plant⁻¹)

PC1 was largely influenced by stem girth (0.87), days to maturity (0.83), and days to 50% flowering (0.76), indicating that these traits were important contributors to variation among the breeding material. The presence of positive and negative loading in a single component indicated the presence of positive and negative correlation trends between the components and the variables. Traits with high positive or negative loading contributed more to the diversity. For instance, PC1 had a negative factor loading for the number of productive tillers (-0.56), indicating a negative correlation with the trait. Similarly, PC2 contributed 18.51% of the total variation through grain yield (0.81), dry fodder yield (0.75), effective tillers (0.73), plant height (0.60), panicle girth (0.13), and 1000-grain weight (0.13). Grain yield was found to increase with the number of productive tillers per plant with high biomass, tall plants with good panicle girth, and bold seed background. PC3 contributed 14.06% of the total variation through flag leaf area (0.74), leaf area (0.58), grain yield (0.40), panicle length (0.26), 1000-grain weight (0.20), and panicle girth (0.10). PC4 showed that grain yield was

enhanced by a greater panicle length, plant height, leaf area, and number of productive tillers per plant.

Traits such as plant height, number of productive tillers per plant, leaf area, panicle length, panicle girth, 1000-seed weight, and biomass contributed positively to the total variation in all the eleven components. These traits could be effectively used for selection in crop improvement programs to obtain superior inbreds with higher yields in pearl millet. Recent studies in pearl millet have also shown similar results. For instance, a study conducted by Govindaraj *et al.*, (2019) reported that grain yield and its components, such as panicle weight, number of panicles per plant, and plant height, significantly contributed to the total variation observed in pearl millet germplasm. Another study by Ojulong *et al.*, (2020) found that the number of tillers per plant, panicle length, panicle weight, and grain yield per plant were the most important traits contributing to the total variation in a set of pearl millet genotypes evaluated under drought stress conditions.

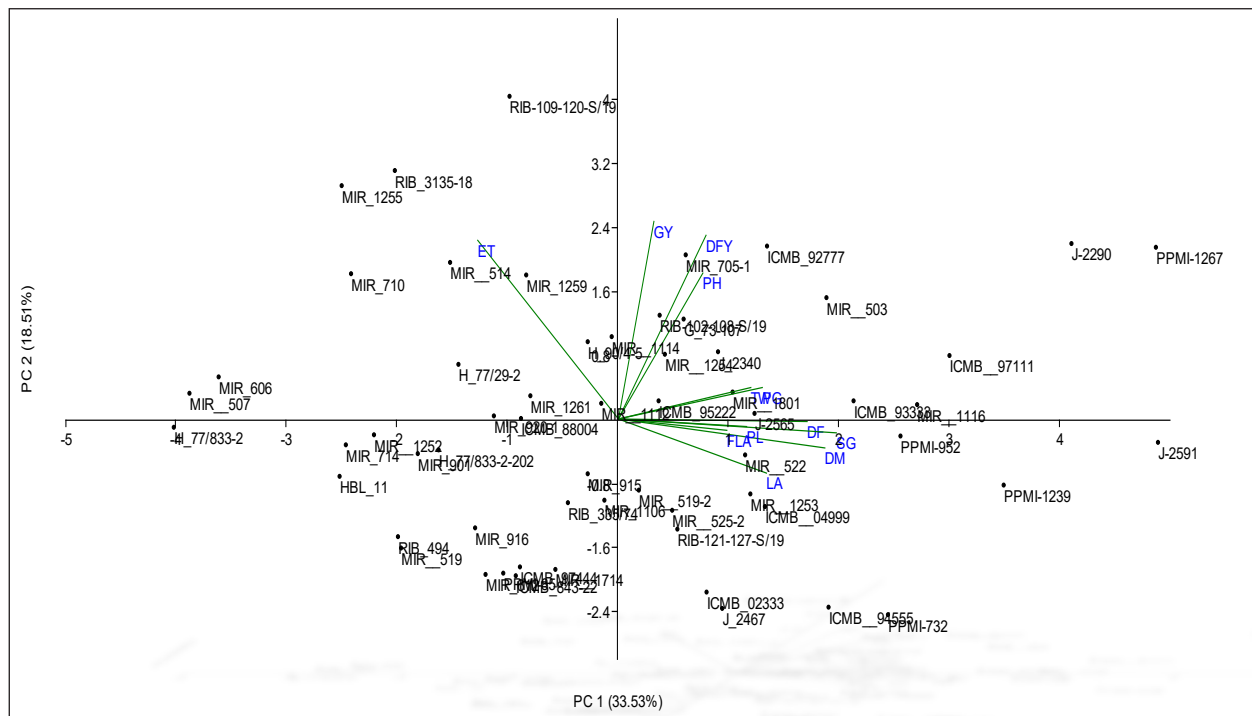


Fig. 3. Biplot relationship between yield and yield attributing traits of pearl millet genotypes on first two principal components. DF: Days to 50% flowering, DM: Days to maturity, LA: Leaf Area (cm), FLA: Flag Leaf Area (cm), PH: Plant Height (cm), PL: Panicle Length (cm), PG: Panicle Girth (cm), SG: stem girth (cm), ET: Effective tillers (no. plant-1), DFY: Dry Fodder Yield (kg Plant-1), TW: 1000 - grain weight (g), GY: Grain Yield (kg Plant-1)

PCA results are generally displayed as a biplot, in which axes correspond to the new system of coordinates (Fig. 3). The direction of arrow denotes the maximum change in quantity and the length could be related with the rate of change. The acute coordinate angle ($<90^\circ$) between the traits or principal component axis and trait shows the positive association between these traits, whereas obtuse angle ($>90^\circ$) shows negative association; whereas right angle ($=90^\circ$) indicates no correlation between the traits (Govindaraj *et al.*, 2020). Most of the traits were in acute angle with the PC1 coordinates except number of productive tillers. The third quadrant did not have any trait plotted in the region. All most all the traits were in acute angle with single plant yield. The lowest acute and adjacent angle with single plant yield were observed for number of productive tillers, dry fodder yield and plant height. Single plant yield showed acute angle with most of the traits indicating positive correlation and exhibited the significance of the trait selection for improvement of yield attributing characters mainly like number of productive tillers, dry fodder yield plant height, 1000-seed weight *etc.* which were highly correlated (Kalagare *et al.*, 2021; Narasimhulu *et al.*, 2022).

Association Analysis

In the present study, a correlation matrix was used to determine the interdependence of several variables and their association with grain yield in pearl millet. The results showed that a number of traits, including effective tillers per plant (0.52***), dry fodder yield (0.51***), plant height (0.32*) and flag leaf area (0.30*), 1000-grain weight (0.25*), and panicle girth (0.25*), had a significant positive association with grain yield. This finding is in agreement with previous studies by Manga (2002), Annamalai *et al.*, (2020) and Narasimhulu *et al.*, (2021a, 2022), which also found a favorable connection between grain yield and these traits.

Days to 50% flowering exhibited a significant and positive relationship (0.87***) with days to maturity, which is consistent with the results of Narasimhulu *et al.*, (2022). Additionally, flowering/maturity and productive tillers per plant were negatively correlated (-0.39** and -0.50***, respectively) with each other, while flowering/maturity and panicle girth showed a positive significant correlation. These findings

are in agreement with the results of Rasitha *et al.*, (2019) and Narasimhulu *et al.*, (2021a).

The length of the panicle was found to be proportionate to the plant's height, days to maturity, and leaf area. These findings agree with the results of Narasimhulu *et al.*, (2021b). Overall, the breeding material in this study was found to have higher number of productive tillers in the medium-maturing type, indicating potential for developing trait-specific parental lines for future breeding programs.

Hence, the correlation matrix analysis conducted in this study identified several traits that were positively associated with grain yield in pearl millet. The findings of this study are consistent with previous research and provide valuable insights for developing trait-specific parental lines for future breeding programs.

Conclusions

The aim of this study was to identify potential parental lines for improving the heterotic expression and to establish the relationships between yield attributing traits in order to provide better selection criteria for enhancing the yield of pearl millet. The results of this investigation indicate a wide range of genetic variation among the parental lines. Based on *per se* performance, character association and cluster analysis, we suggest that the parental lines J-2591, PPMI-1267, RIB-109-120-S/19, RIB 3135-18, ICMB 95222, ICMB 94555, ICMB 04999, ICMB 93333 and ICMB 97111 may be utilized in the crossover programme to obtain better heterosis. Additionally, the traits biological yield, plant height and the number of productive tillers should be given high priority in the selection process to achieve higher yield. The results suggest that the identified parental lines and selected traits can be used in future breeding programs to develop superior pearl millet varieties with higher yields.

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