



RESEARCH ARTICLE

Discrimination of mango (*Mangifera indica* L.) genotypes through multivariate analysis of physico-chemical characters

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Received: 18 March 2026; Accepted: 23 June 2026; Available online: Version 1.0: 04 August 2026

Cite this article: Indian G, Manivannan S, Manonmani S, Paruthi EM, Sravya KT. Discrimination of mango (*Mangifera indica* L.) genotypes through multivariate analysis of physico-chemical characters. Plant Science Today. 2026; 13(sp5): 1-11. <https://doi.org/10.14719/pst.14589>

Abstract

Mango (*Mangifera indica* L.), the “king of fruits” native to India, exhibits wide variation in physical, chemical and nutritional properties, enabling trait-based classification and authentication of varieties. This study evaluated 15 mango genotypes from diverse agroecological zones of India based on bearing nature, quality traits and regional origin. Over 2 years, 27 traits were recorded from fully matured fruits and the data were analysed using principal component analysis (PCA) and linear discriminant analysis (LDA). Among the genotypes evaluated, Kalapad recorded the highest total soluble solids (TSS) (25.78°Brix), while Imampasand recorded the highest phenol content (35.25 mg gallic acid equivalents (GAE) / mL), reflecting superior nutritional quality. Principal component analysis indicated substantial variability among genotypes, with total carotenoids, TSS, fat, TSS : acid ratio, fruit weight and pulp weight identified as major contributors to the overall variability, with the major principal components, PC1 and PC2, together explaining 56.8 % of total variance. Linear discriminant analysis showed that Chinnarasam, Kalapad and Ratnagiri Alphonso clustered closely, showing superior quality traits and achieved a cross-validated classification accuracy of 82.22 % ($k = 0.8095$), confirming the strong discriminatory power of physico-chemical characters among 15 mango genotypes. Linear discriminant analysis also clearly distinguished the regular bearer and alternate bearer, such as Neelum, Bengalura and Imampasand, highlighting the influence of bearing habit on genotype differentiation. The overlap between export genotypes Kesar and Dashehari indicated a similar agroecological origin. These findings demonstrate the effectiveness of multivariate analysis in discriminating mango genotypes, aiding germplasm management, genotype authentication and crop improvement strategies.

Keywords: biochemical; linear discriminant analysis; physical; principal component analysis; proximate traits

Introduction

Mango (*Mangifera indica* L.) is one of the major horticultural crops in the Indian sub-continent and is a significant tropical fruit in the international market. India contributes to nearly 50 % of the world's total production and has enormous varietal diversity with diverse regional adaptations (1). The quality of the mango fruits is highly influenced by the genotype and agro-ecological conditions, resulting in significant variations in physical, biochemical and nutritional properties among the cultivars and growing regions (2, 3). The physico-chemical profiling of mango genotypes is a useful approach to describe horticultural variation among them (4) and to link them to one another and their respective growing regions.

Multivariate methods, including principal component analysis (PCA) and linear discriminant analysis (LDA) are increasingly essential for analysing multi-dimensional fruit quality-related datasets to separate the varietal and environmental effects and have been successfully applied in previous studies (5, 6). Principal component analysis facilitates dimensionality reduction and the identification of principal variables that contribute to overall variation, rendering it especially effective for summarising biochemical and morphological diversity in fruit crops (5). The LDA, conversely, optimises inter-group differentiation and has been extensively utilised for the classification of

fruit cultivars and differentiation of quality attributes based on multivariate characteristics (7). In mango, multivariate analysis has effectively distinguished the cultivars based on sugars, organic acids, antioxidants, minerals, volatile profiles and textural parameters, demonstrating its applicability for genetic and varietal differentiation (8).

Accurate identification of cultivars and varietal characters of mango is an essential need to prevent mislabelling and adulteration (9) with the growing demand in domestic and world trade and the emergence of premium, region specific markets. Physico-chemical and proximate parameters represent reliable indicators to classify varieties and are widely recognised as variables which include the effects of genotype, climate, soil and farming methods. This approach is in line with recent studies where multivariate modelling of physical and biochemical properties has proved successful to increase the accuracy of origin verification and varietal discrimination in major fruit crops (10). Most of the previous investigations have included only individual fruit quality parameters or a few cultivars; however, detailed data that cover the physical, biochemical and proximate fruit quality traits is lacking for multivariate discrimination of the Indian mango genotypes. For this purpose, the present study was undertaken to characterise 15 Indian mango genotypes and to point out the major quality features

differing these genotypes by using multivariate techniques like PCA and LDA.

Materials and Methods

Sample collection

The present study was conducted at the Ionomics and Plant Nutrition Laboratory, Department of Horticulture, in the Central University of Tamil Nadu, Thiruvavur, India. The fifteen mango (*M. indica*) genotypes (Table 1) - each considered as a treatment with two biological replicates per replication were collected from various orchards throughout India during the harvesting season based on specific criteria, including different agro-ecological zones, bearing nature and quality characteristics (Table 2). Fruits were harvested when they reached the physiologically mature, firm green stage. After the collection, fruits were sorted very carefully; damaged, diseased, or mechanically injured fruits were removed from the batch. Only uniform and healthy fruits were selected for further analysis. The chosen fruits were cleaned with pure water, air-dried at room temperature and kept under ambient laboratory conditions until ripening.

Sample preparation

The natural ripening of the fruits was followed by manual peeling, separating the pulp from the peel and stone. The pulp was then sterile blended to obtain a homogenate, which was subsequently used for biochemical and proximate analyses. Meanwhile, whole fruits and their components (peel, pulp and stone) were used to record the physical parameters.

Physical parameters

Physical attributes were measured by a digital weighing balance

Table 1. Treatment details

Treatment	Genotypes
T1	Amarapali
T2	Banganapalli
T3	Bengalura
T4	Cherukurasam
T5	Chinnarasam
T6	Dashehari
T7	Gulabkhas
T8	Imampasand
T9	Kalapad
T10	Kesar
T11	Langra
T12	Mulgoa
T13	Neelum
T14	Ratnagiri Alphonso
T15	Suvernarekha

Table 2. Basic information of mango genotypes collected from different regions of India

Sl. No.	Genotypes particulars	Selection criteria	Genotype name	Place of collection	Latitude	Longitude
I	Based on agroecological zones	North	Gulabkhas	Sabour (Bihar)	25°14'16"N	87°3'2"E
		West	Langra	Bareilly (Uttar Pradesh)	28°24'17.15"N	79°25'30.06"E
			Kesar	Valsad (Gujarat)	20°37'48"N	72°55'48"E
		South	Banganapalli, Suvernarekha	Sangareddy (Telangana)	17°37'30"N	78°04'30"E
II	Based on the bearing nature	Regular bearer	Mulgoa, Kalapad	Krishnagiri (Tamil Nadu)	12°31'6.99"N	78°12'49.45"E
		Alternate bearer	Neelum, Bengalura	Krishnagiri (Tamil Nadu)	12°31'6.99"N	78°12'49.45"E
			Imampasand	Kurnool (Andhra Pradesh)	15°49'59.88"N	78°02'60"E
		Export quality	Dashehari	Valsad (Gujarat)	20°37'48"N	72°55'48"E
			Alphonso	Ratnagiri (Maharashtra)	16°59'40"N	73°18'00"E
III	Based on quality characteristics	Sucking mango	Kesar	Valsad (Gujarat)	20°37'48"N	72°55'48"E
			Chinnarasam, Cherukurasam	Sangareddy (Telangana)	17°37'30"N	78°04'30"E
		Dwarf mango	Amarapali	IARI, New Delhi	28°38'23"N	77°09'27"E
		Self-Incompatible	Langra	Bareilly (Uttar Pradesh)	28°24'17.15"N	79°25'30.06"E
			Dashehari	Valsad (Gujarat)	20°37'48"N	72°55'48"E

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(BR BIOCHEM Life Sciences: BR 1002, India), measuring scale and Vernier calliper. The measurements comprised fruit characteristics (fruit weight, fruit length, fruit width and fruit volume), stone characteristics (stone weight, stone length and stone width), pulp and peel characteristics (pulp weight, peel weight and peel thickness) and specific gravity. The parameters like pulp percentage, peel percentage and stone percentage were derived from the recorded weights. The specific gravity of fruits was determined as the ratio of fruit weight to fruit volume, measured using the water displacement method.

Biochemical parameters

Biochemical attributes of mango fruits were estimated on fully ripened composite pulp samples and values were expressed on a fresh weight basis. Total soluble solids (TSS) were measured with a digital refractometer (Milwaukee: MA871, Romania) at 32 °C and the results were expressed as °Brix. Titratable acidity was estimated by titrating homogenised pulp extract (5–10 g pulp diluted to 100 mL with distilled water) against standardised 0.1 N sodium hydroxide (NaOH) using phenolphthalein as an indicator. Results were expressed as a percentage of citric acid equivalents (11, 12). Ascorbic acid content was determined using the 2,6-dichlorophenol indophenol (DCPI) titration method (13). The concentration of vitamin C / ascorbic acid was computed and expressed as mg 100 g⁻¹ sample. Total carotenoids were measured by first extracting the sample with acetone and then partitioning it into petroleum ether. A ultraviolet-visible (UV-Vis) spectrophotometer (Thermo Scientific: GENESYS 180, USA) was used to measure absorbance at a wavelength of 452 nm. The carotenoid content was determined using a standard extinction coefficient and then reported as mg of β-carotene equivalents per 100 g of pulp (12, 14). Total phenolic content of mango extract was determined using the Folin-Ciocalteu colorimetric method and expressed as milligrams of gallic acid equivalents (GAE) per mL (15, 16). Total phenolic content was calculated from the standard curve. The total flavonoid content of mango extract was measured using the aluminium chloride colorimetric method and it was expressed as milligrams of quercetin equivalents (QE) per mL of sample (17, 18).

Proximate analysis

The study of the proximate composition of fruits was carried out (19). Kjeldahl (Foss Analytical: 60095944, Denmark) method was used to determine nitrogen (N) content and then protein content was derived by multiplying by the N conversion factor (6.25). Moisture content was assessed by drying 5 g of pulp sample in a hot air oven (Precision Scientific Instruments: PHOS-600X600, India) at a temperature of 100 ± 2 °C until obtaining a constant

weight. Crude fat was determined through extraction with petroleum ether in a Soxhlet apparatus (Tulin Equipments: Sox 6, India). Crude fibre was evaluated using defatted fruit samples with a fibre extractor (Tulin Equipments: FRB 6, India). The ash content was determined by burning the sample in a muffle furnace (Khosla Scientific Instruments: KSI MF 0076, India) at $550 \pm 5^\circ\text{C}$ for 5–6 hr (20). Total carbohydrate contents were calculated using the following equation (21):

$$\% \text{ Carbohydrate} = 100 - (\% \text{ moisture content} + \% \text{ crude protein} + \% \text{ ash} + \% \text{ crude fat} + \% \text{ crude fibre})$$

Statistical analysis

The experiment was performed using a completely randomised design (CRD) with three replications for every genotype (treatments). All statistical analysis were performed using Agri analyse online tool and R software version 4.5.2 (2026.04.0+526) with appropriate packages (for LDA-MASS, ggplot2, ggrepel, ellipse, ggalt, ggforce and for PCA-readxl, FactoMineR, factoextra, ggplot2, grid) for DMRT test at $p \leq 0.05$ and multivariate data analysis, respectively. For test / validation, classification accuracy was used as an indicator of the discriminatory power of the linear discriminant functions, by means of resubstitution and leave-one-out cross-validation (LOOCV). A confusion matrix was constructed to check for predicted group membership against actual membership for the 15 treatments. A summary of the overall classification accuracy and Kappa (k) statistic was achieved using the package “caret” in R (22) to provide the strength of the discriminant model.

Results

Physical traits

There were significant differences between mango genotypes for all the physical traits measured in the 2 years of this study (Tables 3 and 4). The

fruit weight ranged from 141.66 g in Amrapali to 622.62 g in Banganapalli which was much more than the others, followed by Imampasand. The volume of fruit was also of a similar trend with higher value in Banganapalli and Imampasand. Bengalura had the longest fruit length and Banganapalli had the wider fruit among the different genotypes. Specific gravity had rather small variation between different genotypes, ranging from 0.99 for Suvermarekha to 1.09 for Amrapali. There was a significant genotype difference in pulp weight with a maximum of 395.73 g for Imampasand, whereas on the other hand maximum pulp recovery was recorded for Bengalura with 67.13 %. Significant differences appeared in the characteristics of the peel and stone. The maximum peel weight was found in Banganapalli, 139.78 g. On the other hand, the peel weight and stone weight were low for Amrapali compared to Mulgoa, which had its stone weight as 74.28 g and peel thickness as 2.96 mm. In general, Banganapalli, Imampasand and Mulgoa proved to be superior in various fruit biomass and pulp characters of the mango germplasm used in the study.

Biochemical traits

The mango genotypes varied significantly for all the biochemical attributes measured (Table 5). Total soluble solids values varied significantly from 11.85 °Brix (Gulabkhas) to 25.78 °Brix (Kalapad), whereas titratable acidity ranged from 0.26 % in Banganapalli to 0.66 % in Chinnarasam. Kalapad and Imampasand showed the highest TSS : acid ratio of 83.16 and 73.15 respectively, which meant it has a better sweetness perception and flavour balance. The ascorbic acid content ranged from 40.96 mg / 100 g in Neelum to 96.73 mg / 100 g in Kalapad with wide differences among the genotypes. The total carotenoid content was also significantly varied from 1.03 mg / 100 g in Banganapalli to 8.59 mg / 100 g in Kalapad. Significantly the lowest amount of total phenolic compounds was observed in Suvermarekha (14.82 mg GAE / mL) and the highest in Imampasand (35.25 mg GAE / mL), whereas the minimum and maximum amount of flavonoids were found in

Table 3. Physical parameters of mango genotypes (Mean $\pm$ SD)

Treatment	FW (g)	FL (cm)	FWD (cm)	FV (cc)	SG	PLP. W (g)	PL. W (g)
T1	141.66 $\pm$ 7.37 ⁱ	9.47 $\pm$ 0.08 ^{fg}	4.91 $\pm$ 0.09 ^h	130.00 $\pm$ 7.60 ⁱ	1.09 $\pm$ 0.02 ^{ab}	79.47 $\pm$ 3.02 ^h	27.09 $\pm$ 2.11 ^h
T2	622.62 $\pm$ 52.92 ^a	13.88 $\pm$ 0.13 ^b	10.19 $\pm$ 0.59 ^a	598.33 $\pm$ 16.07 ^a	1.04 $\pm$ 0.08 ^{bcd}	373.14 $\pm$ 29.24 ^a	139.78 $\pm$ 7.75 ^a
T3	447.29 $\pm$ 34.21 ^c	14.72 $\pm$ 0.89 ^a	8.33 $\pm$ 0.38 ^c	435.00 $\pm$ 31.22 ^c	1.03 $\pm$ 0.01 ^{bcd}	299.51 $\pm$ 26.42 ^c	88.48 $\pm$ 1.56 ^c
T4	287.21 $\pm$ 24.41 ^{ef}	11.28 $\pm$ 0.76 ^{de}	6.91 $\pm$ 0.36 ^{de}	274.17 $\pm$ 15.83 ^{de}	1.05 $\pm$ 0.03 ^{abcd}	164.21 $\pm$ 11.44 ^e	52.74 $\pm$ 3.22 ^{ef}
T5	285.74 $\pm$ 25.66 ^{ef}	11.67 $\pm$ 0.53 ^d	7.11 $\pm$ 0.53 ^d	280.00 $\pm$ 20 ^{de}	1.02 $\pm$ 0.02 ^{cd}	145.06 $\pm$ 6.58 ^{efg}	44.91 $\pm$ 3.41 ^{fg}
T6	331.89 $\pm$ 42.17 ^d	12.80 $\pm$ 0.43 ^c	5.91 $\pm$ 0.44 ^{fg}	309.17 $\pm$ 41.41 ^d	1.07 $\pm$ 0.04 ^{abc}	208.86 $\pm$ 21.35 ^d	62.66 $\pm$ 10.56 ^d
T7	195.13 $\pm$ 8.99 ^h	8.78 $\pm$ 0.58 ^{gh}	5.52 $\pm$ 0.74 ^g	190.00 $\pm$ 8.66 ^{gh}	1.03 $\pm$ 0.01 ^{bcd}	111.91 $\pm$ 6.93 ^g	44.67 $\pm$ 2.28 ^g
T8	593.26 $\pm$ 41.85 ^{ab}	12.82 $\pm$ 0.12 ^c	9.83 $\pm$ 0.18 ^a	580.00 $\pm$ 26.46 ^a	1.02 $\pm$ 0.03 ^{bcd}	395.73 $\pm$ 17.30 ^a	96.23 $\pm$ 6.34 ^c
T9	240.19 $\pm$ 6.91 ^g	8.82 $\pm$ 0.45 ^{gh}	7.18 $\pm$ 0.16 ^d	226.67 $\pm$ 7.22 ^f	1.06 $\pm$ 0.01 ^{abcd}	151.18 $\pm$ 6.35 ^{ef}	43.59 $\pm$ 1.91 ^g
T10	318.03 $\pm$ 5.55 ^{de}	10.69 $\pm$ 0.09 ^e	5.83 $\pm$ 0.07 ^{fg}	296.67 $\pm$ 5.77 ^d	1.12 $\pm$ 0.09 ^a	211.51 $\pm$ 6.67 ^d	44.20 $\pm$ 2.28 ^g
T11	222.79 $\pm$ 10.52 ^{gh}	9.07 $\pm$ 0.05 ^{gh}	6.73 $\pm$ 0.21 ^{de}	218.75 $\pm$ 14.42 ^{fg}	1.02 $\pm$ 0.03 ^{bcd}	146.97 $\pm$ 10.75 ^{ef}	32.44 $\pm$ 4.11 ^h
T12	552.64 $\pm$ 8.61 ^b	11.38 $\pm$ 0.23 ^{de}	9.18 $\pm$ 0.24 ^b	534.17 $\pm$ 12.83 ^b	1.04 $\pm$ 0.01 ^{bcd}	335.27 $\pm$ 45.01 ^b	125.19 $\pm$ 5.95 ^b
T13	259.80 $\pm$ 15.45 ^{fg}	9.54 $\pm$ 0.23 ^{fg}	7.25 $\pm$ 0.28 ^d	248.33 $\pm$ 23.20 ^{ef}	1.05 $\pm$ 0.05 ^{abcd}	155.36 $\pm$ 12.94 ^e	56.27 $\pm$ 1.15 ^{de}
T14	184.80 $\pm$ 4.83 ^h	8.32 $\pm$ 0.30 ^h	6.39 $\pm$ 0.16 ^{ef}	179.17 $\pm$ 5.05 ^h	1.03 $\pm$ 0.02 ^{bcd}	117.77 $\pm$ 5.96 ^{fg}	28.65 $\pm$ 1.29 ^h
T15	242.88 $\pm$ 9.56 ^{fg}	9.83 $\pm$ 0.19 ^f	6.86 $\pm$ 0.08 ^{de}	245.83 $\pm$ 17.06 ^{ef}	0.99 $\pm$ 0.03 ^d	141.61 $\pm$ 13.17 ^{efg}	43.04 $\pm$ 2.54 ^g
Mean	328.40	10.87	7.21	316.42	1.04	202.50	62.00
SEd	20.56	0.34	0.29	15.98	0.03	15.12	3.84
CD at 5 %	41.98	0.70	0.60	32.63	0.07	30.87	7.85
CV %	7.67	3.87	4.97	6.18	3.78	9.14	7.59
T1. Amarapali		T6. Dashehari		T11. Langra			
T2. Banganapalli		T7. Gulabkhas		T12. Mulgoa			
T3. Bengalura		T8. Imampasand		T13. Neelum			
T4. Cherukurasam		T9. Kalapad		T14. Ratnagiri alphonso			
T5. Chinnarasam		T10. Kesar		T15. Suvermarekha			

FW: fruit weight; FL: fruit length; FWD: fruit width; FV: fruit volume; SG: specific gravity; PLP. W: pulp weight; PL. W: peel weight; g: gram; cm: centimeter; cc: cubic centimeter. Different letters indicate significance at $p \leq 0.05$ (DMRT).

Table 4. Physical parameters of mango genotypes (mean $\pm$ SD)

Treatments	PT (mm)	SW (g)	SL (cm)	SWD (cm)	PLP %	S %	PL %
T1	1.44 $\pm$ 0.04 ^{ef}	28.11 $\pm$ 1.58 ^g	8.55 $\pm$ 0.20 ^e	3.85 $\pm$ 0.17 ^{de}	56.39 $\pm$ 1.16 ^e	19.75 $\pm$ 0.15 ^{bc}	19.07 $\pm$ 0.57 ^{bc}
T2	2.45 $\pm$ 0.20 ^b	72.77 $\pm$ 8.28 ^{ab}	11.75 $\pm$ 0.25 ^{ab}	5.53 $\pm$ 0.23 ^a	60.61 $\pm$ 4.85 ^{bcde}	12.09 $\pm$ 2.25 ^{ghi}	22.76 $\pm$ 0.40 ^a
T3	2.24 $\pm$ 0.50 ^{bc}	49.18 $\pm$ 2.36 ^d	12.23 $\pm$ 0.78 ^a	4.73 $\pm$ 0.14 ^b	67.13 $\pm$ 1.06 ^a	11.09 $\pm$ 0.42 ⁱ	19.65 $\pm$ 1.71 ^b
T4	1.28 $\pm$ 0.11 ^{ef}	50.66 $\pm$ 0.43 ^d	9.97 $\pm$ 0.68 ^d	3.86 $\pm$ 0.22 ^{de}	57.42 $\pm$ 2.06 ^{de}	17.80 $\pm$ 1.63 ^{cd}	18.32 $\pm$ 0.50 ^{bc}
T5	1.70 $\pm$ 0.17 ^{def}	62.73 $\pm$ 5.11 ^c	10.65 $\pm$ 0.35 ^c	4.21 $\pm$ 0.22 ^{cd}	51.42 $\pm$ 2.78 ^f	21.73 $\pm$ 1.25 ^a	15.86 $\pm$ 0.28 ^{def}
T6	2.03 $\pm$ 0.17 ^{bcd}	40.81 $\pm$ 5.79 ^e	11.33 $\pm$ 0.38 ^b	3.97 $\pm$ 0.19 ^{de}	62.76 $\pm$ 2.40 ^{abcd}	12.36 $\pm$ 0.78 ^{ghi}	18.95 $\pm$ 1.29 ^{bc}
T7	1.76 $\pm$ 0.02 ^{cde}	35.57 $\pm$ 2.21 ^{ef}	8.02 $\pm$ 0.23 ^{ef}	4.10 $\pm$ 0.10 ^{de}	57.99 $\pm$ 1.36 ^{cde}	17.94 $\pm$ 1.64 ^{cd}	23.71 $\pm$ 1.32 ^a
T8	1.76 $\pm$ 0.30 ^{cde}	67.94 $\pm$ 4.47 ^{bc}	11.25 $\pm$ 0.22 ^{bc}	5.67 $\pm$ 0.73 ^a	66.40 $\pm$ 1.67 ^a	11.77 $\pm$ 1.41 ^{hi}	16.89 $\pm$ 0.71 ^{cde}
T9	2.10 $\pm$ 0.19 ^{bcd}	35.05 $\pm$ 1.69 ^{ef}	7.17 $\pm$ 0.26 ^g	4.58 $\pm$ 0.17 ^{bc}	63.23 $\pm$ 2.55 ^{abc}	14.52 $\pm$ 0.46 ^{ef}	18.06 $\pm$ 1.04 ^{bc}
T10	2.09 $\pm$ 0.16 ^{bcd}	37.20 $\pm$ 1.36 ^{ef}	8.70 $\pm$ 0.16 ^e	3.66 $\pm$ 0.10 ^e	66.42 $\pm$ 2.13 ^a	11.70 $\pm$ 0.39 ^{hi}	13.89 $\pm$ 0.62 ^f
T11	1.23 $\pm$ 0.20 ^f	34.80 $\pm$ 2.38 ^{ef}	7.87 $\pm$ 0.22 ^f	4.31 $\pm$ 0.08 ^{bcd}	64.83 $\pm$ 1.85 ^{ab}	16.36 $\pm$ 0.85 ^{de}	14.30 $\pm$ 1.99 ^f
T12	2.96 $\pm$ 0.72 ^a	74.28 $\pm$ 2.53 ^a	9.47 $\pm$ 0.16 ^d	5.27 $\pm$ 0.25 ^a	60.38 $\pm$ 6.66 ^{bcde}	13.45 $\pm$ 0.56 ^{fg}	22.73 $\pm$ 1.56 ^a
T13	2.28 $\pm$ 0.04 ^b	36.22 $\pm$ 0.62 ^{ef}	8.22 $\pm$ 0.44 ^{ef}	4.65 $\pm$ 0.33 ^{bc}	59.71 $\pm$ 2.07 ^{bcde}	13.99 $\pm$ 0.55 ^{fg}	21.68 $\pm$ 1.65 ^a
T14	1.47 $\pm$ 0.12 ^{ef}	31.99 $\pm$ 1.01 ^{fg}	6.76 $\pm$ 0.35 ^g	4.08 $\pm$ 0.14 ^{de}	63.51 $\pm$ 1.51 ^{abc}	17.52 $\pm$ 0.73 ^d	15.57 $\pm$ 1.04 ^{ef}
T15	1.35 $\pm$ 0.23 ^{ef}	48.69 $\pm$ 3.99 ^d	8.64 $\pm$ 0.32 ^e	3.88 $\pm$ 0.13 ^{de}	58.29 $\pm$ 4.22 ^{cde}	20.06 $\pm$ 1.25 ^{ab}	17.82 $\pm$ 1.68 ^{bcd}
Mean	1.87	47.06	9.37	4.42	61.10	15.48	18.62
SEd	0.23	2.95	0.31	0.22	2.42	0.91	0.99
CD at 5 %	0.46	6.02	0.63	0.44	4.94	1.86	2.03
CV %	14.69	7.67	4.01	5.96	4.85	7.19	6.53
T1. Amarapali			T6. Dashehari			T11. Langra	
T2. Banganapalli			T7. Gulabkhas			T12. Mulgoa	
T3. Bengalura			T8. Imampasand			T13. Neelum	
T4. Cherukurasam			T9. Kalapad			T14. Ratnagiri alphonso	
T5. Chinnarasam			T10. Kesar			T15. Suvernakreha	

PT: peel thickness; SW: stone weight; SL: stone length; SWD: stone width; PLP %: pulp percentage; S %: stone percentage; PL %: peel percentage; mm: milli meter; g: gram; cm: centimeter. Different letters indicate significance at $p \leq 0.05$ (DMRT).

Table 5. Biochemical parameters of mango genotypes (mean $\pm$ SD)

Treatments	TSS (°Brix)	Acidity (%)	TSS : Acid	Ascorbic acid (mg / 100 g)	Total carotenoids (mg / 100 g)	Phenol (mg GAE / mL)	Flavonoids (mg QE / mL)
T1	21.30 $\pm$ 1.07 ^{bc}	0.32 $\pm$ 0.04 ^{de}	66.56 $\pm$ 15.12 ^b	61.90 $\pm$ 1.12 ^{bcd}	8.18 $\pm$ 0.67 ^a	23.66 $\pm$ 1.72 ^c	8.49 $\pm$ 0.32 ^{gh}
T2	13.67 $\pm$ 1.00 ⁱ	0.26 $\pm$ 0.03 ^e	52.58 $\pm$ 10.55 ^c	61.26 $\pm$ 12.96 ^{bcd}	1.03 $\pm$ 0.03 ^g	15.97 $\pm$ 1.10 ^{fg}	5.91 $\pm$ 1.30 ^h
T3	15.65 $\pm$ 1.03 ^h	0.49 $\pm$ 0.10 ^b	32.60 $\pm$ 12.11 ^{de}	55.46 $\pm$ 2.67 ^{cdef}	2.09 $\pm$ 0.58 ^{fg}	16.68 $\pm$ 0.62 ^{fg}	6.43 $\pm$ 1.21 ^{gh}
T4	16.12 $\pm$ 0.81 ^{gh}	0.31 $\pm$ 0.04 ^{de}	52.00 $\pm$ 8.08 ^c	49.21 $\pm$ 5.07 ^{efg}	6.41 $\pm$ 1.43 ^{bc}	17.43 $\pm$ 0.60 ^{efg}	8.37 $\pm$ 2.11 ^{fgh}
T5	16.28 $\pm$ 0.53 ^{gh}	0.66 $\pm$ 0.04 ^a	24.67 $\pm$ 1.63 ^e	63.71 $\pm$ 7.03 ^{bc}	4.00 $\pm$ 0.56 ^{de}	20.79 $\pm$ 1.15 ^d	13.71 $\pm$ 1.41 ^{bc}
T6	19.13 $\pm$ 1.85 ^{de}	0.42 $\pm$ 0.03 ^c	45.55 $\pm$ 5.20 ^{cd}	42.45 $\pm$ 1.50 ^g	5.21 $\pm$ 0.50 ^{cd}	18.40 $\pm$ 0.20 ^{def}	10.14 $\pm$ 2.70 ^{def}
T7	11.85 $\pm$ 1.26 ^j	0.43 $\pm$ 0.05 ^{bc}	27.56 $\pm$ 6.29 ^e	59.51 $\pm$ 0.00 ^{bcd}	4.28 $\pm$ 0.38 ^{de}	16.18 $\pm$ 0.67 ^{fg}	9.87 $\pm$ 0.81 ^{def}
T8	19.75 $\pm$ 0.52 ^{cd}	0.27 $\pm$ 0.03 ^e	73.15 $\pm$ 10.64 ^b	47.03 $\pm$ 7.48 ^{fg}	1.32 $\pm$ 0.87 ^g	35.25 $\pm$ 2.90 ^a	17.17 $\pm$ 1.99 ^a
T9	25.78 $\pm$ 0.56 ^a	0.31 $\pm$ 0.01 ^{de}	83.16 $\pm$ 0.37 ^e	96.73 $\pm$ 3.23 ^a	8.59 $\pm$ 1.50 ^a	31.84 $\pm$ 0.32 ^b	15.61 $\pm$ 0.37 ^{ab}
T10	18.53 $\pm$ 0.15 ^{def}	0.34 $\pm$ 0.01 ^{de}	54.50 $\pm$ 1.13 ^c	44.87 $\pm$ 2.63 ^{fg}	8.37 $\pm$ 0.16 ^a	15.80 $\pm$ 2.46 ^{fg}	8.82 $\pm$ 2.22 ^{efgh}
T11	17.42 $\pm$ 0.95 ^{efg}	0.50 $\pm$ 0.02 ^b	34.84 $\pm$ 0.84 ^{de}	69.90 $\pm$ 11.09 ^b	6.73 $\pm$ 0.21 ^b	19.92 $\pm$ 0.45 ^{de}	12.73 $\pm$ 1.39 ^{bcd}
T12	22.37 $\pm$ 0.96 ^b	0.32 $\pm$ 0.03 ^{de}	69.91 $\pm$ 1.31 ^b	48.31 $\pm$ 0.00 ^{fg}	2.83 $\pm$ 0.91 ^{ef}	19.45 $\pm$ 2.06 ^{de}	12.12 $\pm$ 3.00 ^{cde}
T13	19.76 $\pm$ 0.51 ^{cd}	0.28 $\pm$ 0.04 ^e	70.57 $\pm$ 13.73 ^b	40.96 $\pm$ 5.6 ^g	2.82 $\pm$ 0.55 ^{ef}	24.88 $\pm$ 1.71 ^c	9.58 $\pm$ 3.06 ^{defg}
T14	17.10 $\pm$ 0.31 ^{fgh}	0.37 $\pm$ 0.01 ^{cd}	45.00 $\pm$ 0.88 ^{cd}	51.60 $\pm$ 2.93 ^{defg}	6.13 $\pm$ 0.40 ^{bc}	19.76 $\pm$ 0.58 ^{de}	8.72 $\pm$ 0.55 ^{fgh}
T15	17.48 $\pm$ 1.29 ^{efg}	0.60 $\pm$ 0.04 ^a	29.13 $\pm$ 0.38 ^e	53.79 $\pm$ 3.23 ^{cdef}	3.05 $\pm$ 1.34 ^{ef}	14.82 $\pm$ 0.54 ^g	10.56 $\pm$ 0.13 ^{cdef}
Mean	18.14	0.39	51.40	56.44	4.73	20.72	10.55
SEd	0.78	0.03	6.42	4.71	0.66	1.14	1.45
CD at 5 %	1.59	0.06	13.12	9.63	1.34	2.33	2.96
CV %	5.26	9.90	14.62	10.23	16.96	6.74	16.83
T1. Amarapali			T6. Dashehari			T11. Langra	
T2. Banganapalli			T7. Gulabkhas			T12. Mulgoa	
T3. Bengalura			T8. Imampasand			T13. Neelum	
T4. Cherukurasam			T9. Kalapad			T14. Ratnagiri alphonso	
T5. Chinnarasam			T10. Kesar			T15. Suvernakreha	

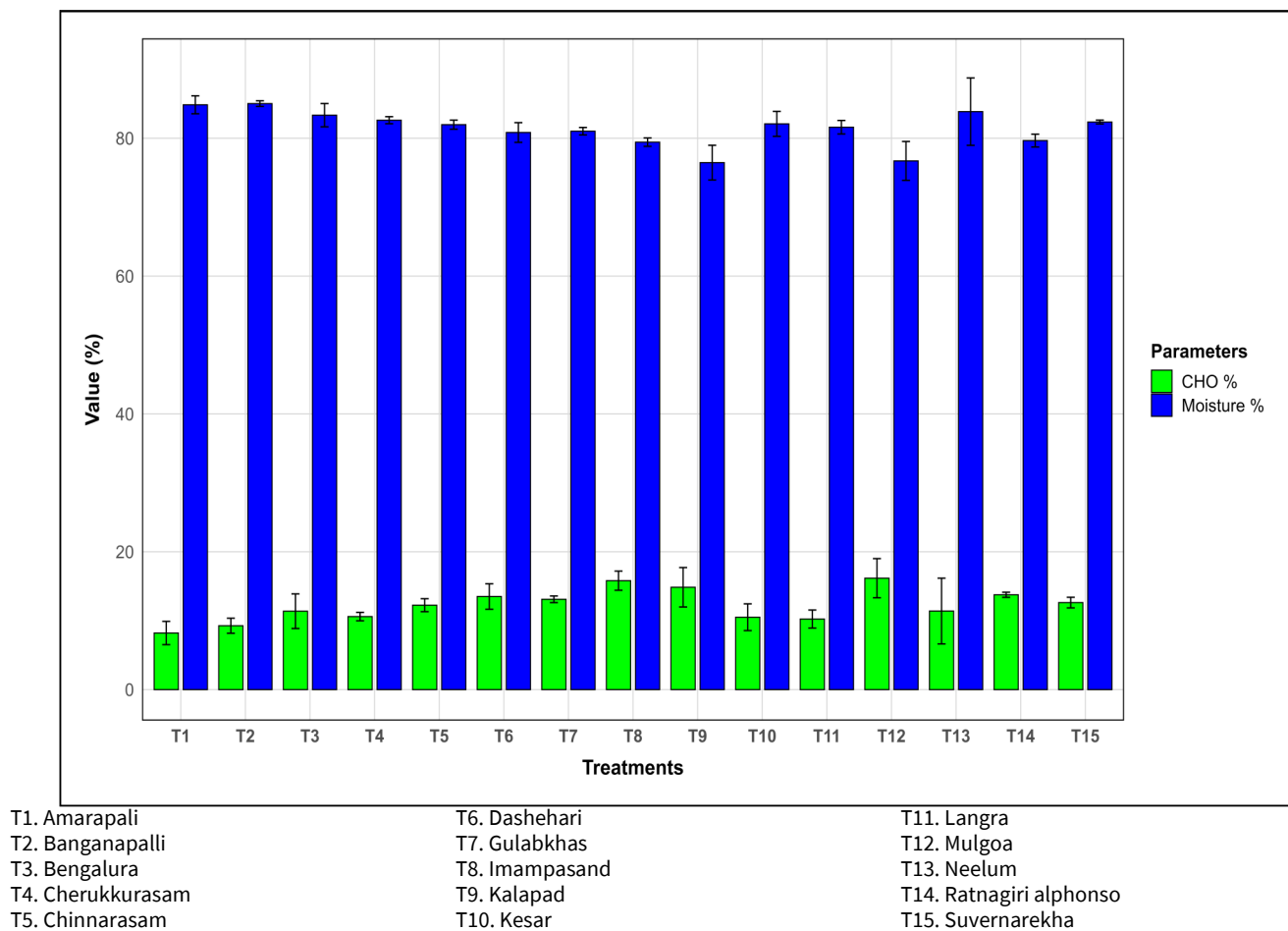
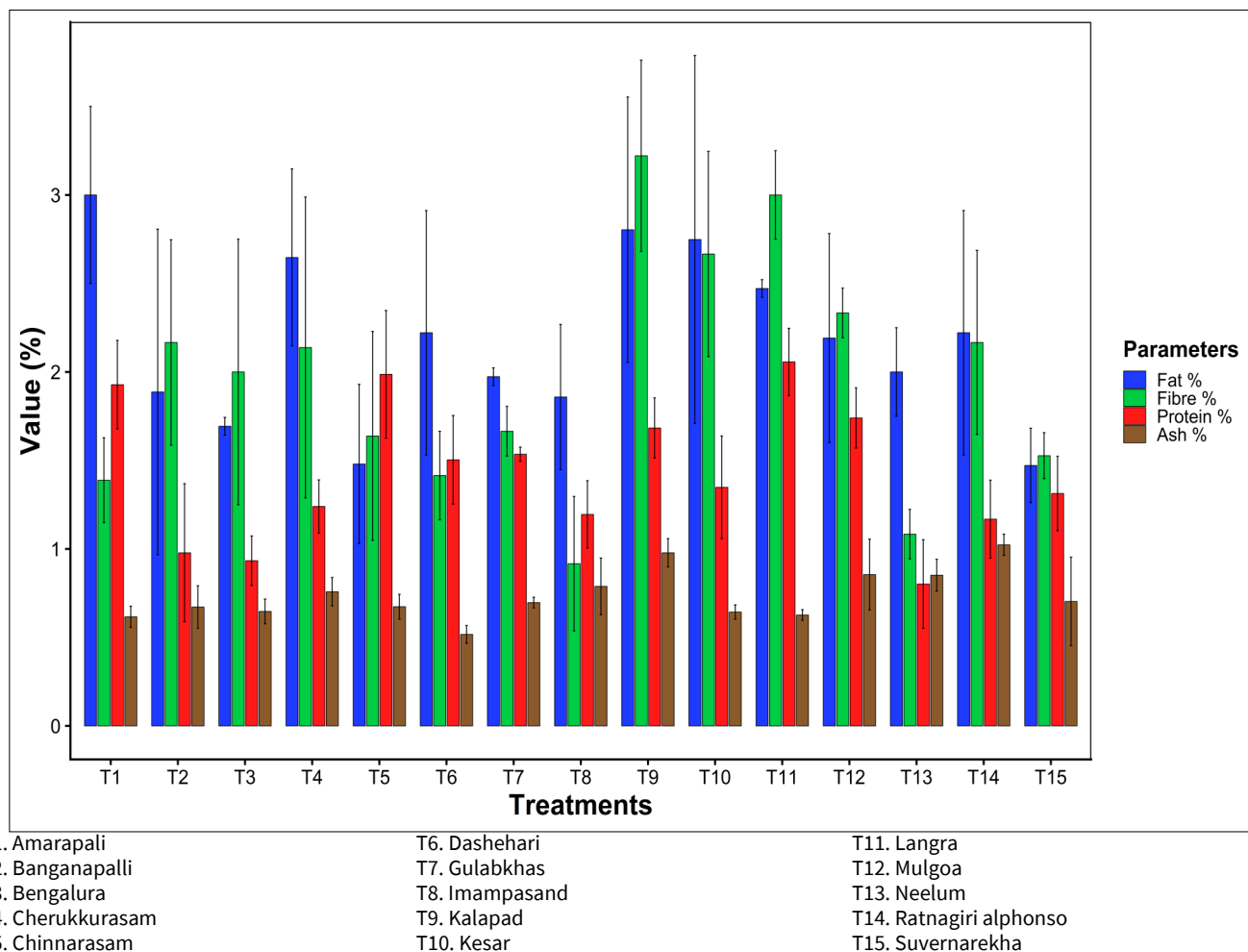
TSS: total soluble solids; mg: milligram; g: gram; GAE: gallic acid equivalent; mL: milli liter; QE: quercetin equivalent. Different letters indicate significance at $p \leq 0.05$ (DMRT).

Banganapalli (5.91 mg QE / mL) and Imampasand (17.17 mg QE / mL) respectively. Overall, the genotypes Imampasand, Kalapad and Mulgoa had relatively better biochemical attributes when compared with the other mango genotypes studied.

Proximate analysis

There were high differences between the mango genotypes in each proximate parameter (Fig. 1a and 1b). The range of crude fat content was 1.47 % for Suvernakreha to 3.00 % for Amrapali; crude fibre ranged from 0.92 % in Imampasand to 3.22 % in Kalapad. Significant differences in the amount of protein were observed between diverse genotypes, ranging from 0.80 % in Neelum to 2.06 % in Langra. Similarly, ash content varied between 0.52 % in

Dashehari to 1.02 % in Ratnagiri Alphonso, while carbohydrate content ranged between 8.21 % in Amrapali to 16.17 % in Mulgoa. However, moisture content varied from 76.46 % in Kalapad to 85.03 % in Banganapalli, signifying differences in pulp composition of the genotypes. Genotypes Amrapali, Imampasand, Kalapad and Mulgoa have generally better proximate and biochemical properties. Fat percentage (25.95 %), fibre content (23.90 %), total carotenoids (16.96 %), flavonoids (16.83 %) and peel thickness (14.75 %) had higher coefficient of variance (CV) values, indicating large variation in the studied mango genotypes in terms of nutritional and quality parameters.



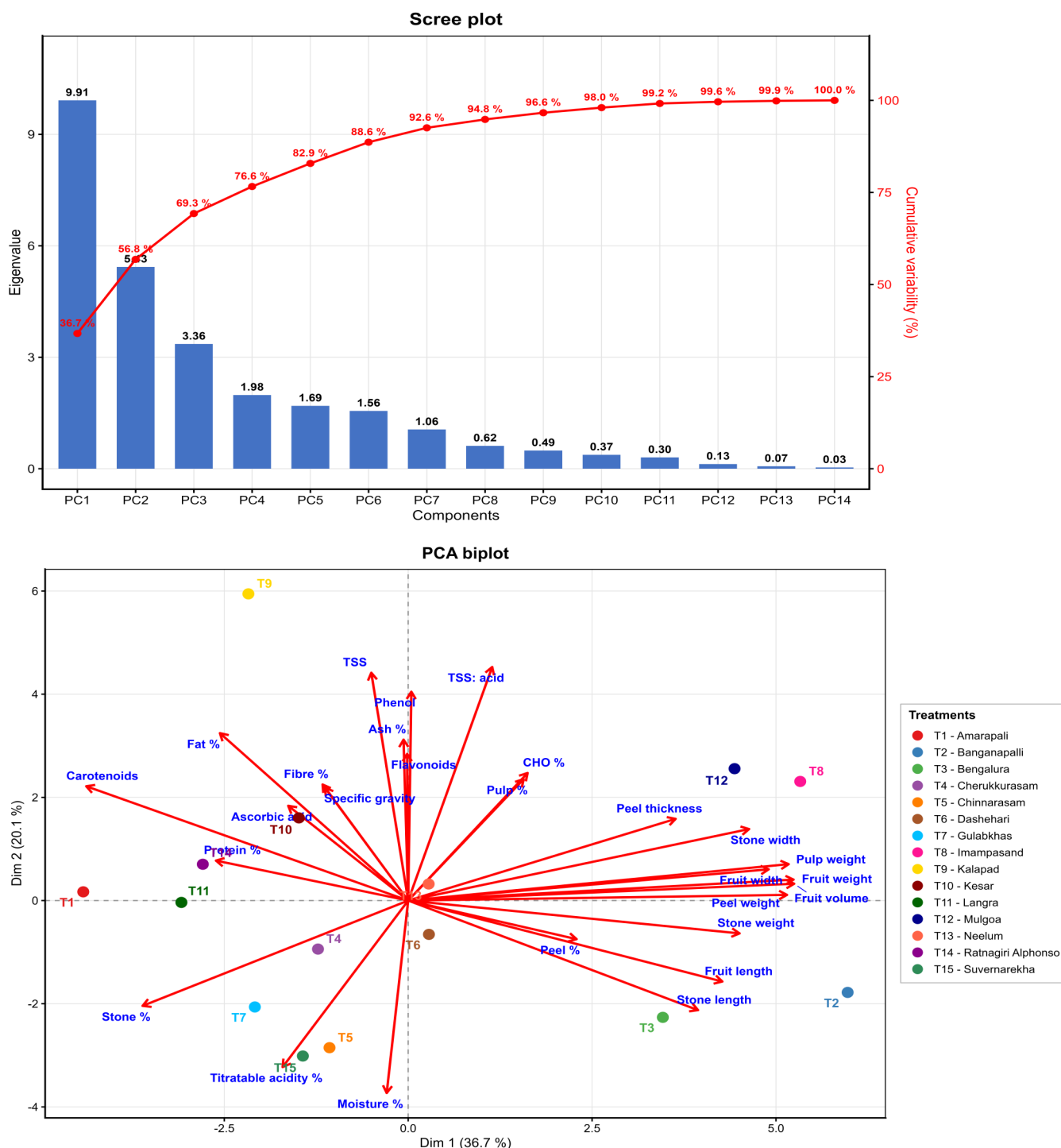


Fig 2. Scree plot and biplot of principal component analysis for mango genotypes.

Multivariate analysis

Principal component analysis

The relative contribution of the various physical, biochemical and proximate traits to differentiation of various genotypes was assessed by PCA (Fig. 2). The total variation was governed by the first two principal components (PC1 and PC2), which accounted for 36.7 % and 20.1 % of the variance, respectively (Table 6). Fruit physical traits, such as fruit weight, fruit volume, fruit width, pulp weight, peel weight and stone weight, exhibited high positive loadings on PC1, consistent with it being primarily associated with fruit physical traits. Closer to the positive side of PC1 were genotypic groups such as Banganapalli, Bengalura, Imampasand and Mulgoa, which were associated with high fruit size, pulp weight and fruit volume. Biochemical and proximate traits, such

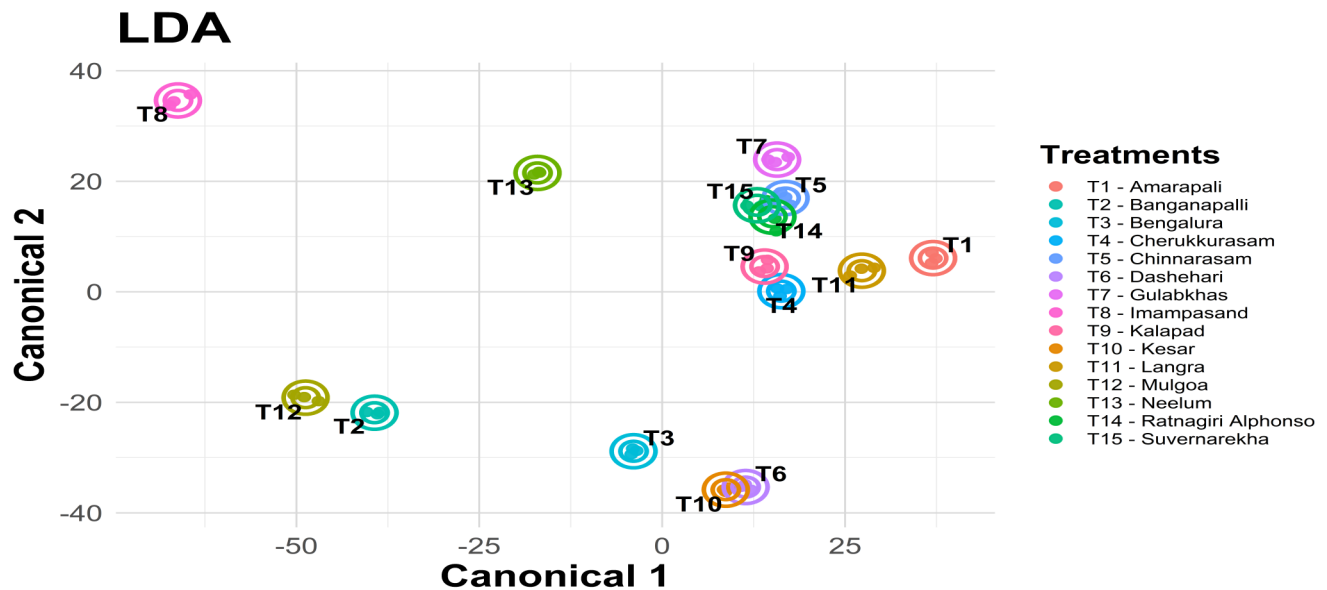
as TSS, phenols, flavonoids, carotenoids, ascorbic acid, fibre, fat and ash content, on the other hand, have made a significant contribution to PC2. Hence, Amrapali, Kesar and Ratnagiri Alphonso were spread towards the positive PC2 side, indicating relatively better biochemical and nutritional properties. The differential spatial distribution of some genotypes revealed the significant genotypic variability of the mango germplasm evaluated for physical and biochemical traits.

Linear discriminant analysis

Overall, the LDA discriminated the mango genotypes well according to their physical, biochemical and proximate attributes (Fig. 3). The genotypes like Banganapalli, Imampasand, Mulgoa and Neelum grouped separately on account of its different fruit biomass, pulp-related and nutritional

Table 6. Eigenvalues and principal component analysis variance explained

Sl. No.	Principal component	Eigen value	Variance explained (%)	Cumulative variance (%)
1.	PC1	9.91	36.7	36.7
2.	PC2	5.43	20.1	56.8
3.	PC3	3.36	12.5	69.3
4.	PC4	1.98	7.3	76.6
5.	PC5	1.69	6.3	82.9

**Fig. 3.** Linear discriminant analysis-based grouping of mango genotypes.**Table 7.** Confusion matrix - linear discriminant analysis classification of 15 mango genotypes leave-one-out cross-validation (LOOCV) based on physico-chemical characteristics

Predicted vs actual	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
T1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2	0	3	0	0	0	0	0	0	0	0	0	1	0	0	0
T3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
T4	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
T5	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0
T6	0	0	1	0	0	2	0	0	0	0	0	0	0	0	0
T7	0	0	0	0	0	0	2	0	0	0	0	0	0	1	1
T8	0	0	0	0	0	0	0	3	0	1	0	0	0	0	0
T9	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
T10	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
T11	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
T12	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
T13	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
T14	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
T15	0	0	1	0	0	0	1	0	0	0	0	0	0	0	2
Correct (%)	100 %	100 %	67 %	100 %	67 %	67 %	67 %	100 %	100 %	67 %	100 %	67 %	100 %	67 %	67 %

Diagonal cells (green): correctly classified; off-diagonal cells (yellow): misclassified; values: number of observations (n = 3 per treatment).

Table 8. Classification accuracy summary

Sl. No.	Method	Value
1.	Resubstitution	100.00 %
2.	LOOCV	82.22 %
3.	Kappa (LOOCV)	0.8095

LOOCV: leave-one-out cross-validation.

characteristics, while Amarapali, Kalapad, Langra and Ratnagiri Alphonso showed comparatively closer grouping due to similarity in their physico-chemical composition. Notably, genotypes characterised by higher protein, carotenoid, ascorbic acid and biochemical richness, such as Amrapali and Ratnagiri Alphonso, were differentiated from larger-fruited genotypes dominated by physical traits. The resubstitution classification accuracy for the linear discriminant model was

evaluated and compared with LOOCV accuracy (Tables 7 and 8). The reliable classifiers showed problems in no cases and 100 % classification accuracy was obtained for the resubstitution approach. The LOOCV method was used to obtain an overall classification accuracy of 82.22 % with the Kappa (k) statistic value of 0.8095, indicating that the classification was almost perfect. In cross-validation, 37 of 45 observations were correctly classified (refer to the confusion matrix in Table 7). The other few

were missing just a little and the errors were between Bengalura (T3) and Dashehari (T6), Chinnarasam (T5) and Dashehari (T6), Gulabkhas (T7) and Ratnagiri Alphonso (T14), Gulabkhas (T7) and Suvernarekha (T15), Kesar (T10) and Imampasand (T8), Mulgoa (T12) and Banganapalli (T2) and Suvernarekha (T15) and Chinnarasam (T5). In the LDA score plot, genotype Bengalura (T3) seemed to be quite clearly separated, but the confusion matrix revealed that T3 has an accuracy of 67 % LOOCV due to one of the replicates being classified as Dashehari (T6).

Discussion

The difference among the evaluated mango genotypes was observed to be significant for all the fruit characteristics analysed, indicating the presence of large phenotypic variation in Indian mango germplasm. Genotypes with high edible biomass and commercial value, like Banganapalli and Imampasand, which had higher fruit weight, fruit volume and traits associated with pulp, may be considered for the fresh market and processing purposes. This genotype-dependent fruit morphological variability and pulp characteristics has been observed in previous mango characterisation studies (4, 23). The difference in various fruit morphological traits - peel thickness, stone weight and pulp content - among the different genotypes also suggests the significance of these characters for varietal identification, breeding and germplasm conservation efforts. Genotypes with high pulp recovery coupled with low non-edible portion have potential for greater industrial use; thickened peel tissue could potentially aid in post-harvest handling and transport. Specific gravities of the studied germplasm exhibited relatively little variation, indicating uniform fruit density characteristics (24, 25). Overall diversity of physical traits suggests possibilities of the use of these mango genotypes for cultivar development and focused commercial exploitations.

The significant variation observed in biochemical traits among the mango genotypes indicated substantial diversity in fruit quality and nutraceutical composition. The genotypes of Kalapad and Imampasand showed better TSS, TSS : acid ratio, ascorbic acid and antioxidant-related compounds, which may have better consumer acceptability due to better sweetness, balance of flavour and better nutrition. Such variation due to genotype has been observed in mango cultivars and these traits were known to affect fruit palatability and market preference to a large extent (26–29). The genotype with high levels of carotenoids, phenolics and flavonoids suggested their role as nutritionally rich and more antioxidant cultivars. Apart from contributing towards attractive pulp colour development, carotenoids impart provitamin-A activity and nutritional value to the fruit, while phenolics and flavonoids are bioactive compounds, known to exhibit antioxidant activity and health-promoting properties (3, 30, 31). The extent of accumulation of these compounds was highly genotype-dependent and fruit-related metabolic characteristics. The significant variation observed in proximate composition among the evaluated mango genotypes reflects considerable nutritional diversity within Indian mango germplasm. The genotypes Mulgoa, Kalapad and Langra with comparatively higher carbohydrate, fibre and protein content indicated their higher nutritional and processing values. Significant cultivar differences in moisture, carbohydrate, protein and fibre content of mango fruits have also been recorded in earlier studies that could be attributed to genotype, ripeness and metabolic

features of the fruit (32, 33). The higher variability observed for fibre, fat, carotenoids and flavonoids further indicated the potential usefulness of these traits in genotype discrimination and nutritional profiling. This type of variability was acknowledged as a valuable factor in germplasm characterisation and selection of elite cultivars and breeding to enhance functional attributes and fruit quality (34). The nutritional diversity observed in the mango genotypes taken up in the present study, in turn, indicated their usefulness for cultivar improvement as well as value addition in food processing and preservation of genetically distinct germplasm resources.

The PCA indicated considerable variation in the mango genotypes analysed and distinguished the groups principally based on their fruit biomass-related and biochemical characters. The fruits which were found to be strongly associated with their various genotypes, such as Banganapalli, Imampasand and Mulgoa, showed more fruit size, pulp weight and fruit volume suitable for fresh consumption and processing applications. On the other hand, biochemical and proximate traits were relatively higher in Amrapali, Kesar and Ratnagiri Alphonso, suggesting their superior nutritional potency. Multivariate separation of different morpho-biochemical and bioactive traits has been reported in recent fruit diversity studies (35, 36). Genotypes such as Banganapalli and Imampasand were classified as large fruit-sized and tended to cluster together, indicating the presence of a common fruit biomass group, which may be found beneficial for the breeding programme for export quality and processing quality. The spatial separation of the genotypes in the PCA biplot showed that the Indian mango germplasm consisted of a distinct combination of traits. The information presented in these findings could be valuable for cultivation and germplasm banking and for selecting desirable fruit quality and nutritional fruit types for breeding and cultivar improvement.

The LDA effectively discriminated among mango genotypes using combined physical, biochemical and proximate traits. The genotypes Banganapalli, Imampasand and Mulgoa formed a distinct cluster because of their higher values for fruit biomass and associated pulp traits, while the genotypes Langra, Kalapad, Imampasand and Amrapali, which showed high levels of protein, carotenoid, ascorbic acid, phenol, flavonoids and fat, were distinguished separately. Such discrimination of fruit genotype by physico-chemical attributes by a multivariate approach has been reported earlier (37–39). Likewise, the grouping of genotypes according to bearing type and their nutritional profile, the multi-sensory appeal of physico-chemical properties for variety identification and preservation of genetically distinct ones of mango germplasm was emphasised.

The selected physico-chemical and nutritional characters were found to be quite effective in discriminating mango genotypes with a high classification value of LOOCV 82.22 % and Kappa value $k = 0.8095$. Based on those results, all support the usefulness of LDA as an effective method to discriminate the fruit crop varieties, as suggested by the previous studies (40–42), indicating that there is an almost perfect matching between the group predicted and the actual group membership (22). A similar multivariate approach, based on physico-chemical traits, was adopted in mango germplasm research, particularly for cultivar diversity analysis in mango cultivars grown in India (43). The correct associations between some genotypes viz., Bengalura and Dashehari; Chinnarasam and Dashehari, suggested that there was a similar fruit

quality and nutritional “fingerprint” between these genotypes, consistent with previous work (40). To avoid any misclassification by LDA, the LOOCV accuracy is a better tool to reflect the generalisation performance of the model for predicting new and unseen cases (44).

In the present study, Imampasand, Kalapad and Banganapalli were identified as superior genotypes with respect to some important physical and biochemical characteristics. There was a clear separation between regular bearers (Neelum, Bengalura) and alternate bearer (Imampasand), suggesting genotype differentiation due to the influence of bearing habit. Kesar and Dashehari were also very close, indicating an agro-climatic and regional similarity. The polymorphic nature of phenolics, flavonoids and other biochemical properties of the mango cultivars highlights the need for a biochemical profile to identify nutritionally superior and commercially valuable cultivars (45). These findings provide useful insights for genotype selection, breeding programmes and germplasm conservation.

Conclusion

The present study demonstrated substantial variability among the 15 mango genotypes for physical, biochemical and proximate traits, highlighting the rich diversity within Indian mango germplasm. Multivariate analyses showed that the fruit biomass-related traits, total soluble solids (TSS), TSS : acid ratio, acidity and pulp percentage, were major traits contributing to the genotype differentiation and biochemical traits associated with antioxidants were also among the discriminating traits. Genotypes like Banganapalli, Imampasand, Kalapad and Mulgoa had good quality characteristics and the significant differences observed in PCA / LDA results revealed differences related to fruit size, fruit nutritional and bearing behaviour. The high genetic similarity of Kesar and Dashehari further indicated that they have similar agro-climatic adaptive and regional origin. The LDA confusion matrix, based on the leave-one-out cross-validation (LOOCV) classification accuracy of 82.22 % and a Kappa value $k = 0.8095$ (almost perfect agreement), further confirmed that the discriminant model was effective in distinguishing the 15 mango genotypes, based on their physico-chemical and nutritional profiles. The findings of the present study offer valuable implications for mango breeding programs for fruit quality, nutritional traits and yield stability. Furthermore, the physico-chemical characteristics can be used as potential criteria to identify the mango varieties and for germplasm characterisation and conservation of elite mango varieties. In the future, with the incorporation of molecular markers, metabolomic profiling and multi-location assessments, the identification of the genotypes can be strengthened and this would help the development of nutritionally superior and climate-resilient mango cultivars.

Acknowledgements

The authors sincerely thank the farmers who generously provided mango fruits from their farms for this research work. The authors extend their gratitude to Mr. Ramesh Kumar (Horticulture officer), Mr. Tamilarasan (Assistant Horticulture Officer), Mr. Venkatachalam (Assistant Horticulture Officer), Mr. T. Gopinath (Bank of Baroda), Mr. Sreedar (nursery entrepreneur) and Mr. Charan Reddy (PhD scholar) for their valuable support in collecting the fruit samples from different parts of India. The

authors also express their sincere thanks to Dr. Satheeskumar (Assistant Professor, SRM University) and Mr. Sathish Kumar M Ponnaiya for their support in statistical analysis. Finally, the authors acknowledge the Department of Horticulture, Central University of Tamil Nadu, Thiruvavur, for providing the laboratory facilities to carry out the research.

Authors' contributions

IG executed and wrote the main manuscript. MS¹ designed the methodology, supervised the research work and drafted the manuscript. MS², PEM and SKT helped with lab work and data interpretation. All authors read and approved the final manuscript. (MS¹ stands for Manivannan S and MS² stands for Manonmani S)

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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