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Multivariate assessment of genetic variability in Mundu chilli (*Capsicum annuum* L.) accessions for yield and quality traits

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Abstract

Mundu chilli (*Capsicum annuum* L.) is an important rainfed spice cum vegetable crop cultivated in the coastal regions of Tamil Nadu, valued for its yield stability and quality attributes. The present study evaluated 27 purified Mundu chilli genotypes collected from Ramanathapuram district to assess variability for yield and quality traits using multivariate approaches. The experiment was conducted over three consecutive years (2022–25) in a randomized block design (RBD) with 3 replications. Significant variation was observed among genotypes for growth, phenological, yield and quality parameters. Among the accessions, CP7 (507.91 g), S6 (403.75 g) and CR8 (330.36 g) recorded superior yield performance, with CP7 producing the highest fruit yield per plant. Quality analysis revealed appreciable differences for dry matter, ascorbic acid, oleoresin, capsaicin and proline contents, with CP7 excelling in oleoresin, capsaicin and proline contents. Principal component analysis (PCA) revealed that the first four principal components accounted for 81.80 % of the total variability, with yield per plant and number of fruits per plant contributing most to genetic divergence. Correlation and biplot analyse highlighted number of fruits per plant, yield per plant, fruit weight and earliness traits as key selection criteria. The identified superior genotypes can be effectively utilised for varietal improvement and breeding programmes in Mundu chilli.

Keywords: *Capsicum annuum*; genetic variability; Mundu chilli; principal component analysis; quality parameters; yield traits

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1. Introduction

Chilli (*Capsicum annuum* L.) is a member of the family Solanaceae and is a diploid species with a chromosome number of 2n = 2x = 24. It is the second most important solanaceous vegetable crop after tomato and India is the world's leading producer, consumer and exporter, with green chilli cultivated over 411 thousand hectares producing 4363 thousand metric tons and dry chilli grown in 702 thousand hectares with a production of 2049 thousand metric tons (1). Chilli has its evolutionary roots in the tropical regions of Central and South America. Historical evidence suggests that the earliest domestication took place in Mexico, which is regarded as the primary centre of origin, while Guatemala is recognised as an important secondary centre of diversity (2).

Contemporary taxonomic classification identifies five principal cultivated species of *Capsicum*, among which *C. annuum* is the most widely grown and it is particularly well adapted to hot and humid climatic conditions. (3). The crop is widely grown in tropical and subtropical regions, with an optimal temperature requirement ranging from 20–30 °C and it can also be successfully cultivated under rainfed conditions (4).

Ramnad Mundu chilli is a locally adapted round to oblong chilli type cultivated predominantly under rainfed conditions for spice production in Tamil Nadu, India (5). It is mainly grown in the coastal saline tracts of Ramanathapuram, Virudhunagar and Thoothukudi districts, characterised by alkaline soils (pH 7.5–9.0) and low annual rainfall. The variety possesses a thick pericarp, moderate pungency, high oleoresin content (0.26–0.38 %) and desirable colour value, making it highly preferred by farmers and consumers as a superior alternative to samba chilli.

Capsaicin and capsanthin are key chemical constituents of chilli with high commercial value. Capsanthin and related carotenoids impart the red colour, while capsaicin and dihydrocapsaicin determine pungency. Capsaicin, concentrated mainly in the placenta, also possesses antioxidant, anticancer, analgesic and anti-arthritic properties and is widely used in medicinal, food and beverage industries (6).

Exploitation of heterosis in crop improvement requires the evaluation of germplasm to assess genetic variability and divergence, which is essential for selecting superior parents and achieving effective hybridisation and transgressive segregation (7). Multivariate analyses such as principal component analysis (PCA) and correlation analysis are useful tools for identifying important yield-contributing traits, understanding the extent of genetic variability and determining the relationships among characters for effective selection in chilli breeding programmes. Therefore, the present study was undertaken to evaluate the extent of variability among 27 Mundu chilli (*C. annuum*) genotypes collected from different locations of Ramanathapuram district, Tamil Nadu, with the objective of identifying promising genotypes suitable for cultivation under both irrigated and rainfed chilli-growing environments.

2. Materials and Methods

The present investigation was carried out at the Department of Vegetable Science, Horticultural College and Research Institute (HC&RI), Tamil Nadu Agricultural University (TNAU), Coimbatore, India, during three consecutive seasons from 2022–25. The observations recorded during three consecutive years were pooled and subjected to statistical analysis to obtain the mean performance of the genotypes across seasons. The experimental site represents a tropical agro-climatic condition, which is suitable for chilli cultivation under both irrigated and rainfed situations.

A total of 45 Mundu chilli (*C. annuum*) genotypes were collected from major chilli-growing tracts of Ramanathapuram district, Tamil Nadu, based on farmer preference, local adaptability and variability in fruit and yield traits. Owing to the presence of considerable intra-genotypic variability, purification of the collected germplasm was undertaken using the single seed descent method from selfed populations. The purification programme was continued for three seasons, during which genotypes exhibiting poor yield potential and undesirable quality traits were eliminated based on their performance in the preceding seasons. At the end of the purification process, 27 stable and uniform genotypes were selected and advanced for detailed evaluation.

The purified 27 genotypes were evaluated in field trials for three consecutive seasons (2022–25). The experiment was laid out in a randomized block design (RBD) with 3 replications in each season. The experimental plot possessed sandy loam soil and seedlings were planted in a spacing of 60 × 45 cm and uniform plant population was maintained in each plot (3 × 3 m). A recommended fertiliser dose of 120 : 60 : 30 kg NPK ha^{-1} along with furrow irrigation and standard crop management practices was uniformly followed as per TNAU recommendations for chilli cultivation.

Mean performance of the genotypes was recorded for nine morphological traits (plant height, number of branches per plant, days to flowering, days to fruiting, fruit length, fruit girth, fruit weight, number of fruits per plant and yield per plant) and five quality parameters. Quality parameters including dry matter, ascorbic acid, oleoresin, capsaicin and proline content were analysed using standard Association of Official Analytical Chemists (AOAC) procedures (7). Further, to derive the pooled mean, assess the extent of variability and to identify the traits contributing most to total variation among genotypes, PCA and correlation analysis were carried out using standardised mean values of yield and quality traits with the R based GRAPES platform developed by the Department of Agricultural Statistics, Vellayani (8, 9).

3. Results and Discussion

Mean performance of Mundu chilli accessions

The pooled mean performance of 27 Mundu chilli accessions evaluated over three years (2022–25) revealed significant variation for growth, flowering, fruiting, yield and quality traits, indicating the presence of considerable phenotypic variability among the accessions (Table 1). The low values of coefficient of variation (CV %) for all the traits studied (ranging from 1.14–1.81 %) indicated high experimental precision and reliability of the recorded data. The availability of significant critical difference (CD) values at both 5 % and 1 % levels further confirmed the presence of real differences among the accessions.

Morphological traits of superior Mundu chilli accessions

Plant height varied widely among the accessions, ranging from 26.67 cm (CS 9) to 73.01 cm (S7). The accession S7 (73.01 cm) recorded the tallest plants, followed by CP5 (68.85 cm) and CR8 (64.52 cm), suggesting better vegetative vigour. Number of branches per plant ranged from 5.49 (CS 8) to 10.34 (CP4), with CP4 (10.34), CR2 (10.28) and S1 (10.09) recording higher branching, which is a desirable trait for enhanced fruit bearing. Significant results were previously reported (10).

Earliness is an important attribute in chilli cultivation. Days to flowering ranged from 52.51 days (S2) to 60.91 days (CP2). The accession S2 was the earliest to flower, followed by CP7 (53.46 days) and CS 7 (53.75 days). Similarly, days to fruiting varied from 61.23 days (S2) to 69.20 days (S1), indicating considerable diversity for earliness among the accessions. Similar observations for earliness in chilli were previously reported (11).

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Table 1. Pooled mean performance of Mundu chilli genotypes for three years (2022–25)

Sl. No	Acc. No	Plant height (cm)	No of branches	Days to flowering	Days to fruiting	Fruit length (cm)	Fruit girth (cm)	Fruit weight (g)	No.of fruits/ plant	Yield/ plant (g)
1.	CS 2	63.69	8.31	57.84	63.87	3.59	9.32	3.93	63.58	248.24
2.	CS6	59.49	8.27	58.94	65.38	3.13	7.91	3.73	58.34	112.17
3.	CS 7	47.96	7.14	53.75	62.34	3.36	8.30	3.29	63.78	203.11
4.	CS 8	56.66	5.49	56.73	64.10	3.45	9.52	4.15	61.12	251.56
5.	CS 9	26.67	6.34	58.30	64.80	2.96	8.93	3.29	57.16	186.84
6.	CP 2	34.07	7.26	60.91	67.77	3.18	6.19	4.89	55.20	264.72
7.	CP3	56.42	9.10	60.57	67.19	3.57	9.52	4.62	63.32	273.45
8.	CP4	53.76	10.34	59.24	66.79	3.21	6.29	4.53	46.06	198.35
9.	CP5	68.85	7.56	57.68	65.34	3.47	8.46	4.21	45.18	187.15
10.	CP7	57.73	9.41	53.46	64.02	3.75	7.76	4.54	110.46	507.91
11.	CP9	65.90	7.35	56.11	65.36	3.20	5.89	3.65	54.88	203.70
12.	CR1	45.31	7.65	57.01	64.34	3.69	9.27	3.01	77.81	217.21
13.	CR2	51.65	10.28	58.06	66.46	3.99	9.32	1.62	51.96	82.34
14.	CR4	55.35	7.26	59.37	64.87	3.49	9.97	2.77	76.19	209.87
15.	CR5	63.34	6.37	57.61	63.02	3.73	8.70	3.68	72.57	283.26
16.	CR6	48.14	6.52	55.72	62.20	3.18	8.31	3.72	73.47	248.00
17.	CR7	62.12	9.23	54.46	62.94	2.63	8.91	4.58	45.70	152.22
18.	CR8	64.52	8.61	54.78	65.26	4.05	9.55	4.01	81.97	330.36
19.	CR 9	43.46	6.26	58.88	67.40	4.14	9.63	3.42	68.54	196.40
20.	S1	49.66	10.09	60.16	69.20	3.07	6.85	3.65	43.12	153.57
21.	S2	63.33	7.81	52.51	61.23	2.67	6.19	3.57	67.01	161.08
22.	S4	64.21	8.53	55.95	63.45	3.30	7.07	4.26	44.92	192.35
23.	S5	60.84	7.59	56.93	64.75	3.47	7.46	3.60	60.59	197.77
24.	S6	57.45	6.42	55.41	64.60	3.64	6.57	3.82	99.64	403.75
25.	S7	73.01	5.61	55.26	62.69	2.79	7.92	3.50	54.72	145.36
26.	S8	57.98	7.18	56.78	66.03	3.55	7.69	4.24	57.25	198.15
27.	S10	55.76	6.13	58.70	65.95	3.18	7.68	3.60	86.07	236.26
	S.EM	0.58	0.06	0.42	0.68	0.03	0.05	0.04	0.60	1.01
	SE.d	0.82	0.15	0.71	0.90	0.06	0.03	0.02	0.84	2.21
	CV	1.14	1.25	1.30	1.60	1.46	1.28	1.21	1.81	1.54
	CD (5 %)	1.08	0.18	1.32	1.14	0.12	0.46	0.24	1.23	4.32
	CD (1 %)	2.01	0.30	1.71	2.01	0.36	0.49	0.28	2.10	5.10

Fruit length ranged from 2.63 cm (CR7) to 4.14 cm (CR 9), while fruit girth varied between 5.89 cm (CP9) and 9.97 cm (CR4). Higher fruit weight was recorded in CP2 (4.89 g), followed by CP7 (4.54 g) and CR7 (4.58 g), indicating the contribution of fruit size traits towards yield as previously reported (12).

The number of fruits per plant showed wide variation, ranging from 43.12 (S1) to 110.46 (CP7) (Fig. 1). The accession CP7 recorded the maximum number of fruits per plant, followed by S6 (99.64) and CR8 (81.97), reflecting their superior fruiting ability. Fruit yield per plant exhibited marked variability among the accessions, ranging from 82.34 g (CR2) to 507.91 g (CP7). The accession CP7 recorded the highest yield per plant (507.91 g), which could be attributed to its early flowering, higher fruit number and better fruit weight. This was followed by S6 (403.75 g) and CR8 (330.36 g), indicating their consistent yield potential. The presence of significant differences among accessions for yield suggests ample scope for selection of superior genotypes. The results corroborated the previous findings (13).

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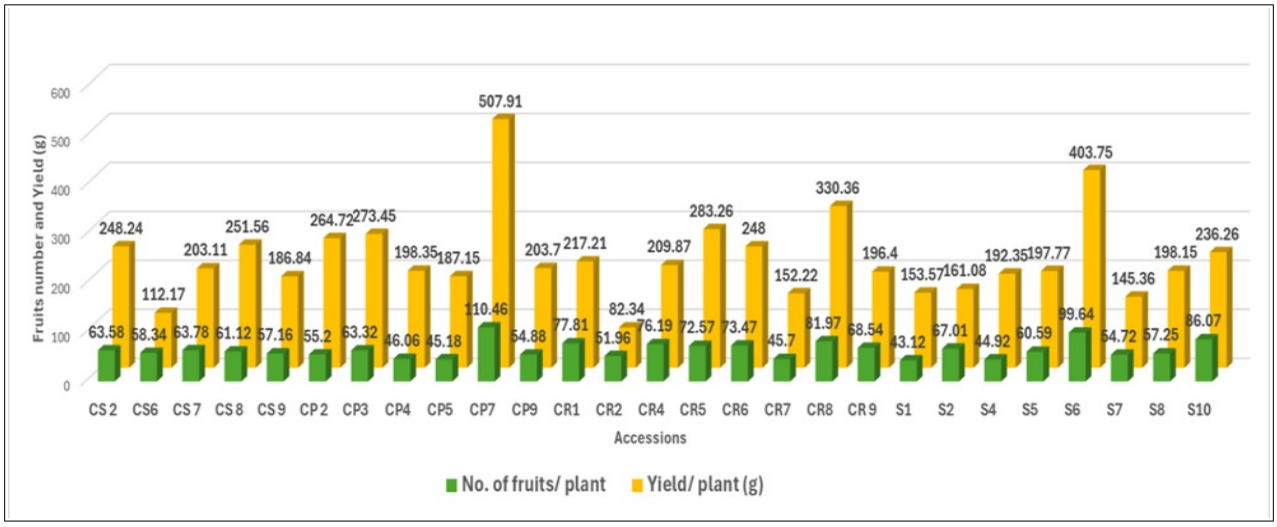


Fig. 1. Mean performance of Mundu chilli accessions for number of fruits and fruit yield.

Based on pooled mean performance, the accessions CP7, S6 and CR8 emerged as promising genotypes owing to their superior yield and favourable yield-contributing traits. These accessions can be effectively utilised for direct cultivation and as potential parental lines in future breeding programmes aimed at improving yield and quality in Mundu chilli.

Quality parameters of superior Mundu chilli accessions

The quality attributes of the three best-performing Mundu chilli accessions, CP7, CR8 and S6, were evaluated in both green and dry chilli forms and the results revealed appreciable variation among the genotypes for all the quality traits studied (Table 2).

Dry matter content in green chilli ranged from 14.12 % (CR8) to 15.26 % (CP7), while in dry chilli it varied from 83.41 % (CP7) to 87.33 % (S6). The genotype S6 recorded the highest dry matter content in dry chilli, indicating its suitability for dry chilli production and processing, as higher dry matter is generally associated with better drying efficiency and storage quality.

Ascorbic acid content was considerably higher in green chilli than in dry chilli across all genotypes. In green chilli, the highest ascorbic acid content was recorded in CP7 (165.92 mg/100 g), followed by CR8 (163.36 mg/100 g), whereas S6 recorded comparatively lower values (129.67 mg/100 g). In dry chilli, CR8 (91.47 mg/100 g) and S6 (87.33 mg/100 g) retained higher ascorbic acid content compared to CP7 (64.17 mg/100 g), suggesting better retention of vitamin C during drying in these genotypes. Similar findings for ascorbic acid and dry matter content were also previously reported (14).

In green chilli, oleoresin content ranged from 13.18 % (CR8) to 13.92 % (CP7), while in dry chilli, it ranged from 15.93 % (CR8) to 16.87 % (CP7). The consistently higher oleoresin content observed in CP7 indicates its potential suitability for oleoresin extraction and value-added processing as found in early results (15).

Capsaicin content, which determines pungency, showed noticeable variation among the genotypes. In green chilli, capsaicin content ranged from 1.53 mg/g (CR8) to 1.76 mg/g (CP7). In dry chilli, significantly higher capsaicin levels were observed, with CP7 recording the highest value (3.58 mg/g), followed by S6 (3.12 mg/g) and CR8 (2.98 mg/g). The increase in capsaicin content in dry chilli may be attributed to moisture loss and concentration effects during drying. Comparable results for capsaicin content were previously reported (16).

Proline content, often associated with stress tolerance and physiological stability, was higher in dry chilli compared to green chilli. In green chilli, proline content ranged from 306.48 µg/g (S6) to 352.87 µg/g (CP7), while in dry chilli it ranged from 427.18 µg/g (CR8) to 463.26 µg/g (CP7). The higher proline accumulation in CP7 suggests its better adaptability and tolerance to environmental stress conditions (17).

Principal component analysis

Principal component analysis (PCA) was performed to quantify the contribution of individual traits to total variability among the evaluated Mundu chilli genotypes and to identify influential characters for selection. The PCA was used to summarise variation among traits and to identify major components contributing to genetic divergence.

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Table 2. Quality parameters of best performing Mundu chilli genotypes

Genotypes characters	Green chilli			Dry chilli		
	CP7	CR8	S6	CP7	CR8	S6
Dry matter (%)	15.26	14.12	14.78	83.41	84.52	87.33
Ascorbic acid (mg/100 g)	165.92	163.36	129.67	64.17	91.47	87.33
Oleoresin (%)	13.92	13.18	13.46	16.87	15.93	16.46
Capsaicin (mg/g)	1.76	1.53	1.68	3.58	2.98	3.12
Proline (µg/g)	352.87	312.76	306.48	463.26	427.18	437.63

Principal component analysis indicated that the first four principal components (PCs) possessed eigenvalues greater than unity and cumulatively accounted for 81.80 % of the total variability among the Mundu chilli genotypes (Table 3). Among these, PC1 explained the maximum proportion of variation (29.18 %), followed by PC2 (23.16 %), PC3 (17.94 %) and PC4 (11.51 %). The remaining components (PC5 –PC9) individually contributed less than 10 % of the total variance and therefore played a minor role in explaining genetic divergence. This pattern suggests that most of the variability present in the dataset could be effectively captured using the first four PCs, making them important for genotype discrimination and selection. These observations concur with previous results (18).

The scree plot illustrated a sharp decline in eigenvalues from PC1–PC4, followed by a gradual levelling off from PC5 onwards (Fig. 2). This clear inflection point after the fourth PC indicates that the first four components accounted for the major share of total variability among the Mundu chilli genotypes. Subsequent components contributed only marginally to the explained variance, confirming that retention of the first four PCs was sufficient for meaningful interpretation of genetic diversity and trait associations. Traits contributing strongly to the first two PCs were primarily related to yield and fruit attributes, indicating their major role in genotype differentiation.

Percentage contribution of variables to principal components

The PCA trait contribution analysis showed that PC1 was mainly influenced by yield per plant (27.01 %) and number of fruits per plant (26.87 %), indicating the dominance of yield components in overall variability (Table 4). PC2 was largely contributed by fruit length (30.83 %) and days to fruiting (21.71 %), highlighting the role of fruit size and phenological traits. PC3 was strongly associated with fruit girth (33.43 %) and fruit weight (30.93 %), while PC4 was primarily influenced by number of branches (47.66 %) and plant height (37.65 %). These results confirm that yield attributes, fruit size traits and earliness parameters are the major contributors to genetic divergence among Mundu chilli genotypes.

Principal component analysis biplot analysis

The PCA biplot depicted the relationships between Mundu chilli genotypes and the studied traits based on the first two PCs, which together explained a major proportion of the total variability of 52.34 % (Fig. 3). Vectors representing number of fruits per plant and yield per plant were long and closely aligned, indicating a strong positive contribution to yield variation. Genotypes positioned in the direction of these vectors, such as CP7, CR8 and S6, exhibited superior yield performance and were identified as high-yielding types.

The angle between the trait vectors indicated the nature and direction of association among the studied characters. Yield per plant and number of fruits per plant contributed predominantly to the variability observed among genotypes such as CR8, CP7 and S6. In contrast, traits including days to flowering, days to fruiting, fruit length, fruit girth and number of branches per plant contributed considerably to the divergence among genotypes CR2, CR9 and CP3. Genotypes S1, CR2, CR9, CR8, CR7 and S2 were located far from the origin in the biplot, indicating greater contribution towards overall genetic variability in relation to their respective PCs. Similar findings were obtained in previous reports (19).

Table 3. Eigenvalues and per cent contribution of variables towards principal components

Principle components	Eigenvalue	Percentage of variance	Cumulative percentage of variance
PC1	2.627	29.184	29.184
PC2	2.084	23.158	52.342
PC3	1.615	17.944	70.287
PC4	1.036	11.51	81.797
PC5	0.722	8.018	89.815
PC6	0.555	6.163	95.978

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PC7	0.239	2.651	98.629
PC8	0.11	1.218	99.847
PC9	0.014	0.153	100

Table 4. Trait contribution to divergence in principal components

Variables	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Plant height (cm)	6.584	6.787	0.173	37.647	23.979	19.203	5.537	0.051
No. of branches	0.595	2.547	13.581	47.663	18.925	14.231	0.04	2.36
Days to flowering	21.835	11.349	1.953	1.13	8.811	1.359	13.084	40.474
Days to fruiting	10.682	21.709	10.583	0.013	0.317	6.679	1.396	48.559
Fruit length (cm)	1.423	30.826	7.555	4.416	1.032	6.269	44.72	3.064
Fruit girth (cm)	0.23	6.152	33.432	3.559	11.629	32.847	7.416	4.695
Fruit weight (g)	4.775	0.003	30.934	2.279	31.575	18.602	8.294	0.013
No. of fruits per plant	26.868	9.754	0.005	1.66	3.533	0.764	16.026	0.083
Yield per plant (g)	27.009	10.872	1.785	1.634	0.2	0.045	3.488	0.701

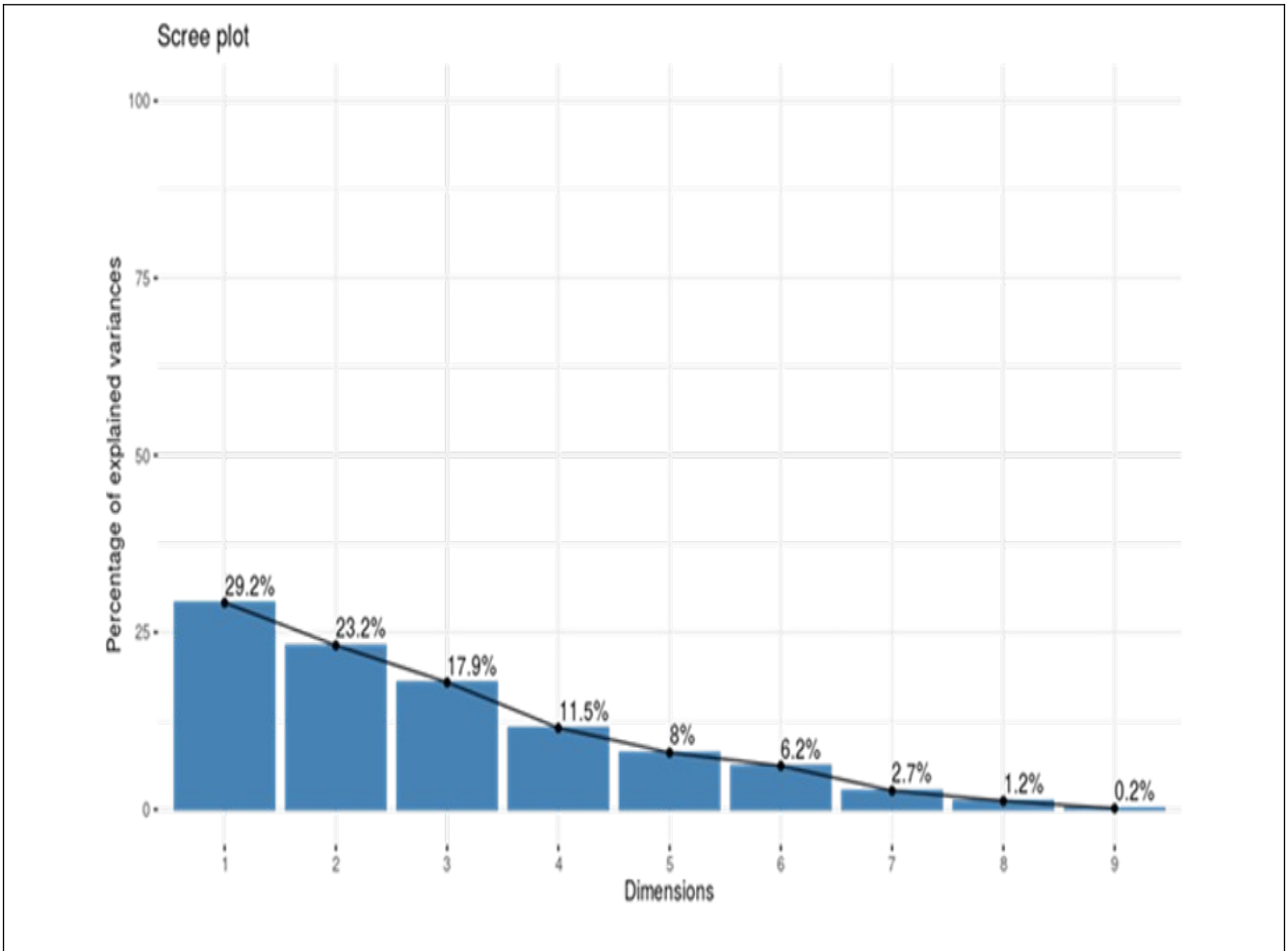


Fig. 2. Scree plot illustrating the contribution of different principal components to total divergence.

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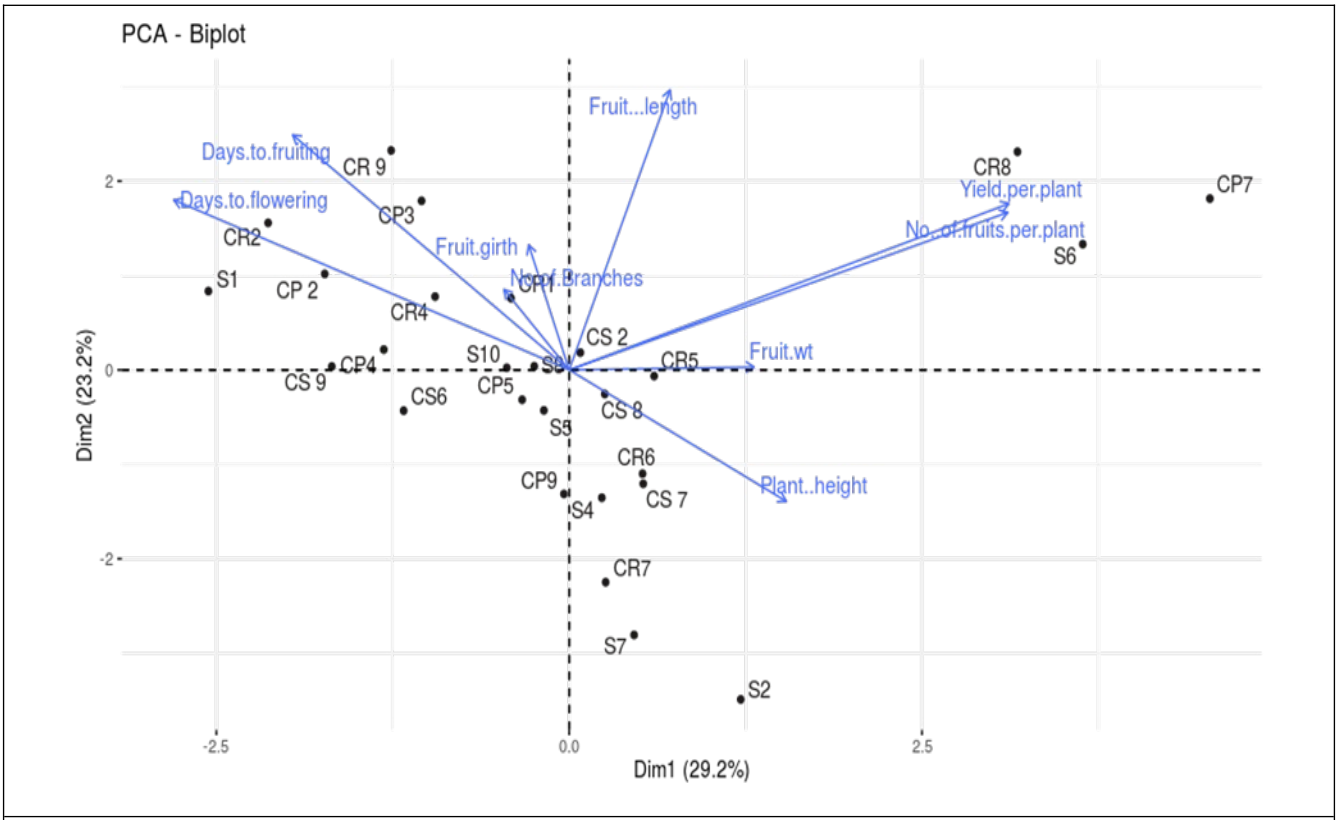


Fig. 3. Biplot depicting the relationship between PC1 and PC2.

The angle formed between the trait vectors signifies the direction of association between the traits. It reflected that yield per plant and number of fruits per plant mostly contributed towards variability among genotypes viz.,CR 8, CP 7 and S6. On the other hand, traits such as days to flowering, days to fruiting, fruit length, fruit girth and number of branches per plant contributed significantly to the variability among genotypes CR 2, CR 9 and CP3. The genotypes S1, CR 2, CR 9, CR8, CR7and S2 were positioned farthest from the origin in the biplot, signifying that they accounted for more trait variability associated with their respective principal components compared to other genotypes.

Overall, the biplot clearly differentiated genotypes based on yield, fruit traits and phenological characteristics, highlighting CP7, CR8 and S6 as promising genotypes combining high yield with desirable traits. These genotypes can be effectively utilised in selection and improvement programmes for Mundu chilli.

Correlation analysis

The heat map analysis provided an integrative visual representation of the relationships and associations among the studied traits (Fig. 4). The correlation matrix revealed clear associations among yield and its component traits in Mundu chilli. Yield per plant exhibited a very strong positive correlation with number of fruits per plant (r = 0.96), indicating that fruit number was the primary determinant of yield. Yield also showed moderate positive associations with fruit length (r = 0.42) and fruit weight (r = 0.41), suggesting that improvement in fruit size traits could further enhance productivity.

Days to flowering and days to fruiting were strongly and positively correlated (r = 0.79), reflecting synchronised phenological development among genotypes. Both traits showed moderate negative correlations with yield per plant (r = –0.35 and –0.06, respectively) and number of fruits per plant (r = –0.40 and –0.13), indicating that early flowering and fruiting genotypes tend to be more productive. Plant height and number of branches exhibited weak correlations with yield, implying a limited direct role in yield improvement.

Overall, the correlation analysis emphasised number of fruits per plant as the most influential trait governing yield, while earliness and fruit size traits also contributed positively. These characters can therefore be effectively utilised as key selection criteria in breeding programmes aimed at improving yield in Mundu chilli. These outcomes are consistent with the early findings (20).

Correlation between variables and principal components

The PCA correlation plot illustrated the relationships between traits and the first two PCs, which together accounted for a large proportion of the total variability among Mundu chilli genotypes (Fig. 5). The colour gradient represents both the magnitude and direction of associations among traits, with blue shades indicating strong positive correlations and red shades reflecting negative relationships. PC1 showed strong positive associations with number of fruits per plant

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and yield per plant, suggesting that this component mainly represented yield-related variation.

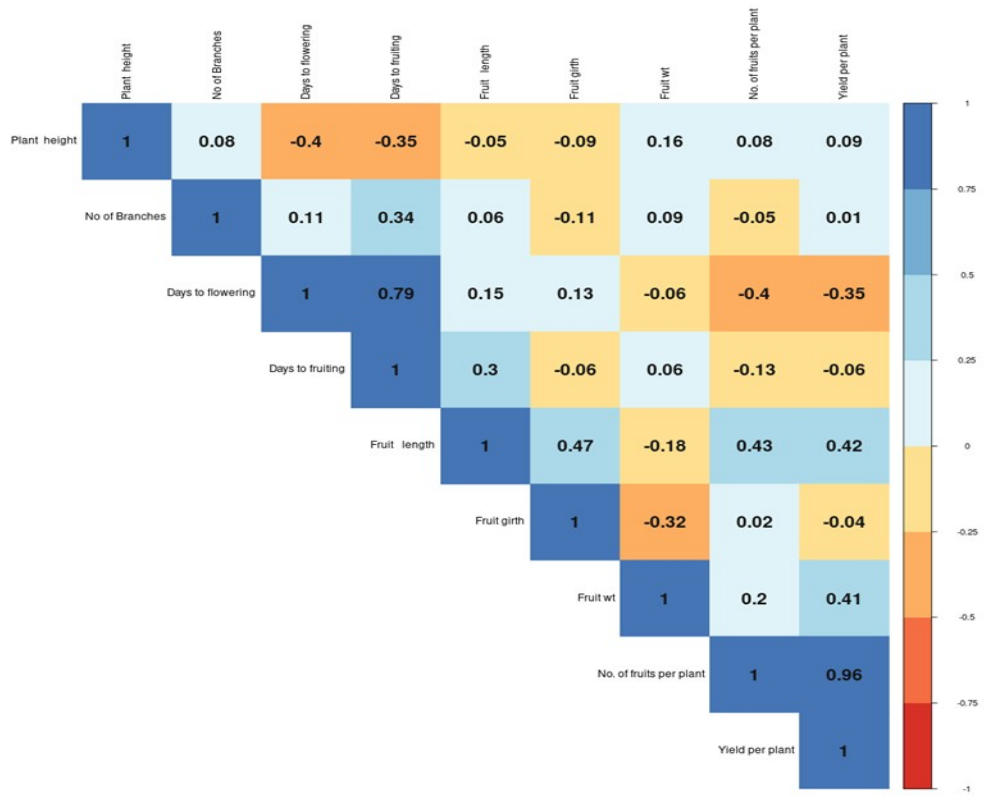


Fig. 4. Visualisation of relationships among traits.

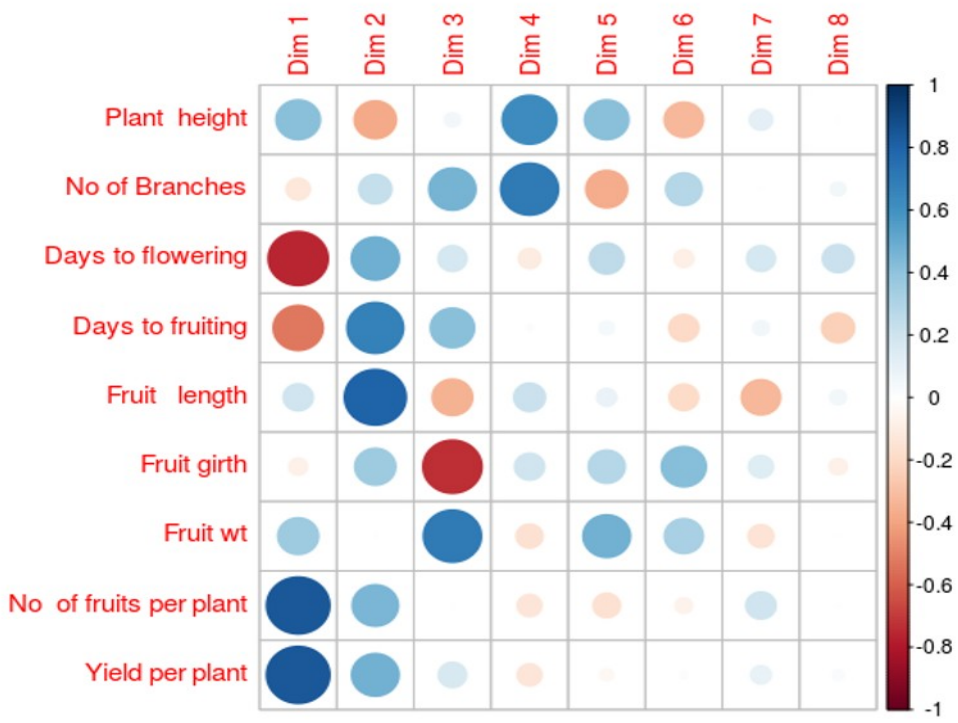


Fig. 5. Correlation plot of variables vs principal components.

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Negative correlations of days to flowering and days to fruiting with PC1 indicated that early maturing genotypes were associated with higher yield.

PC2 was positively correlated with fruit length and fruit weight, reflecting the contribution of fruit size traits to genetic divergence. Other traits such as fruit girth and number of branches contributed to later components, indicating their comparatively minor role in overall variability. Overall, the PCA results highlighted yield components, fruit weight and earliness traits as the major contributors to genetic diversity and important targets for selection in Mundu chilli improvement programmes.

4. Conclusion

The present investigation revealed substantial genetic variability among the evaluated Mundu chilli genotypes for yield and quality attributes. Based on pooled mean performance and multivariate analyses, genotypes CP7, S6 and CR8 emerged as superior, combining high yield potential with desirable quality traits. Principal component analysis (PCA) confirmed that yield per plant, number of fruits per plant, fruit weight and earliness traits were the major contributors to total variability. Correlation and biplot analyses further emphasised the importance of fruit number as the primary determinant of yield. The identified elite genotypes can be recommended for cultivation under irrigated and rainfed conditions and may serve as promising parental lines for future breeding programmes aimed at improving productivity and quality in Mundu chilli. Further studies involving multi-location evaluation, molecular characterisation and screening for biotic and abiotic stress tolerance may facilitate the development of high-yielding and climate-resilient Mundu chilli varieties.

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Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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