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Multi-trait Characterization of Twenty-eight Mango Cultivars for Fruit Quality, Market Suitability and Ambient Shelf Life

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ABSTRACT

Twenty-eight indigenous and exotic mango (*Mangifera indica* L.) cultivars were characterized in West Bengal, India, for morphological, physical, physicochemical, sensory and ambient shelf-life traits. Fruits were obtained from a single orchard during one season, and the comparative analyses used cultivar-level summary values (n = 28). Fruit weight ranged from 87 to 535 g and pulp weight from 30 to 365 g; fruit weight and pulp weight were strongly related (r = 0.928; FDR-adjusted q < 0.001). Total soluble solids (TSS) ranged from 5.0 to 22.0 °Brix, titratable acidity from 0.15 to 0.45%, and firmness from 2.5 to 12.0 kg cm^{-2}. After Benjamini-Hochberg correction across 78 pairwise correlations, the previously noted associations of taste with TSS, aroma and firmness were not all statistically supported. Principal component analysis of 13 standardized traits showed that PC1 and PC2 explained 30.7% and 16.5% of the variance, respectively; five components had eigenvalues >1 and together explained 76.4%. A sensitivity analysis excluding Chitalkhas, which had an unusually low TSS value (5.0 °Brix), preserved the broad PCA structure but weakened the TSS-taste association. Osteen and Dofala had the longest recorded ambient shelf-life ranges (12–15 d), whereas Manjeera, Chiang Mai and BARI-4 were notable for high fruit or pulp weight. Shelf-life values were derived from previously recorded thesis ranges rather than replicate-level measurements with a uniform quantitative endpoint. Accordingly, the results are preliminary cultivar-level comparisons that require replicated, multi-season validation using standardized maturity and shelf-life criteria.

INTRODUCTION

Mango (*Mangifera indica* L.) is a major tropical fruit valued for its flavour, appearance, nutritional quality and diverse fresh and processed uses. India is an important centre of mango diversity, with traditional cultivars, chance seedlings, hybrids and introduced selections occurring across contrasting environments. This diversity is commercially valuable, but cultivar performance cannot be reliably inferred from reputation, origin or fruit size alone (Rajan and Yadav, 2021; Singh *et al.*, 2013). Cultivar value depends on a combination of traits. Fruit shape and peel colour influence market appeal, while fruit and pulp weights affect pack-out and processing yield. Firmness and peel thickness determine handling tolerance, whereas soluble solids, acidity, aroma and texture influence eating quality. Ambient shelf life is also important where cold-chain facilities are limited, as cultivars differ in their suitability for local consumption and distant distribution (Jha *et*

al., 2010b; Siddiq *et al*., 2012).

Morphological and pomological characterization provides a basis for documenting diversity and identifying cultivars for different commercial uses. Descriptor systems emphasize fruit dimensions, shape, peel colour, shoulder, beak and stone characteristics, although their expression varies with genotype, maturity and environment, necessitating regional evaluation (International Plant Genetic Resources Institute, 2006; International Union for the Protection of New Varieties of Plants, 2006; Jha *et al*., 2010a; Khadivi *et al*., 2022; Saheda *et al*., 2019). Because individual quality traits may not reliably indicate overall suitability, multitrait evaluation is useful for identifying complementary characteristics and preliminary market functions. Accordingly, 28 indigenous and exotic mango cultivars were characterized under a common postharvest environment in West Bengal for morphological, physical, physicochemical, sensory and ambient shelf-life traits. Potential processing relevance was considered only in relation to fruit and pulp weight; processing suitability was not directly evaluated because replicated pulp recovery, fibre content, colour stability and industrially relevant pH were not assessed.

MATERIALS AND METHODS

Study site and fruit material

The investigation was conducted during 2025–26 at the Department of Post Harvest Technology, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, West Bengal, India. Fruits of 28 cultivars were procured from a single orchard at Madanpur, Nadia (23.006° N, 88.492° E) and evaluated during one season. The Experiment 1 record reports ambient temperature of 27–40 °C (mean 33.5 °C) and approximately 62% relative humidity. The collection comprised Pusa Desi, Bombay Green, Chiang Mai, Banana, Nam Doc Mai, Nileswari, Sarenga, CISH-949, Dofala, Osteen, Anwar Ratool, Champa, Pusa Arunima, Chitalkhas, Catimon, 3-Taste, Miyazaki, Sensation, Himsagar, Pusa Lalima, Langra, Pusa Arunika, Zardalu, Amrapali, Manjeera, Kensington Pride, BARI-4 and Apple. A uniform cultivar-appropriate harvest-maturity index was not documented for all 28 cultivars; this limitation is addressed explicitly below.

Morphological and physical measurements

Fruit, peel, pulp and stone weights were determined gravimetrically. Fruit and stone dimensions were measured using a digital calliper, and peel and stone thickness were recorded in millimetres. The make and model of the calliper were not documented in the original laboratory record. Fruit shape was classified using recognized mango descriptors (International Plant Genetic Resources Institute, 2006; International Union for the Protection of New Varieties of Plants, 2006), and ripe-fruit peel colour was recorded using the Royal Horticultural Society colour chart (Royal Horticultural Society, 2015). Fruit firmness was measured at two opposite peeled sites using an FT 327 fruit pressure tester (Made in Italy), and the two readings were averaged and reported as kg cm^{-2}, as recorded in the thesis dataset. The probe diameter and penetration depth were not documented and therefore cannot be reconstructed retrospectively. Peelability was assessed at ripeness on a 1–9 scale based on resistance to peel removal, continuity of peeling, pulp adherence and pulp damage, with higher scores indicating easier peeling.

Physicochemical and sensory evaluation

Total soluble solids (TSS) were measured with an Erma hand refractometer, corrected to 20 °C and expressed as °Brix. Titratable acidity was determined by titration with 0.1 N NaOH and expressed as percentage citric acid; the TSS:acid ratio was calculated from these two measurements. Aroma and taste were evaluated on a 1–9 hedonic scale. The thesis methods specify a taste panel of 10 semi-trained members comprising faculty and students of the Department of Post Harvest Technology; samples were coded before serving, plain water was provided for palate rinsing, and efforts were made to retain the same panel across assessments. Aroma was recorded using the same 1–9 hedonic framework. The original records do not document a formal training duration, repeated sensory sessions or inter-rater reliability statistics; these limitations are therefore acknowledged rather than inferred.

Source and interpretation of shelf-life data

The shelf-life values were taken from Kankana Sarkar's M.Sc. thesis, Studies on Effect of Ethephon and Storage of Some Selected Mango Varieties, submitted to Bidhan Chandra Krishi Viswavidyalaya in 2026. For Experiment 1, the thesis classifies shelf life under ambient storage and reports a temperature range of 27–40 °C (mean 33.5 °C) with approximately 62% relative humidity. However, a separate site-description section reports 25–35 °C and 85–95% relative humidity during August–September; therefore, the exact ambient conditions associated with every shelf-life range cannot be reconstructed unequivocally. The thesis describes shelf life conceptually as the period for which fruit retains marketable appearance, acceptable texture and eating

quality before excessive softening, shrivelling, decay or physiological breakdown, but it does not provide a single quantitative rejection threshold applied uniformly to all cultivars. Accordingly, the reported cultivar-level ranges were summarized by their midpoints for descriptive comparison only and were not treated as replicated inferential measurements.

Statistical analysis

Analyses were based on 28 cultivar-level summary values; replicate-level observations for Experiment 1 were not available, so within-cultivar variance could not be estimated and ANOVA was not applied. Pearson correlation coefficients were calculated across the 28 cultivar means (df = 26) for the 13 primary variables used in the multivariate analysis: fruit weight, fruit length, fruit width, peel thickness, pulp weight, stone weight, TSS, acidity, peelability, firmness, aroma, taste and shelf-life midpoint. The derived TSS:acid ratio was excluded from the correlation family to avoid mathematical redundancy. The 78 unique pairwise P-values were adjusted using the Benjamini-Hochberg false discovery rate (FDR) procedure, with $q < 0.05$ considered significant. Principal component analysis (PCA) was performed on z-standardized values of the same 13 variables. Components with eigenvalues >1 were retained by the Kaiser criterion; eigenvalues, variance explained and cumulative variance are reported in Table 5. Because Chitalkhas had an unusually low TSS value (5.0 °Brix), sensitivity analyses repeated both the correlation analysis and PCA after excluding this cultivar. All inferential results therefore describe associations among cultivar means and must not be extrapolated directly to individual-fruit relationships.

RESULTS AND DISCUSSION

Fruit morphology and external diversity

Marked diversity in fruit outline was observed among the cultivars (Figure 1), with 18 detailed shape states ranging from elongated and slender forms in Chiang Mai and Banana to compact round-to-oval forms in BARI-4 and Apple. Sarenga, CISH-949, Dofala, Osteen and Anwar Ratool showed oblong-associated forms, while Pusa Arunika was distinguished by an ovate-to-oblique outline. The intermediate forms indicate that mango fruit shape represents a morphological continuum rather than sharply separated classes.

Although Figure 1 illustrates the morphological diversity in fruit shape and external appearance among the 28 mango cultivars, the photographs were not presented at a common scale. Therefore, the images are intended to illustrate qualitative morphological differences and should not be used to compare relative fruit size or dimensions visually. Quantitative comparisons of fruit dimensions are based on the measurements reported in the Results and tables.

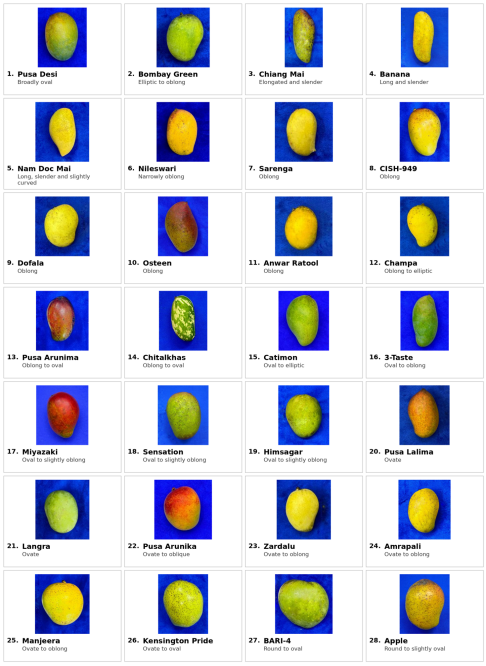


Figure 1: Morphological diversity in fruit shape and external appearance among the 28 mango cultivars evaluated in the study. Photographs are not presented at a common scale and are intended for qualitative morphological illustration only; relative fruit dimensions should not be inferred from the images.

Fruit shape is useful for preliminary varietal identification and consumer recognition, but reliable identification requires a combination of characters, including dimensions, shoulders, stalk cavity, stylar end, beak and stone traits (International Plant Genetic Resources Institute, 2006; International Union for the Protection of New Varieties of Plants, 2006). Figure 1 provides a visual reference; photographs are not presented at a common scale.

Fruit size, pulp weight and handling attributes

Fruit weight ranged from 87 g in Sarenga to 535 g in 3-Taste (mean 245.86 g; CV 54.5%), while fruit length and width varied from 7.0–19.0 cm and 5.8–9.8 cm, respectively (Tables 1 and 2). Pulp weight ranged from 30.0 g in Pusa Desi to 365.0 g in 3-Taste (CV 70.7%). Fruit weight and pulp weight showed the strongest relationship in the dataset ($r = 0.928$, $P = 1.23 \times 10^{-12}$, $q < 0.001$), and this association remained essentially unchanged after exclusion of Chitalkhas ($r = 0.927$, $q < 0.001$). Peel thickness ranged from 0.40–2.50 mm and stone weight

Table 1: Descriptive statistics and extreme cultivars for major fruit and quality traits.

Trait	Range	Mean ± SD	CV (%)	Cultivars at minimum and maximum
Fruit weight (g)	87.00-535.00	245.86 ± 134.08	54.5	Min: Sarenga; Max: 3-Taste
Fruit length (cm)	7.00-19.00	10.77 ± 3.05	28.3	Min: Pusa Arunika; Max: Chiang Mai
Peel thickness (mm)	0.40-2.50	1.27 ± 0.68	53.7	Min: Himsagar; Max: Zardalu
Pulp weight (g)	30.00-365.00	125.32 ± 88.63	70.7	Min: Pusa Desi; Max: 3-Taste
Stone weight (g)	13.20-60.00	37.86 ± 12.39	32.7	Min: Champa; Max: Sensation, BARI-4
TSS (°Brix)	5.00-22.00	16.29 ± 3.47	21.3	Min: Chitalkhas; Max: Amrapali
Acidity (%)	0.15-0.45	0.32 ± 0.08	24.0	Min: Pusa Lalima; Max: Pusa Desi, Dofala
TSS:acid ratio	12.50-116.67	55.93 ± 22.44	40.1	Min: Chitalkhas; Max: Pusa Lalima
Firmness (kg cm^{-2})	2.50-12.00	6.64 ± 2.38	35.8	Min: Apple; Max: Catimon
Taste score (1-9)	3.00-9.00	6.68 ± 1.83	27.4	Min: Chitalkhas, Catimon, Pusa Arunika; Max: Amrapali, Apple
Shelf-life midpoint (d)	7.00-13.50	10.45 ± 1.79	17.1	Min: Bombay Green, Himsagar; Max: Dofala, Osteen

Table 2: Selected physical characteristics of the different mango cultivars.

Cultivar	Fruit wt (g)	Length (cm)	Width (cm)	Pulp wt (g)	Peel thick. (mm)	Stone wt (g)
Pusa Desi	140.0	8.3	9.8	30.0	0.90	45.0
Bombay Green	152.0	8.5	6.5	62.5	2.00	37.4
Chiang Mai	500.0	19.0	9.0	285.0	0.70	40.0
Banana	260.0	16.0	7.0	150.0	0.60	35.0
Nam Doc Mai	150.0	10.5	7.0	70.0	0.60	40.0
Nileswari	130.0	8.5	7.0	53.0	1.00	35.0
Sarenga	87.0	8.0	5.8	30.1	1.80	24.6
CISH-949	220.0	9.5	7.8	85.0	1.00	40.0
Dofala	272.0	9.5	7.0	186.5	2.20	42.4
Osteen	515.0	16.5	8.5	200.0	0.90	55.0
Anwar Ratool	138.0	9.2	6.5	70.6	2.00	23.6
Champa	90.0	9.0	6.8	36.7	2.10	13.2
Pusa Arunima	135.0	8.5	7.2	50.0	1.50	20.0
Chitalkhas	150.0	11.5	6.2	43.0	0.70	56.0
Catimon	230.0	12.0	7.2	155.0	0.60	20.0
3-Taste	535.0	18.0	8.5	365.0	0.90	55.0
Miyazaki	230.0	9.5	7.5	100.0	0.80	40.0
Sensation	325.0	11.5	9.5	125.0	1.10	60.0
Himsagar	265.0	9.0	7.5	100.5	0.40	39.5
Pusa Lalima	202.0	11.0	7.8	97.6	2.30	30.7
Langra	255.0	9.5	8.5	140.0	1.40	35.0
Pusa Arunika	120.0	7.0	6.8	40.0	2.30	25.0
Zardalu	137.0	10.5	7.5	72.6	2.50	32.0
Amrapali	156.0	9.5	6.4	118.0	0.70	25.8
Manjeera	470.0	10.0	7.5	320.0	1.00	45.0
Kensington Pride	250.0	9.0	7.5	140.0	0.60	40.0
BARI-4	430.0	10.0	7.6	235.0	2.30	60.0
Apple	340.0	12.5	9.5	148.0	0.60	45.0

from 13.2–60.0 g. These variations highlight the importance of considering fruit size, pulp quantity and non-edible fractions together rather than using fruit size alone as a market or processing proxy.

Peel-colour diversity and visual market appeal

Royal Horticultural Society colour assessment separated the cultivars into four broad visual groups: 10 green, yellow-green or greenish-yellow cultivars; seven yellow cultivars; five yellow-orange or orange cultivars; and six red, orange-red, red-purple or prominently red-blushed cultivars. Green-retaining types included Langra, Himsagar, Amrapali, Manjeera and Bombay Green. Yellow and orange types included

Sarenga, Banana, Nam Doc Mai, Anwar Ratool, Dofala, 3-Taste and Zardalu. Pusa Arunima, Miyazaki and Sensation showed intense red or purple tones, while Osteen, Pusa Lalima, Pusa Arunika, CISH-949, Apple and Kensington Pride displayed contrasting ground and blush colours.

The colour differences are consistent with variation in mango peel pigments. Chlorophyll retention contributes to green appearance; carotenoid accumulation produces yellow and orange shades; and anthocyanins contribute to red or purple colour and blush (Medlicott *et al.*, 1986; Ranganath *et al.*, 2018). Visual colour can support branding and cultivar recognition, but it is not a dependable substitute for internal ripeness. Green-skinned cultivars may develop acceptable eating quality without conspicuous yellowing, while red blush may be influenced by exposure and genotype.

Physicochemical and sensory quality

Total soluble solids varied from 5.0 °Brix in Chitalkhas to 22.0 °Brix in Amrapali (Tables 1 and 3). Nam Doc Mai, Sarenga, Anwar Ratool and Himsagar also recorded high TSS. Titratable acidity ranged from 0.15% in Pusa Lalima to 0.45% in Pusa Desi and Dofala, giving TSS:acid ratios from 12.50 to 116.67. Peelability scores ranged from 2 in Osteen and Sensation to 8 in Pusa Desi, Banana, Sarenga, Pusa Arunima and Catimon. The particularly low TSS of Chitalkhas was treated as a potential maturity-related outlier and examined by sensitivity analysis rather than being attributed solely to genotype.

The observed quality ranges were broadly compatible with cultivar-dependent variation reported elsewhere, but direct numerical comparisons require caution because maturity, location and methods differed. In West Bengal, Singh *et al.* (2014) reported 22 °Brix TSS for Amrapali and 0.17% titratable acidity for Himsagar. Saroj and Prasad (2023), working under 25 ± 4 °C and 65 ± 5% relative humidity, reported 21.76 °Brix for Amrapali and documented substantial genotype-dependent postharvest variation. Saheda *et al.* (2019) likewise reported wide physical and biochemical diversity among mango varieties and hybrids under Kodur conditions. In the present dataset, the 5.0 °Brix value for Chitalkhas was far below the next-lowest value (12.0 °Brix), and the absence of a uniformly documented harvest-maturity criterion means this value cannot be interpreted as an inherent genetic characteristic with confidence.

Sensitivity analysis showed that Chitalkhas materially affected some quality-trait correlations. With all 28 cultivars, TSS and taste had $r = 0.406$ ($P = 0.032$; $q = 0.190$); after excluding Chitalkhas, the relationship weakened to $r = 0.218$ ($P = 0.274$; $q = 0.595$). Thus, the apparent TSS–taste association was not robust to this outlier. By contrast, the aroma–taste correlation increased from $r = 0.447$ ($P = 0.017$; $q = 0.134$) to $r = 0.541$ ($P = 0.0036$; $q = 0.029$) after exclusion. These changes reinforce the need to interpret quality-trait associations as exploratory, particularly where harvest maturity was not standardized.

Across the full 13-variable correlation matrix, six of 78 pairwise relationships remained significant after FDR correction, and most involved fruit-size traits. In addition to fruit weight–pulp weight, significant relationships included fruit weight–length ($r = 0.734$, $q < 0.001$), length–pulp weight ($r = 0.681$, $q = 0.0017$), fruit weight–stone weight ($r = 0.653$, $q = 0.0032$), fruit weight–width ($r = 0.554$, $q = 0.034$) and stone weight–TSS ($r = -0.541$, $q = 0.039$). The previously reported correlations of taste with TSS ($q = 0.190$), aroma ($q = 0.134$) and firmness ($r = -0.452$, $q = 0.134$) did not meet the FDR threshold in the full dataset. Accordingly, soluble solids, aroma and firmness are discussed as plausible contributors to sensory preference rather than as independently confirmed statistical predictors.

Firmness ranged from 2.5 kg cm^{-2} in Apple to 12.0 kg cm^{-2} in Catimon. Manjeera, CISH-949, Chitalkhas and Langra were also relatively firm. The direction of the cultivar-level relationships was consistent with ripening physiology—firmer fruit tended to have lower taste scores and lower TSS—but neither firmness–taste ($r = -0.452$, $q = 0.134$) nor firmness–TSS ($r = -0.398$, $q = 0.190$) remained significant after FDR correction. Cell-wall disassembly is a central component of mango softening (Yashoda *et al.*, 2006), but genotype and harvest maturity preclude using firmness as a universal eating-quality index.

Ambient shelf life and preliminary market orientation

Cultivar-level ambient shelf-life records ranged from 6–8 d in Bombay Green and Himsagar to 12–15 d in Osteen and Dofala; Anwar Ratool and Pusa Arunima were recorded at 12–14 d (Table 3). These are descriptive ranges from the thesis rather than replicate-level estimates with a uniform quantitative endpoint. Therefore, the 6.5-d difference between the shortest and longest midpoints is potentially relevant commercially but cannot be subjected to valid cultivar-level significance testing from the available records.

No cultivar was superior for every trait. Amrapali combined high TSS with a high taste score, Pusa Lalima combined low acidity with a high TSS:acid ratio,

Table 3: Physicochemical, sensory and cultivar-level ambient shelf-life characteristics of the 28 mango cultivars.

Cultivar	TSS (°Brix)	Acidity (%)	TSS:acid	Firmness (kg cm^{-2})	Aroma (1-9)	Taste (1-9)	Shelf life (d)	Peelability (1–9)
Pusa Desi	13.3	0.45	29.56	8.5	6	8	8-10	8
Bombay Green	16.0	0.42	38.10	5.7	7	6	6-8	7
Chiang Mai	13.0	0.24	54.17	6.0	7	8	11-13	4
Banana	18.5	0.28	66.07	2.6	7	6	8-10	8
Nam Doc Mai	21.5	0.20	107.50	5.5	3	7	8-10	4
Nileswari	13.0	0.32	40.62	4.5	6	7	9-11	7
Sarenga	21.0	0.35	60.00	4.7	7	8	9-11	8
CISH-949	19.0	0.36	52.78	9.5	5	4	11-13	7
Dofala	14.5	0.45	32.22	4.8	6	8	12-15	6
Osteen	14.0	0.26	53.85	8.0	5	7	12-15	2
Anwar Ratool	20.0	0.32	62.50	4.5	7	7	12-14	6
Champa	18.0	0.28	64.29	5.6	8	7	8-10	7
Pusa Arunima	17.2	0.30	57.33	8.5	5	8	12-14	8
Chitalkhas	5.0	0.40	12.50	9.5	7	3	8-10	7
Catimon	16.0	0.35	45.71	12.0	6	3	10-12	8
3-Taste	12.0	0.31	38.71	5.0	4	5	9-11	7
Miyazaki	16.5	0.20	82.50	7.1	6	6	10-14	7
Sensation	17.0	0.42	40.48	8.0	3	8	11-13	2
Himsagar	20.0	0.22	90.91	4.6	6	8	6-8	3
Pusa Lalima	17.5	0.15	116.67	7.5	8	8	10-12	5
Langra	16.4	0.34	48.24	9.0	7	8	7-10	5
Pusa Arunika	16.0	0.35	45.71	7.5	2	3	10-12	4
Zardalu	17.2	0.25	68.80	6.6	8	8	8-10	6
Amrapali	22.0	0.35	62.86	2.7	8	9	10-12	7
Manjeera	14.4	0.28	51.43	10.0	8	8	10-12	7
Kensington Pride	16.5	0.30	55.00	7.5	5	6	9-11	6
BARI-4	13.5	0.34	39.71	8.0	3	4	10-12	5
Apple	17.2	0.36	47.78	2.5	7	9	8-10	7

and Osteen and Dofala had the longest recorded ambient shelf-life ranges. Anwar Ratool showed a comparatively balanced quality–storage profile, while 3-Taste, Manjeera, Chiang Mai and BARI-4 were notable for large fruit and/or pulp weight. Saroj and Prasad (2023) evaluated mango genotypes during ambient storage at 25 ± 4 °C and 65 ± 5% relative humidity and reported genotype-dependent shelf life, including 9–12 d for Amrapali. Because the present thesis records contain internally inconsistent descriptions of the exact ambient conditions and no uniform quantitative rejection threshold, direct shelf-life comparisons with published studies are limited. These cultivars should therefore be treated as priorities for standardized follow-up trials rather than as definitive recommendations for distribution or processing.

These contrasting profiles support practical market segmentation (Table 4). Premium fresh-market cultivars should combine attractive appearance, flavour and acceptable texture. Cultivars intended for distant distribution require sufficient firmness and shelf life, whereas processing cultivars should be evaluated primarily for pulp recovery, fibre, colour and composition. The proposed groups are preliminary and must be validated through replicated, multi-season trials at standardized maturity.

Table 4: Preliminary market orientation based on the observed trait combinations.

Potential orientation	Indicative cultivars	Basis in the present dataset
Premium fresh/eating quality	Amrapali, Pusa Lalima, Anwar Ratool, Zardalu, Apple	High TSS, favourable sweetness-acid balance and/or high aroma and taste scores.
Extended ambient marketing	Osteen, Dofala, Anwar Ratool, Pusa Arunima	Cultivar-level shelf-life records of 12-15 or 12-14 d.
High fruit or pulp weight	3-Taste, Manjeera, Chiang Mai, BARI-4, Osteen	High absolute fruit and/or pulp weight; processing recovery requires confirmation.
Firm handling types	Catimon, Manjeera, CISH-949, Chitalkhas, Langra	Comparatively high firmness at the evaluated stage.
Rapid local marketing	Bombay Green, Himsagar	Short cultivar-level ambient shelf life of 6-8 d.

Trait relationships and multivariate positioning

PCA of the 13 standardized variables produced eigenvalues of 4.144, 2.226, 1.554, 1.264 and 1.106 for PC1–

Table 5: Eigenvalues and variance explained by all principal components from the 13-variable standardized dataset.

Component	Eigenvalue	Variance explained (%)	Cumulative variance (%)
PC1	4.144	30.741	30.741
PC2	2.226	16.511	47.252
PC3	1.554	11.530	58.783
PC4	1.264	9.379	68.162
PC5	1.106	8.206	76.368
PC6	0.881	6.533	82.902
PC7	0.816	6.051	88.953
PC8	0.486	3.607	92.560
PC9	0.413	3.066	95.626
PC10	0.297	2.200	97.827
PC11	0.170	1.259	99.086
PC12	0.099	0.733	99.819
PC13	0.024	0.181	100.000

PC5, respectively; these five components met the Kaiser criterion (eigenvalue >1) and together explained 76.4% of the total variance (Table 5). PC1 and PC2 explained 30.7% and 16.5%, respectively (47.2% cumulatively), so the two-dimensional biplot (Figure 2) represents less than half of the total standardized variation. PC1 was dominated by fruit weight, pulp weight, stone weight, length and width, whereas PC2 was most strongly associated with taste, firmness, acidity, TSS and aroma. Accordingly, the biplot is interpreted as an exploratory visualization of trait structure rather than as definitive cultivar clustering.

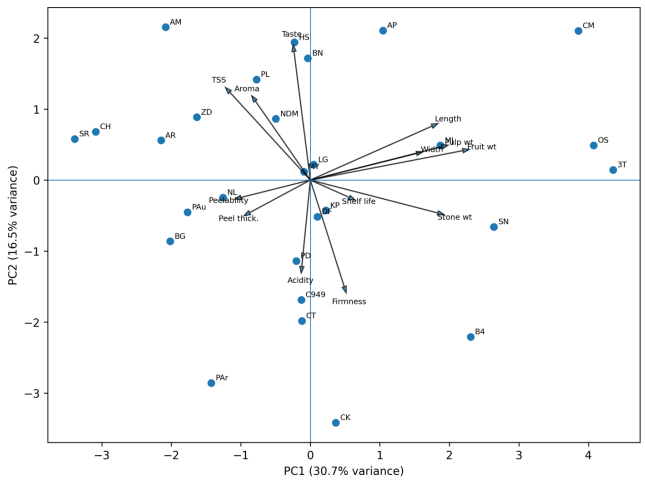


Figure 2: Principal component biplot for 28 mango cultivars based on 13 standardized variables. PC1 and PC2 explained 30.7% and 16.5% of total variance, respectively (47.2% cumulatively). Because more than half of the total variance lies outside these two axes, cultivar separation is interpreted as exploratory. Cultivar abbreviations correspond to the names listed in Tables 2 and 3.

The broad PCA structure was robust to exclusion of Chitalkhas. In the sensitivity analysis, PC1 and PC2 explained 33.1% and 15.9% of the variance (48.9% cumulatively), and the dominant PC1 loadings remained fruit weight, pulp weight, stone weight, length and width; PC2 continued to emphasize taste, aroma, firmness and acidity. Thus, the main size-related multivariate pattern was not driven by the low TSS value of Chitalkhas, although the sensitivity analysis demonstrated that specific bivariate relationships involving TSS were less robust. This pattern is broadly compatible with the strong fruit-size and pomological variation described in the multivariate characterization of Khadivi *et al.* (2022), while differences in genotype sets and measured traits preclude direct equivalence of component structures.

The bivariate positioning of TSS and shelf-life midpoint further illustrated the absence of a single optimum cultivar (Figure 3). Amrapali occupied the high-TSS region but had intermediate shelf life, while Osteen and Dofala combined longer shelf life with moderate TSS. Anwar Ratool approached a useful compromise between sweetness and marketing duration. Bubble size, representing fruit weight, showed that large fruit size was distributed independently of these quality and storage traits. Together, the analyses reinforce the value of trait-specific selection rather than a single overall ranking.

Limitations of the study

This study has six principal limitations. First, the fruit collection represents one season, one orchard and one geographic location in West Bengal, limiting extrapolation to other years and agro-climatic zones. Second, a uniform, cultivar-appropriate harvest-maturity criterion was not documented across all 28 cultivars; maturity differences may therefore confound comparisons of TSS, acidity, firmness and sensory quality, particularly the unusually low TSS recorded for Chitalkhas.

Third, the analyses use cultivar-level summary val-

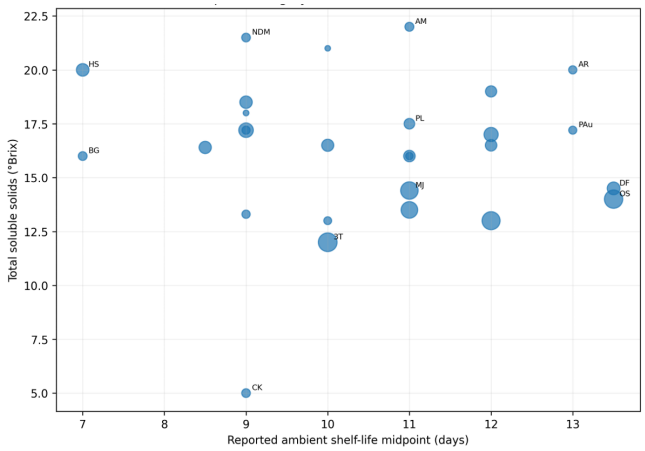


Figure 3: Positioning of mango cultivars by total soluble solids and cultivar-level ambient shelf-life midpoint; bubble size represents fruit weight. (PD, Pusa Desi; BG, Bombay Green; CM, Chiang Mai; BN, Banana; NDM, Nam Doc Mai; NL, Nileswari; SR, Sarenga; C949, CISH-949; DF, Dofala; OS, Osteen; AR, Anwar Ratool; CH, Champa; PAu, Pusa Arunima; CK, Chitalkhas; CT, Catimon; 3T, 3-Taste; MY, Miyazaki; SN, Sensation; HS, Himsagar; PL, Pusa Lalima; LG, Langra; PAr, Pusa Arunika; ZD, Zardalu; AM, Amrapali; MJ, Manjeera; KP, Kensington Pride; B4, BARI-4; AP, Apple.)

ues rather than replicated fruit-level observations, so within-cultivar variance cannot be estimated and correlations are ecological associations among cultivar means. Fourth, sensory scores were derived from an in-house semi-trained panel; the original records do not document formal training duration, repeated sessions or inter-rater reliability. Fifth, shelf-life comparisons are based on thesis-level ranges with an incompletely standardized endpoint and internally inconsistent records of ambient storage conditions.

Sixth, image scale was not standardized across the cultivar photographs in Figure 1, so the plate is suitable only for qualitative shape and appearance, not visual size comparison. Future work should use replicated fruit-level sampling across seasons and locations, standardized maturity indices, documented sensory protocols with reliability assessment, and predefined shelf-life endpoints under controlled ambient conditions.

CONCLUSION

The 28 mango cultivars showed substantial diversity in morphology, fruit and pulp size, physicochemical quality, sensory scores and recorded ambient shelf life. The most statistically robust association was between fruit weight and pulp weight, while several sensory-quality correlations did not remain significant after FDR correction and were sensitive to the Chitalkhas TSS outlier. For West Bengal, the present data identify priority candidates for replicated validation rather than immediate commercial recommendation: Amrapali and Pusa Lalima for eating-quality traits; Osteen and Dofala for recorded longer ambient life; Anwar Ratool for a balanced preliminary quality–storage profile; and 3-Taste, Manjeera, Chiang Mai and BARI-4 for high fruit or pulp weight. Growers and packhouse operators can use these contrasts to select cultivars for follow-up storage and market trials, while breeders may use contrasting size, quality and storage profiles to define parent combinations for local improvement programmes. Multi-season, multi-location trials with standardized maturity, replicated fruit-level measurements and validated shelf-life endpoints are required before cultivation, processing or distribution recommendations are made.

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AUTHOR CONTRIBUTIONS

Suhrrita Chakrabartty Das: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. Kankana Sarkar: Investigation, Data curation, Validation, Writing – review and editing. Fatik Kumar Bauri: Resources, Investigation, Validation, Writing – review and editing. Karabi Biswas: Methodology, Interpretation of data, Writing – review and editing. All authors reviewed and approved the final version of the manuscript.

DATA AVAILABILITY

The cultivar-level dataset supporting the findings of this study is available from the corresponding author on reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this article.

ETHICS STATEMENT

Sensory evaluation involved adult departmental volunteers and edible mango samples, and informed consent was obtained before participation.

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