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Morpho-Biochemical Diversity and Elite Hybrid Selection in Amrapali × Sensation Mango (*Mangifera indica* L.) Progenies

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Abstract

Mango (*Mangifera indica* L.) is among the most valued tropical fruits, recognized for its taste, nutrient profile, and worldwide significance. The increasing preference for cultivars with increased sweetness, nutrition and dietary quality has created a strong impetus for targeted and trait-oriented breeding. In this study, 35 hybrids derived from an Amrapali × Sensation cross were comprehensively evaluated for morpho-biochemical diversity, integrating detailed sugar and organic acid profiling with quantitative morphological traits that are critical to fruit quality. The hybrids displayed wide phenotypic variability, with both intermediate and transgressive segregation across fruit, stone, peel, and pulp traits. Fruit size varied substantially (length: 63.71–121.45 mm; weight: 70.48–324.69 g), whereas significant differences were observed in fruit shape, peel thickness, and pulp recovery. Biochemical profiling revealed broad variation in TSS (12.63–22.03 °Brix), sucrose (16.01–74.46 mg/g), glucose (4.55–24.78 mg/g), fructose (5.00–25.41 mg/g), and organic acids, including ascorbic acid (1.79–9.71 mg/g) and citric acid (1.03–11.74 mg/g). Multivariate analyses, including PCA, correlation, and hierarchical clustering, successfully dissected trait variability, with PCA identifying a clear size-quality block and hierarchical clustering grouping progenies into four different clusters. Notably, transgressive segregation for traits such as the pulp: stone ratio (up to 9.28) and TSS (22.03 °Brix) indicates the potential for selecting superior recombinants among the progenies. Overall, this study demonstrates the identification of superior hybrid progenies and the effectiveness of crossbreeding among heterozygous mango hybrids in generating genetic variability, while establishing morpho-biochemical profiling and multivariate analysis as strong tools for identifying elite ideotypes for future mango improvement programs.

Keywords: Phenotypic variability, Sugars, Organic acids, Nutritional, Transgressive segregants

Introduction

Mango (*Mangifera indica* L.), a member of the family Anacardiaceae, is among the world's most economically vital and nutritionally rich tropical fruits. Renowned for its unique flavor profile, exceptional sensory attributes, and diverse phytochemical composition, it is universally known as the

“King of Fruits”¹. It is cultivated in more than 115 countries and ranks among the most significant fruit crops in tropical and subtropical regions, contributing substantially to nutritional security by providing nearly 50% of the recommended vitamin C intake². Global mango production exceeds 55.10 million metric tonnes annually, with India accounting for more than 40% of total production (23.14 million tonnes from 2.41 million ha), highlighting its immense economic and dietary importance^{3,4}. In addition to being economically important, mango is a dense source of essential carbohydrates, organic acids, vitamins, and health-promoting bioactive constituents. Fruit quality is a multifaceted, quantitative trait influenced by synergistic interactions among morphological, physiological, and biochemical variables. External attributes, specifically fruit length, width, weight, thickness, and the fruit shape index (FSI), are important in determining visual appeal, commercial grading, and marketability. Simultaneously, internal yield parameters, *viz.* Pulp weight, the pulp-to-stone ratio, and stone morphology (length, width, thickness, and weight), along with peel thickness and stone fiber length, affect the efficiency of edible recovery and suitability for industrial processing.

Biochemical constituents, particularly the interplay between sugars and organic acids, are key drivers of mango fruit quality, governing the critical balance of sweetness, acidity, and overall flavor of the fruits. Over the past few decades, numerous studies have documented the nature and quantity of sugars and organic acids in mango fruits⁵⁻⁷. Nevertheless, most existing studies have focused on characterizing individual constituents and comparing their levels across cultivars. The concentrations of individual sugars, predominantly sucrose, glucose, and fructose, dictate both the intensity of sweetness and the energy density of the fruit. Conversely, organic acids, such as malic acid and citric acid, provide the necessary acidity and flavor depth while supporting various metabolic functions in fruits. This sugar–acid equilibrium is a well-established benchmark for assessing palatability and marketability^{8,9}. Sweetness levels varied across sugar components; if sucrose was scored as 1, fructose was scored as 1.75, glucose was scored as 0.75, and sorbitol was scored as 0.5^{10,11}. Sucrose plays various roles in plants. It affects respiration and photosynthesis, is a critical component of storage compounds, and aids in maintaining osmotic equilibrium in the cytosol¹². When choosing mangoes, consumers generally favor those with a rich sweetness balanced by a mild tang. Organic acids in fruits originate primarily from carboxylation reactions, which underpin key metabolic pathways and contribute directly to flavor development and nutritional quality¹³. These acids are not only essential for flavor but also contribute to fruit coloration by stabilizing anthocyanins. In addition, they help prolong the shelf-life of both fresh produce and processed fruit products¹⁴. In addition to their organoleptic impact, organic acids serve a vital physiological function by promoting digestive enzyme secretion and regulating various human metabolic pathways¹⁵. From a clinical standpoint, the specific carbohydrate profile and sugar–acid ratio have gained significant attention owing to the increasing global prevalence of metabolic disorders, such as *diabetes mellitus*. Mangoes with a balanced sugar–acid ratio may facilitate a more controlled glycemic response, positioning them as a functional component of health-oriented dietary strategies. Furthermore, the fruit is a prolific source of bioactive compounds that exhibit potent antioxidative, anticarcinogenic, and antimutagenic activities, as well as the ability to inhibit angiogenesis¹⁶. The medicinal properties highlight the potential of mango consumption against disease prevention. These health-promoting attributes further underscore the need for breeding programs that prioritize high-resolution biochemical quality alongside morphological fruit traits.

The genetics and inheritance pattern of important traits are poorly understood in mango owing to its ploidy level and heterozygous nature; therefore, genetic enhancement primarily involves hybridization between elite cultivars to consolidate essential traits, including yield stability, superior fruit quality, and environmental adaptability¹⁷. The cultivar ‘Amrapali’ is distinguished by its precocity, high pulp-to-stone ratio, high TSS, and dwarf architecture, whereas ‘Sensation’ is prized for its exceptional organoleptic profile and aesthetic appeal. Crossbreeding these hybrids establishes a robust genetic foundation for generating variability and isolating transgressive segregants with optimized morpho-biochemical attributes and commercial value. The fruit crops improvement through breeding programs ultimately depends on a comprehensive evaluation of genetic diversity within progenies and

the precise identification of elite genotypes for further advancement of crop¹⁸. The integration of morpho-biochemical characterization offers a more robust and precise framework for determining fruit quality. The application of advanced and precise analytical techniques, such as high-performance liquid chromatography (HPLC), enables the rigorous quantification of specific carbohydrate fractions, facilitating high-resolution metabolite mapping. When integrated with morphological and yield-related data, these methodologies significantly increase the resolution of diversity analyses and enable more targeted, precision-based selection strategies. To navigate these complex datasets, multivariate analytical tools such as correlation matrices, principal component analysis (PCA), and heatmap clustering have become indispensable for dissecting trait interactions. These methods have demonstrated high efficacy in identifying superior genotypes across various horticultural crops, including almond, walnut, fig, and pomegranate^{19–22}.

Against this backdrop, the current investigation was designed to provide an in-depth evaluation of morpho-biochemical diversity among progenies derived from an Amrapali (♀) × Sensation (♂) cross. The specific objectives were to evaluate the variability in key morphological and yield-related traits, including fruit dimensions, pulp and stone characteristics, and TSS; quantify sugar fractions and organic acids *via* high-performance liquid chromatography (HPLC)-based profiling; and identify elite hybrid progenies with potential utility in future mango improvement programs for improved fruit quality and consumer acceptance.

Materials and methods

This work was carried out at the ICAR- Indian Agricultural Research Institute, New Delhi (28.40° N, 77.10° E; 228.16 m above sea level), employing thirty-five F₁ mango hybrids derived from the Amrapali (♀) × Sensation (♂) cross, which was evaluated across the 2024 and 2025 growing seasons. All hybrid mango progenies were cultivated and maintained under standardized management practices in the mango hybrid evaluation block of the Division of Fruits and Horticultural Technology (FHT), ICAR-IARI, New Delhi, India. The experimental site for this research is located in the Trans-Gangetic plains of India, an agroclimatic region typified by semiarid, subtropical conditions. This region experiences distinct seasonal extremes, with cold winters and hot, dry summers. The peak summer months extend from mid-May to the end of June, with recorded maximum temperatures between 42 °C and 46 °C, whereas the peak winter months are from mid-December to the end of January, with minimum temperatures between 4 °C and 8 °C. Fruits were harvested at the mature firm stage and ripened naturally under ambient conditions without artificial ripening treatment. The experiment included three replicates. After the morphological traits of the fruits were documented, the fresh mango pulp samples were preserved at –80 °C in a deep freezer for further assessment of sugars and organic acids.

i) Amrapali

Amrapali, released in 1979, originated from a cross between Dushehari and Neelum. It is a late-bearing, dwarf variety known for consistent and abundant yields, making it well-suited for high-density orchards. The fruits are medium-sized (150–250 g) with a high pulp proportion (~74.8%) and elevated total soluble solids (~22.8 °Brix). The pulp is rich in an orange-red hue and contains significantly more β-carotene than either parent. Because of its compact growth habit, reliable productivity, and strong combining ability, Amrapali is widely adopted as a female parent in mango breeding programs²³.

ii) Sensation

Sensation is an exotic cultivar from Florida, USA, which is believed to be a hybrid of Haden × Brooks. It is valued in breeding programs for its striking red peel color. The fruits are oval, weighing between 250 and 450 g, with dark plum-red skin dotted by pale lenticels. The pulp is light yellow, mildly sweet, low in fiber, and has a pleasant aroma. As a late-season, monoembryonic variety, it ripens from the last week of July to mid-August and is frequently used as a pollen parent in hybridization programs to increase peel coloration in new hybrids.

Fruit physical parameters

The fruits were randomly collected at physiological maturity from each hybrid tree and ripened naturally to determine average phenotypic values. A total of 15 quantitative traits, including fruit, stone, peel, and pulp, were recorded according to standard protocols. Morphometric measurements were taken *via* digital Vernier calipers (Mitutoyo Model 500-147), whereas fruit weights were determined via a digital balance (Adair Dutt-1620C, USA).

Determination of sugars

The total soluble solids (TSS) content of fresh mango pulp was measured via a digital refractometer (MA871; Milwaukee, Romania). The quantification of individual sugar fractions, glucose, fructose, and sucrose was done *via* high-performance liquid chromatography (HPLC) technique following the protocol of Medlicott⁵. External standards (Sigma–Aldrich) were used to generate a calibration curve over a concentration range of 5000–35714 ppm. For extraction, a 5 g mango pulp sample was crushed with double-distilled water in a pre-sterilized mortar and pestle, then centrifuged for 20 minutes at 15,000 rpm. The residual material was again extracted, and the supernatants were pooled to yield a final volume of 25 mL, which was filtered through Sep-Pak C18 cartridges (Waters Associates) and Millipore membranes with a 0.45 µm filter size before chromatographic analysis.

The analysis was carried out in triplicate on an Agilent 1260 Infinity II system equipped with a refractive index detector (RID). The carbohydrate column, Agilent Hi-Plex H (7.7 × 300 mm, 8 µm), was used for chromatographic separation, maintained under isocratic conditions at 80 °C with 0.005 M sulfuric acid at a flow rate of 0.6 mL min⁻¹. Individual Sugar fractions were determined *via* calibration curves with high correlation coefficients, ensuring analytical precision and reproducibility.

Determination of organic acids

Organic acids, including citric, ascorbic, malic, succinic, and oxalic acids, in fresh mango pulp were measured using HPLC, a procedure from Medlicott's protocol⁵. Analyses were conducted on a reverse-phase HPLC system (Alliance, Waters 2998 Corp., USA) equipped with an e2695 separation module, a quaternary pump, and a 2998 photodiode array (PDA) detector operated through Empower 2 software. Separation was carried out on an Agilent Hi-Plex H carbohydrate column (7.7 × 300 mm, 8 µm), maintained at 65 °C and a flow rate of 0.6 mL/min with 0.005 M sulfuric acid as the mobile phase. Detection was performed at 210 nm, and quantification was based on retention time (RT) and calibration curves to ensure data accuracy.

Statistical analysis

Data expressed as the mean values accompanied by their respective standard deviations. Differences among hybrids were analyzed, and significance was determined at $P < 0.05$ using the agricolae package in R (RStudio version 2026.01.1+403) after testing for homogeneity of variance. Pearson correlation coefficients were computed via the *cor* function and visualized via the *corrplot* package. Multivariate analyses, including principal component analysis (PCA) and hierarchical clustering, were performed using the *ggbiplot* package to assess relationships among mango hybrids and biochemical traits. Graphs and scatter plots were prepared via OriginPro 2022 (OriginLab, USA).

Results

In this study, morpho-biochemical traits were evaluated, and genetic diversity was assessed among hybrids and their parents (Table 1). This characterization represents a first crucial step toward the systematic, target-oriented and effective utilization of germplasm. The findings of this investigation are presented below, organized by subheading.

Fruit physical parameters

Substantial variability in fruit morphometric traits was evident across the thirty-five hybrid progenies and their parental lines, Amrapali and Sensation (Table 2 & Fig. 1). Fruit quality attributes, *viz.* The length, width, fruit shape index, weight, stone size, pulp proportion, peel thickness, and peel coloration represent critical selection criteria in the development of novel mango hybrids tailored to consumer and market demands. Fruit length ranged between 63.71 mm and 121.45 mm. The fruit length was the longest in H-1-6 (121.45 mm), followed closely by Amrapali (120.10 mm). Conversely, the hybrid H-3-5 produced the shortest fruits, with an average length of 63.71 mm. The fruit width ranged between 40.67 mm in H-6-13 and 77.11 mm in Sensation. With respect to length, H-1-6 significantly exceeded the population average, although it was statistically comparable to those of Amrapali (120.10 mm) and H-1-5 (119.14 mm). For width, sensation was the leading component (77.11 mm), followed by H-14-2 (72.50 mm), both of which showed marked deviation from the trial mean. The fruit shape index (fruit length/width ratio) displayed broad variation, ranging from H-6-13 (2.22) to H-3-5 (1.16). In contrast, the parental hybrids Amrapali and Sensation presented values of 1.75 and 1.48, respectively. The consistently high values for length and width, along with the absence of significant block effects, highlight the strong genetic regulation of these morphometric traits. Consequently, H-1-6, Sensation, and H-1-5 can be considered elite candidates for targeted breeding.

The ANOVA revealed highly significant genotypic variation for fruit weight ($p < 0.001$), with a nonsignificant block effect ($p = 0.163$), confirming that the recorded diversity was due primarily to genetic factors rather than to environmental factors. Fruit weight was widely distributed, with H-1-5 having the highest weight (324.69), significantly outperforming the entire hybrid population. The top-tier hybrids, including Sensation (284.09), H-14-2 (278.77), and Amrapali (271.84), formed a secondary high-weight cluster, exhibiting statistical parity among themselves, but significant divergence from the low-weight group led by H-1-10 (70.48). The majority of hybrid progenies were concentrated in the range of 150–250 g (30), followed by 271–325 g (4) and 70–98 g (3), indicating a predominance of medium-sized fruits in the population. Significant variation in fruit thickness was observed among the hybrid progenies, ranging from 37.35 mm for H-6-13 to 66.75 mm for H-20-2. The majority of hybrids clustered within the 50–60 mm interval, indicating a predominance of medium-thick fruits. Notably, H-20-2, Sensation, and H-14-2 demonstrated consistent performance for these traits.

The mango hybrid progenies and their parental genotypes exhibited substantial genotypic variation for all stone-related traits (Fig. 2). The stone length ranged from 53.11 mm to 109.77 mm. The longest stones were recorded in H-3-11 (109.77), which were at par with H-11-1 (109.13 mm). Similarly, the smallest stone was H-3-5 (53.10 mm). The majority of hybrids clustered in the 75–87 mm range, indicating a central tendency toward moderate stone size. The stone thickness ranged from H-1-3 (10.54 mm) to H-7-4 (22.89 mm). Nearly 43% of the hybrids clustered within the 15.5–18.0 mm interval, indicating a high degree of uniformity across the population. Among them, H-7-4 (22.89 mm), H-14-2 (21.65 mm), and Sensation (20.78 mm) were identified as superior for stone robustness. The parental hybrid, Amrapali, recorded values of 93.25 mm and 19.99 mm for stone length and thickness, respectively, whereas Sensation had values of 85.75 mm and 21.60 mm, respectively.

Stone fiber length in mango is a significant trait, as it directly influences fruit texture, the ease of pulp separation, and consumer preference. Stone fiber length ranged from H-20-2 (0.32 cm) to H-3-14 (3.27 cm). The majority of hybrids fell within the 0.91–1.50 cm interval, suggesting a dominance of medium fiber length types. Hybrids such as H-3-14 (3.27 cm) and H-4-3 (2.95 cm) stood out for their relatively high fiber content, whereas H-20-2 (0.32 cm) and Amrapali (0.85 cm) were favorable for low-fiber traits. Stone width and weight also revealed marked genetic variability. Sensation (44.37 mm, width) and H-14-2 (51.17 g, weight) consistently ranked first. While most hybrids clustered in the 24.1–30.9 g range for stone weight, width was more even across all hybrids. At the other end of the spectrum, H-6-13 (31.22 mm, width; 18.45 g, weight) presented the lowest values, emphasizing its strong importance for breeding initiatives focused on optimizing the pulp-to-stone balance.

The results also revealed highly significant genotypic variation for all pulp and peel related traits, indicating substantial diversity within the population (Fig. 3). The peel thickness ranged from H-1-8 (0.66 mm) to H-3-9 (1.49 mm), with most hybrids concentrated in the 0.99-1.16 mm range. Pulp weight varied widely, ranging from H-1-10 (32.79 g) to H-1-5 (232.64 g), with the majority of hybrids grouped within the 72.8-112.7 g category. The pulp content varied from 33.19% to 75.63%, with nearly half of the hybrids clustered in the 58.7–67.1% range, while Amrapali recorded the highest pulp percentage. The pulp-to-stone ratio varied from 1.64 to 9.28, with most hybrids falling between 3.17 and 4.70. Notably, H-1-5 exhibited superior performance in terms of the highest pulp weight and peel weight along with the maximum pulp: stone ratio.

Biochemical traits

The mango hybrid progenies, along with Amrapali and Sensation, exhibited substantial variation in the assayed fruit biochemical parameters, TSS, sugars, and organic acids. Linearity plots for sugar fractions and organic acid standards, illustrating the relationship between analyte concentration and detector response, are presented in Fig. 4 and Table 3. The results of the quantitative profiling of sugars and organic acids in fresh mango pulp via HPLC are presented in Table 4 and Figs. 5 & 6.

Organic acids

The ANOVA results confirmed highly significant genotypic variation across all the organic acid traits, reflecting substantial biochemical diversity among the evaluated mango hybrids. Ascorbic acid in humans plays a vital role as an antioxidant, supporting immune defense and collagen formation and enhancing iron absorption, thereby contributing to overall health and resilience against oxidative stress. The ascorbic acid content ranged from H-4-2 (1.79 mg/g) to H-1-8 (9.71 mg/g), with nearly 60% of the hybrids falling within the range of 3.37–6.54 mg/g, which is indicative of moderate vitamin C levels in most hybrids. Hybrids such as H-1-8 (9.71 mg/g) and H-6-13 (8.92 mg/g) presented relatively high concentrations, underscoring their potential value in breeding programs aimed at enhancing nutritional quality, especially Vit C.

Citric acid constitutes a central carboxylic acid within the Krebs cycle, serving as a pivotal intermediate in cellular respiration and energy metabolism, where it initiates the oxidation of glucose and other substrates to release energy, making it essential for cellular respiration and energy production in living organisms²⁴. Pronounced genotypic variation was observed for both the citric acid and malic acid contents, reflecting considerable biochemical diversity among the mango hybrids. The citric acid content ranged from 1.03 mg/g to 11.74 mg/g, with most hybrids concentrated at the lower end, indicating a general tendency toward mild acidity. A distinct cluster comprising H-7-1 (11.74 mg/g), H-4-3 (10.62 mg/g), and H-3-5 (9.87 mg/g) presented markedly greater acidity, whereas Sensation (1.03 mg/g) presented the lowest value, making it particularly favorable for fresh consumption.

Malic acid also showed broad variability, with concentrations ranging from 0.09 mg/g to 11.94 mg/g, with nearly 81% of hybrids confined to the lower range, suggesting a limited contribution to overall acidity in most od hybrids. Only H-4-1 (11.94 mg/g) and H-3-14 (10.87 mg/g) presented distinctly elevated malic acid levels, underscoring their potential to increase the degree of tartness through breeding.

The oxalic acid levels remained consistently low across hybrids, with only minor variation, and most values clustered within a narrow range. Although oxalic acid was present in very small amounts, H-7-9, H-22-1, and H-4-3 presented the highest concentrations (0.18 mg/g). In contrast, succinic acid displayed the greatest variability, reaching H-4-2 (122.79 mg/g), while the majority of hybrids ranged from 1.22–25.54 mg/g, reflecting a skewed distribution. Hybrids such as H-4-2 (122.79 mg/g) and Sensation (118.63 mg/g) stood out for their exceptionally high succinic acid content.

Sugars

Highly significant genotypic variation was detected for TSS and all sugar fractions, with sucrose showing the strongest genetic influence. The TSS values ranged from H-4-8 (12.63 °Brix) to H-9-7 (22.03 °Brix), with approximately 35% of the hybrids concentrated in the 18.27–20.15 °Brix range, reflecting a predominance of moderately high sweetness. Amrapali (21.76 °Brix) ranked among the sweeter entries, whereas Sensation (13.74 °Brix) was comparatively lower. Among the individual sugars, sucrose was the dominant fraction, ranging from Sensation (16.01 mg/g) to H-3-11 (74.46 mg/g), with nearly half of the hybrids distributed across intermediate to higher levels. Fructose ranged from 5.00–25.41 mg/g, indicating a strong central tendency, whereas glucose ranged from 4.55–24.78 mg/g, indicating broader variability and a partially bimodal distribution.

Hybrids such as H-4-3 and Amrapali were distinguished for their relatively high fructose and glucose contents, respectively. Moreover, H-9-7 and Amrapali presented elevated TSS values, underscoring their suitability as superior table fruits with increased sweetness and consumer appeal. The biochemical profile was dominated by sucrose, reaching up to 74.46 mg/g, accompanied by high TSS levels exceeding 20 °Brix. This was complemented by a diverse organic acid composition, with ascorbic and citric acids contributing most to flavor variation within an otherwise low-acidity population. Overall, hybrids such as H-1-5, H-9-7, and H-14-2 emerged as standout performers, combining greater fruit weight and pulp recovery with increased sweetness and stable biochemical traits.

Correlation matrix analysis

Pearson's correlation matrix (PCA) highlighted robust trait interdependencies among the studied hybrid population and their parental hybrids (Fig. 7). A heatmap of the correlation coefficients was constructed to visualize these associations. In the correlation matrix, color gradients range from reddish color (-ve correlations) to bluish color (+ve correlations). Pale hues denote weak associations between the analyzed traits ($-0.30 < r < +0.30$), whereas reddish and bluish colors signify strong negative ($r < -0.70$) and strong positive ($r > +0.70$) relationships, respectively. The intensity of color shows the magnitude of correlation between the traits. Statistical significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$ is denoted by *, **, and *** respectively.

Fruit weight highlights its strongest association with pulp weight ($r = 0.92^{***}$). Similarly, its robust positive association was also seen for fruit width, length, and thickness at ($r = 0.76^{***}$), ($r = 0.74^{***}$), and ($r = 0.66^{***}$), respectively, highlighting the integrated contribution of these morphometric parameters to overall fruit size. The intense blue regions in the heatmap confirm that larger fruit dimensions, *viz.*, length, width, and thickness, directly contribute to the overall proportion of consumable fruit and to fruit weight. Similarly, stone length and overall fruit length ($r = 0.87^{***}$) were highly correlated, indicating that longitudinal fruit growth is largely governed by internal stone development. Stone weight and fruit weight also showed a strong positive association ($r = 0.55^{***}$), highlighting their interdependent growth dynamics. A positive correlation was depicted between the pulp-to-stone ratio and fruit weight ($r = 0.54^{***}$) but was negatively influenced by stone weight ($r = -0.27$), represented by the transition into red hues.

The total soluble sugars (TSS) and glucose fraction ($r = 0.31^*$) were significantly positively correlated, whereas no strong associations were detected with sucrose ($r = 0.10$) or fructose ($r = -0.01$). These findings indicate that TSS in the present population is primarily driven by glucose accumulation. Ascorbic acid (vitamin C) was observed to be positively correlated with glucose ($r = 0.40^*$) and fructose ($r = 0.34^*$), suggesting a coordinated accumulation of vitamin C and primary sugars. In contrast, a negative correlation between citric acid and glucose ($r = -0.36^*$) appeared as red regions in the heatmap, which was consistent with the expected inverse relationship between sweetness and acidity. Interestingly, while stone length has emerged as a major determinant of fruit shape, stone

fiber length has a negligible correlation with fruit weight or sugar content ($r \approx 0.02$), indicating that it can be selected as an independent quality trait in mango without compromising yield.

Principal component analysis

Principal component analysis effectively divided the total phenotypic variance into distinct orthogonal components, with the first few principal axes capturing the majority of trait variability among the hybrid progenies and their parental hybrids (Figs. 8 & 9). PC1 establishes a clear size-quality gradient. High negative loadings for fruit weight ($r = -2.20$) and pulp weight ($r = -2.14$) on PC1 identified H-1-5 and Sensation as the main drivers of biomass variation, whereas positive loadings for TSS and ascorbic acid highlighted H-6-13 as a reservoir of nutritional density. PC2 revealed a physiological trade-off between structural traits (stone width) and edible recovery (pulp: stone ratio), positioning Amrapali as a benchmark for metabolic efficiency. These findings suggest that simultaneous improvement in size and quality will require breaking the linkage observed along the PC1 axis through strategic hybridization between the identified clusters.

Principal component analysis (PCA) further quantified the contributions of morpho-biochemical parameters to address overall phenotypic diversity with respect to mango hybrids. The first principal component (PC1) axis explained the largest proportion of variance (26.13%), followed by others, with progressively smaller contributions. Overall, the first four principal components explained 58.10% of the total variation. Variables with loadings ≥ 0.5 were considered significant contributors to diversity²⁵.

PC1 and fruit quality related traits seem to be highly correlated, particularly total soluble solids (TSS, 0.88), while showing substantial negative associations with fruit length (-1.88), fruit width (-2.03), pulp weight (-2.14), and fruit weight (-2.20). Accounting for 26.9% of the total variation, this component primarily reflects a trade-off between fruit biomass and metabolic concentration, effectively separating large-fruited hybrids from nutrient-dense accessions. PC2, explaining 13.6% of the variability, highlighted a contrast between structural and acidic traits versus edible efficiency. High positive loadings were detected for stone width (1.51), succinic acid (1.40), and citric acid (1.34), whereas strong negative loadings were detected for glucose (-2.18), the pulp: stone ratio (-1.92), and sucrose (-1.91). This axis, therefore, captures the balance between sugar accumulation and pulp recovery versus structural waste and acidity. PC3 explained 9.2% of the total variation, driven by stone length (0.87) and the fruit shape index (FSI, 0.57), reflecting diversity in internal fruit architecture. PC4, which explained 8.4% of the variance, was associated with individual sugar dynamics, with notable contributions from fructose (0.62) and stone thickness (0.51). Successive components (PC5–PC8) explained the remaining significant variability through moderate contributions from specific organic acids and peel traits. Collectively, these results provide a comprehensive multidimensional view of phenotypic architecture, demonstrating that the studied morpho-biochemical parameters effectively partition genetic diversity and can guide targeted selection in mango breeding programs.

Cluster analysis

Agglomerative hierarchical clustering divided the 35 mango hybrid progenies and parental hybrids into 4 distinct functional groups, each reflecting a unique morpho-biochemical attribute (Fig. 10). Cluster I (the high-biomass elite group) contained 6 hybrids, including commercial, Amrapali and Sensation, as well as superior hybrids H-1-5 and H-1-6. This group was characterized by the largest fruit dimensions, with H-1-5 having the highest mean fruit weight (324.69 g) and maximum pulp yield, making it the leading cluster for yield-focused selection. Cluster II (intermediate group), the largest with twelve hybrids (e.g., H-3-2 and H-7-1), presented a moderate fruit size and balanced biochemical traits, representing phenotypically stable accessions suitable for consistent fruit quality. Cluster III (nutritional density group) comprised nine hybrids, including H-6-13 and H-1-10, which were characterized by smaller fruit sizes but significantly higher concentrations of organic acids and TSS, serving as reservoirs of nutritional density, particularly vitamin C. Cluster IV (metabolic diverse group) included ten hybrids,

such as H-9-7, H-4-1, and H-4-2, distinguished by unique metabolic fingerprints, including peak succinic acid levels in H-4-2 (122.79 mg/g) and maximum TSS in H-9-7 (22.03 °Brix). The clearcut separation between yield centric Cluster I and metabolically dense Cluster IV underscores a physiological trade-off within the hybrid population. These results suggest that hybridization between elite biomass donors from Cluster I and metabolic diverse group from Cluster IV could break the size–quality linkage, enabling the development of transgressive segregants that combine high fruit yield with superior sweetness and nutritional value.

Most hybrids aggregated within three large clusters (Clusters II, III, and IV), indicating broad phenotypic affinities, whereas Cluster I remained the most distinct. The Mahalanobis D^2 distance matrix further corroborated these results, revealing clear genetic divergence among the hybrids and substantiating the trait-based groupings identified through PCA. Cluster I exhibited the greatest divergence from all other groups, with the largest inter-cluster distances recorded against Cluster III ($D^2 = 188.55$), Cluster IV ($D^2 = 123.17$), and Cluster II ($D^2 = 102.29$). This highlights that the elite, yield-centric hybrids in Cluster I are genetically most distinct from the rest of the population. In contrast, Clusters II and IV showed the least divergence ($D^2 = 34.55$), suggesting high genetic relatedness and overlapping biochemical profiles, whereas Cluster III showed closer affinity with Cluster IV ($D^2 = 77.47$) than with Cluster I, confirming the metabolic proximity of small-fruited, high-density hybrids. Clusters II and IV grouped closely, reflecting low inter-cluster distances, whereas Clusters I and III exhibited pronounced divergence from the overall mean. Collectively, these findings emphasize the heterogeneity of morpho-biochemical traits across hybrids and their genetic structuring, suggesting that crossing highly divergent hybrids from Cluster I (e.g., H-1-5 or Sensation) with Cluster III (e.g., H-6-13 or H-1-10) would maximize variability and facilitate the development of superior transgressive segregants in future breeding programs.

Discussion

The challenge for mango breeders in the 21st century lies in creating hybrids that simultaneously meet consumer expectations for taste, deliver nutritional richness, and fulfill export-oriented standards²⁶. The parameters assessed in this study directly influence fruit quality and therefore serve as critical targets for improvement programs. Morpho-biochemical characterization remains indispensable for distinguishing and grouping perennial fruit germplasms, as demonstrated in crops such as guava²⁷, persimmon²⁸, mango^{29,30}, bael³¹, and walnut³². The extensive phenotypic diversity observed among the thirty-five mango hybrid progenies derived from an Amrapali × Sensation cross underscores a rich genetic reservoir, with highly significant variation across morphological and biochemical attributes and nonsignificant block effects, confirming that genetic factors primarily govern this diversity. This provides a reliable foundation for selecting elite donors and designing strategic hybridization schemes. The observed variability in fruit length, diameter, and weight appears to originate from both genetic and physiological factors, corroborating earlier findings on fruit shape reported by several researchers^{33–41}. Studies show that seed length is directly proportional to fruit length^{42,43}. However, seed width and thickness did not exhibit a consistent pattern. Collectively, these findings highlight the genetic basis of mango diversity and reinforce the importance of morpho-biochemical profiling as a cornerstone for mango improvement programs.

The variability observed in mango fruit weight can be attributed to agroclimatic influences, genetic background, and nutrient provisioning, underscoring the integrated role of both external and internal determinants⁴⁴. The genetic makeup of a plant exerts a dominant influence on pulp and stone characteristics, accounting for variability in weight, percentage, and dimensional attributes^{45,46}. Fruit size variation reflects inherent varietal traits, which are further shaped by environmental inputs such as soil moisture, crop load, and the source–sink relationship regulating carbohydrate allocation^{47,48}. Moreover, as a perennial fruit crop, mango is highly heterogeneous in nature, with polygenes regulating traits such as fruit size and weight, making these characteristics highly variable across geographic locations and environmental conditions. While consumers generally prefer medium-sized fruits with a

good acid–sugar blend, other traits, such as pulp content (%) and firmness, remain critical for dessert and culinary applications.

A comprehensive phenotypic landscape was observed, characterized by substantial genotypic variation ($p < 0.001$) across all physical parameters, most pronounced in terms of fruit weight, which showed a nearly five-fold difference. The identification of H-1-5 as the premier “yield ideotype” was statistically validated by its maximum mean weight of 324.69 g compared with H-1-10 (70.48 g), underscoring a robust genetic basis for biomass accumulation. This highlights the potential of specific hybrids as elite donors for yield-centric breeding programs.

The structural architecture among the studied mango hybrids varied considerably, with fruit lengths varying from 73.31 mm to 121.45 mm, where H-1-6 and Amrapali emerged as benchmarks for longitudinal growth. Fruit thickness peaked in H-20-2 (66.74 mm) and Sensation (64.65 mm), directly influencing the fruit shape index (FSI). The most elongated types were H-6-13 (FSI; 2.22) and H-3-11 (FSI; 2.08), which are commercially important traits for packaging and transportation. A primary breeding objective is to increase consumable biomass of fruit by balancing its weight, dimensions, and pulp content. The close relationship between fruit weight and dimensional measures illustrates that selection for girth and length translates into greater mass. In contrast, the exceptionally high association between stone length and fruit length ($r = 0.87$) indicates that longitudinal growth is closely tied to stone elongation. Variations in stone, peel, and pulp contents in hybrids are attributed to genetic constitution, fruit-to-stone ratios, and photosynthate transport⁴⁹, with stone weight variation corroborated by earlier reports^{50,38}. From a processing perspective, H-1-5 represents the ideal ideotype, recording the maximum fruit weight (324.69 g), absolute pulp weight (232.64 g), and the highest pulp-to-stone ratio (9.28), identifying it as an outlier in terms of resource allocation efficiency. Moreover, compared with elite hybrids, Amrapali remains the benchmark for pulp percentage (75.63%), although its lower absolute yield highlights that newer selections successfully combine high recovery with superior biomass accumulation.

Principal component analysis (PCA) provides a clear partitioning of variance along the PC1 axis into a size–quality gradient, with parameters with absolute values closer to unity exerting the strongest influence^{51,52}. The observed correlations and trait differences are in agreement with previous investigations on mango, underscoring the reproducibility of such findings in independent studies^{53–55}. The strong negative loadings of fruit weight and width and the positive loadings of TSS and ascorbic acid highlight a physiological dilution effect, likely arising from rapid water influx outpacing metabolite biosynthesis. However, multivariate clustering demonstrated that this linkage was not absolute; for example, Cluster IV hybrids such as H-9-7 maintained peak TSS (22.03 °Brix) despite moderate size, proving that sweetness can be retained outside the small-fruit “nutritional reservoir” group. The positive synergy between ascorbic acid and glucose ($r = 0.40$) further suggests a coordinated metabolic pathway.

The biochemical landscape of this study was dominated by a sucrose-centric sugar matrix ($F = 279.89$), with unique fingerprints, such as high succinic acid in H-4-2 and elite sucrose levels in H-3-11, indicating distinct enzymatic activities. The negative correlation between citric acid and glucose ($r = -0.36$) illustrates the typical metabolic competition that influences palatability. Regional cultivars such as Brazilian and Floridian Sensation presented lower TSS values (13.84–15.86 °Brix), whereas Amrapali consistently presented superior sugar profiles (21.76 °Brix)^{56,57}. As fruit ripens, the amount of monosaccharides increases^{58,59}, with fructose ranging from 10–20 g/100 g DW⁶⁰. Significant differences in biochemical traits among the 30 germplasms, coupled with high variation in the pooled analysis, provide ample opportunities for population improvement^{61,62}. The average coefficients of variation for sugars (32.88%) and acids (140.53%) suggest greater selection potential for acidity⁶³.

Finally, the D^2 distance matrix and hierarchical clustering provide a roadmap for breeding, with the greatest divergence observed between Clusters III and V, representing a key polarization for maximizing heterosis. Future strategies should prioritize crossing biomass elite hybrids (H-1-5, H-14-2) with high metabolic donors (H-9-7) to stack genes for size, pulp recovery, and sugar–acid balance.

Importantly, the negligible correlation between stone fiber length and quality traits supports the independent selection of low-fiber, soft-textured fruits without compromising weight or sweetness, thereby increasing consumer acceptability and processing potential.

Conclusion

This investigation demonstrated that morpho-biochemical characterization is indispensable for dissecting genetic diversity in mango and guiding precision breeding. This study revealed highly significant genotypic variation across fruit dimensions, pulp recovery, sugars, and organic acids, confirming a strong genetic basis for trait regulation. PCA and clustering analyses highlighted clear physiological trade-offs between fruit biomass accumulation and metabolic concentration, but also identified hybrids capable of maintaining high sweetness and nutritional density outside conventional small-fruit reservoirs. The divergence between yield-centric Cluster I and metabolically dense Cluster IV provide a strategic axis for hybridization, enabling the stacking of complementary traits. Hybrids such as H-1-5, H-14-2, H-6-13, and H-9-7 have emerged as promising parental candidates for breaking the size–quality linkage and generating transgressive segregants with increased consumer appeal, nutritional richness, and processing suitability. Ultimately, integrating advanced biochemical profiling with multivariate statistical tools provides a robust framework for mango improvement programs, enabling the development of next-generation hybrids that meet the dual demands of domestic markets and international trade.

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Author Contributions

Research conceptualization: JP, MS, KS, GK; Design of experiments: JP, GK, MS, KS, NS; Experiment execution and data collection: GK, JP, SS, NN; Data analysis and interpretation: JP, GK; Manuscript drafting: GK, JP, GoK, VK, ML, PU, NS, RS, MAI, DK.

Ethics declarations

The authors declare that there are no ethical issues associated with this study.

Data availability

Data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Additional Information

The authors confirm that they have no financial or non-financial competing interests to disclose.

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Fig. 1. The newly developed mango hybrid progenies and parental hybrids evaluated in the present study. 1. H-1-1, 2. H-1-10, 3. H-1-3, 4. H-1-5, 5. H-1-6, 6. H-1-8, 7. H-11-1, 8. H-14-2, 9. H-20-2, 10. H-22-1, 11. H-3-11, 12. H-3-14, 13. H-3-2, 14. H-3-4, 15. H-3-5, 16. H-3-6, 17. H-3-7, 18. H-3-9, 19. H-4-1, 20. H-4-10, 21. H-4-2, 22. H-4-3, 23. H-4-6, 24. H-4-8, 25. H-6-13, 26. H-6-2, 27. H-6-9, 28. H-7-1, 29. H-7-2, 30. H-7-4, 31. H-7-9, 32. H-9-1, 33. H-9-4, 34. H-9-7, 35. H-9-8, P1-Amrapali, P2-Sensation.



Fig. 2. The newly developed mango hybrid progenies and parental hybrids evaluated in the present study. 1. H-1-1, 2. H-1-10, 3. H-1-3, 4. H-1-5, 5. H-1-6, 6. H-1-8, 7. H-11-1, 8. H-14-2, 9. H-20-2, 10. H-22-1, 11. H-3-11, 12. H-3-14, 13. H-3-2, 14. H-3-4, 15. H-3-5, 16. H-3-6, 17. H-3-7, 18. H-3-9, 19. H-4-1, 20. H-4-10, 21. H-4-2, 22. H-4-3, 23. H-4-6, 24. H-4-8, 25. H-6-13, 26. H-6-2, 27. H-6-9, 28. H-7-1, 29. H-7-2, 30. H-7-4, 31. H-7-9, 32. H-9-1, 33. H-9-4, 34. H-9-7, 35. H-9-8, P1-Amrapali, P2-Sensation.

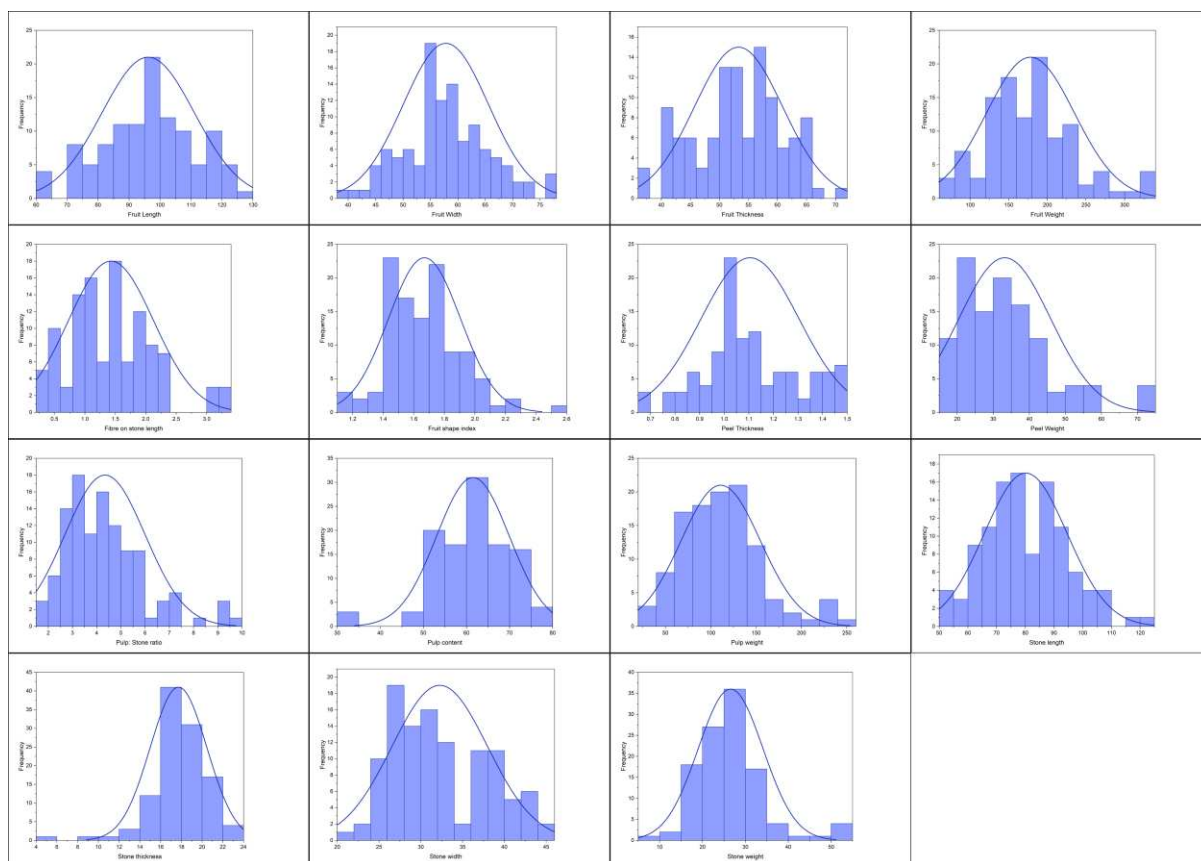


Fig. 3. Frequency distribution plots of morphological traits in 35 mango hybrid progenies and parental hybrids, Amrapali and Sensation.

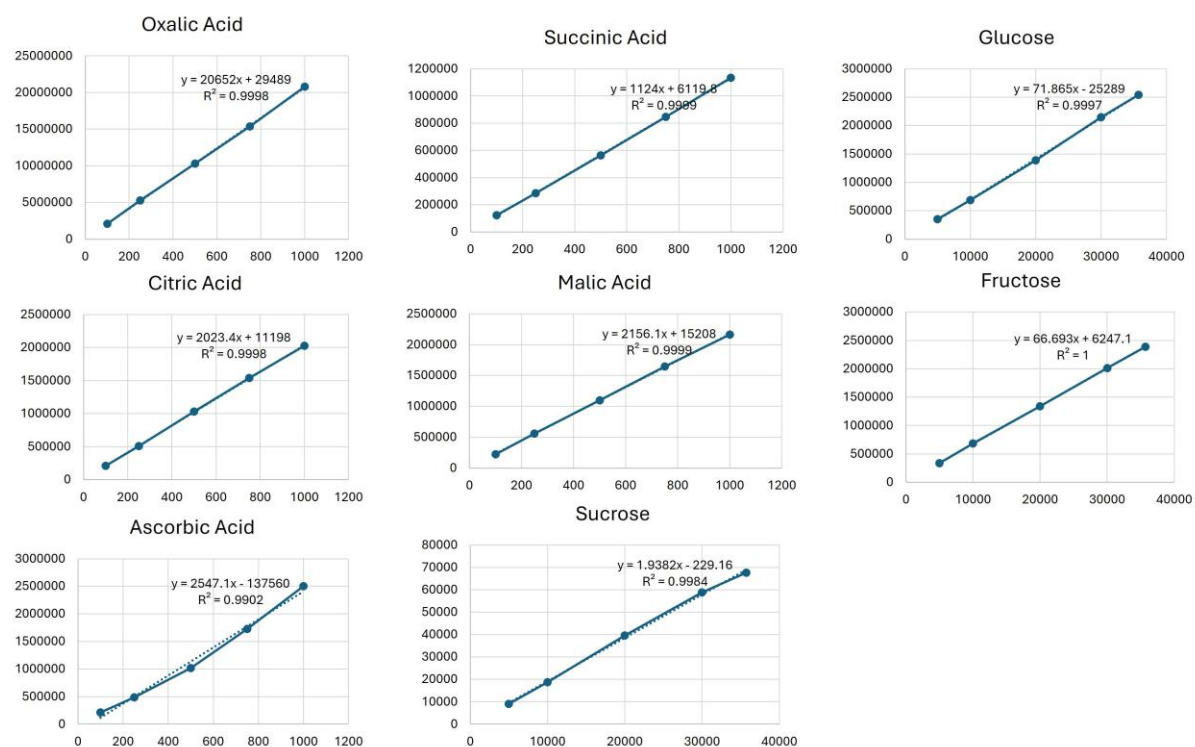


Fig. 4. Linearity plot of organic acid and sugar standards to assess the relationship between the concentration and the detector response.

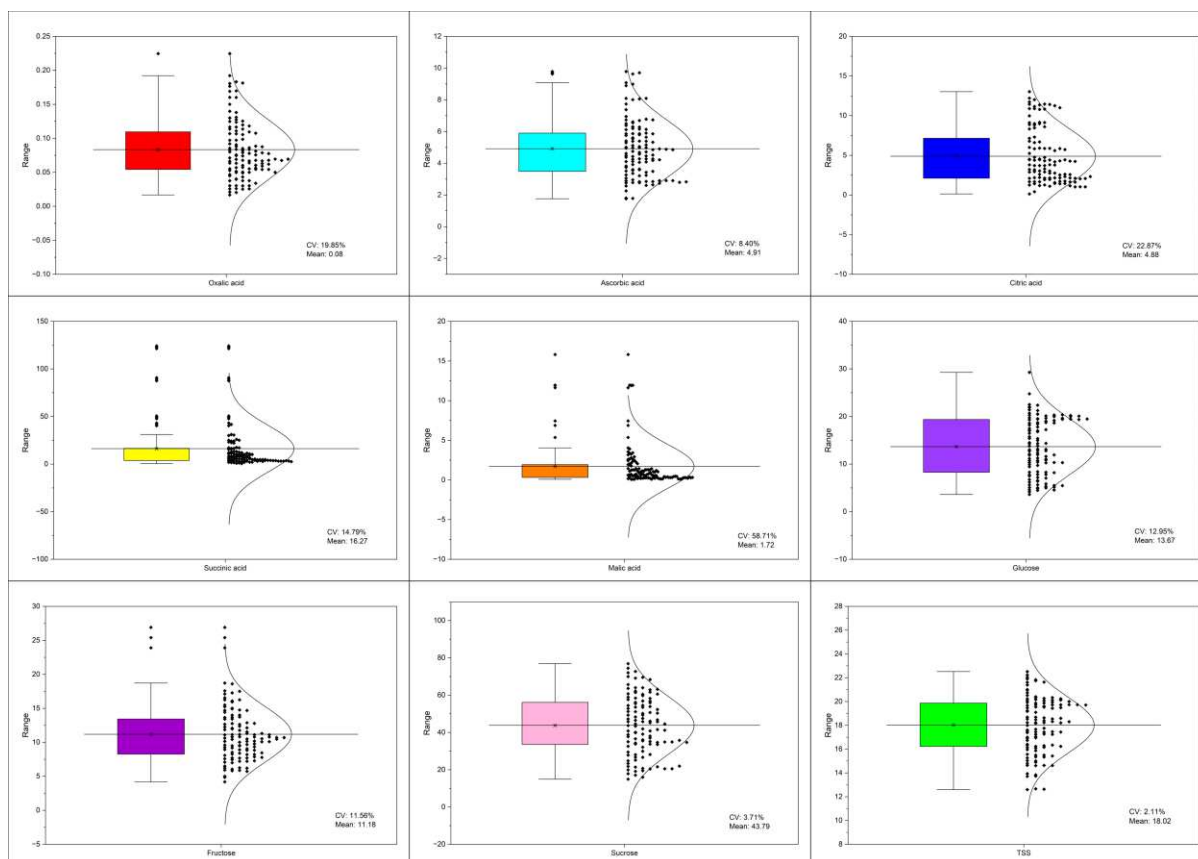


Fig. 5. Distribution of sugar and acid components in 35 mango hybrid progenies and parental hybrids, Amrapali and Sensation. Each scatter indicates the content of each material. The line on the right shows the fitted distribution curve. CV, coefficient of variation.

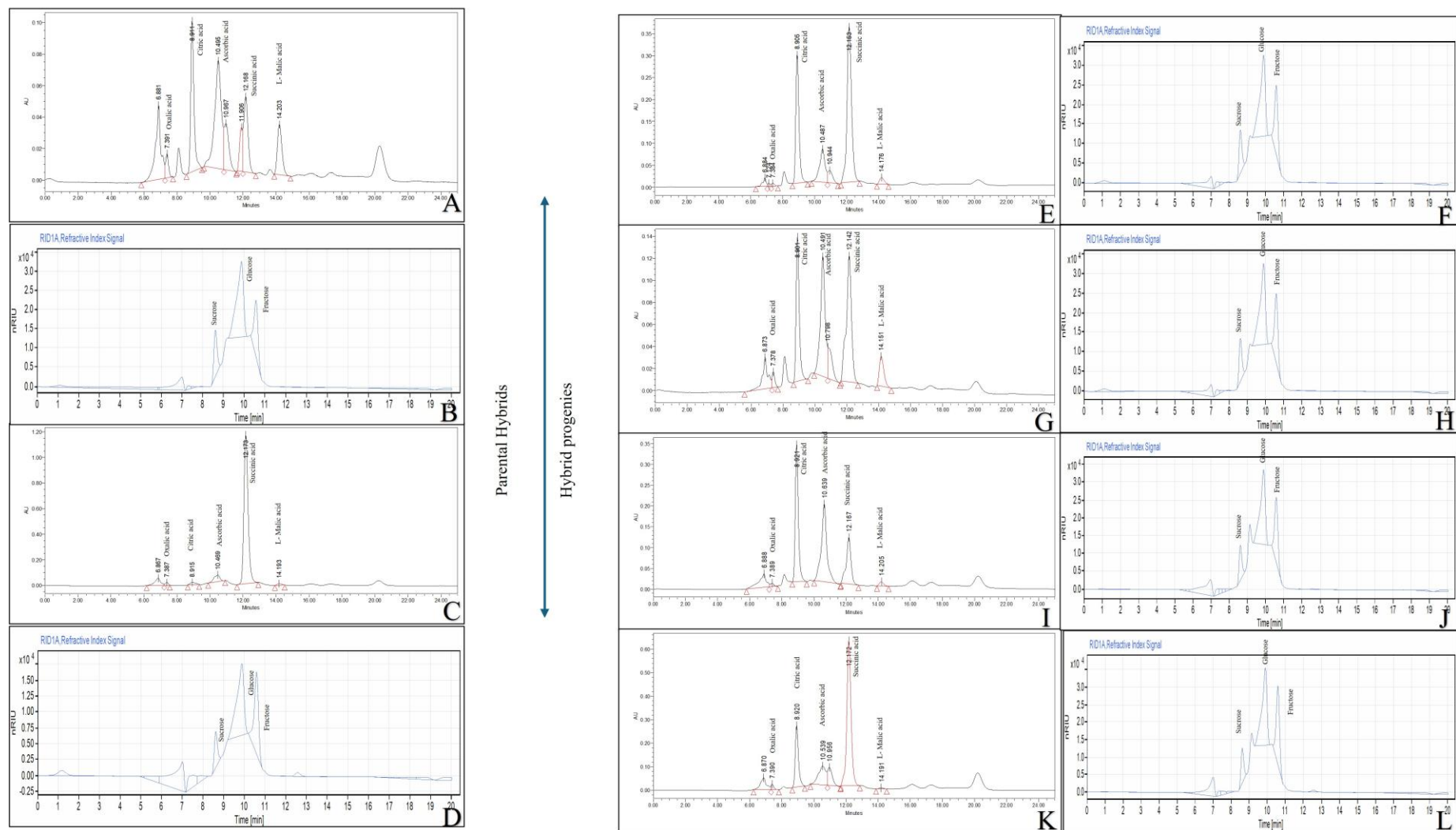


Fig. 6. Chromatograms of organic acid and sugar quantification: A. Organic acids (Amrapali), B. Sugars (Amrapali), C. Organic acids (Sensation), D. Sugars (Sensation), E. Organic acids (H-9-7), F. Sugars (H-9-7), G. Organic acids (H-1-5), H. Sugars (H-1-5), I. Organic acids (H-6-13), J. Sugars (H-6-13), K. Organic acids (H-14-2), L. Sugars (H-14-2),

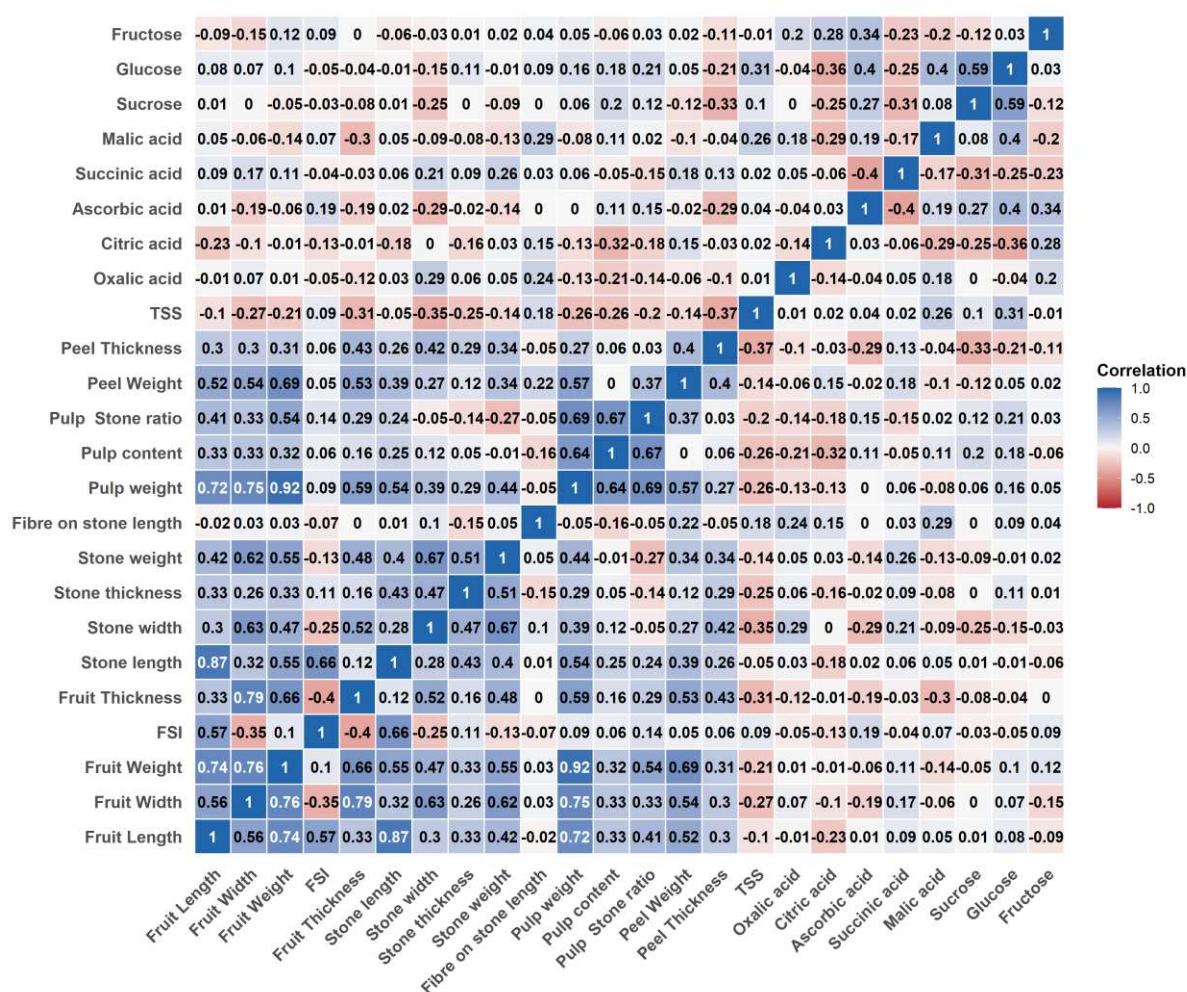


Fig. 7. Simple correlations among quantitative parameters evaluated among the hybrid progenies and their parents. Stronger positive correlations are shown in deeper blue, whereas negative correlations are indicated in reddish.

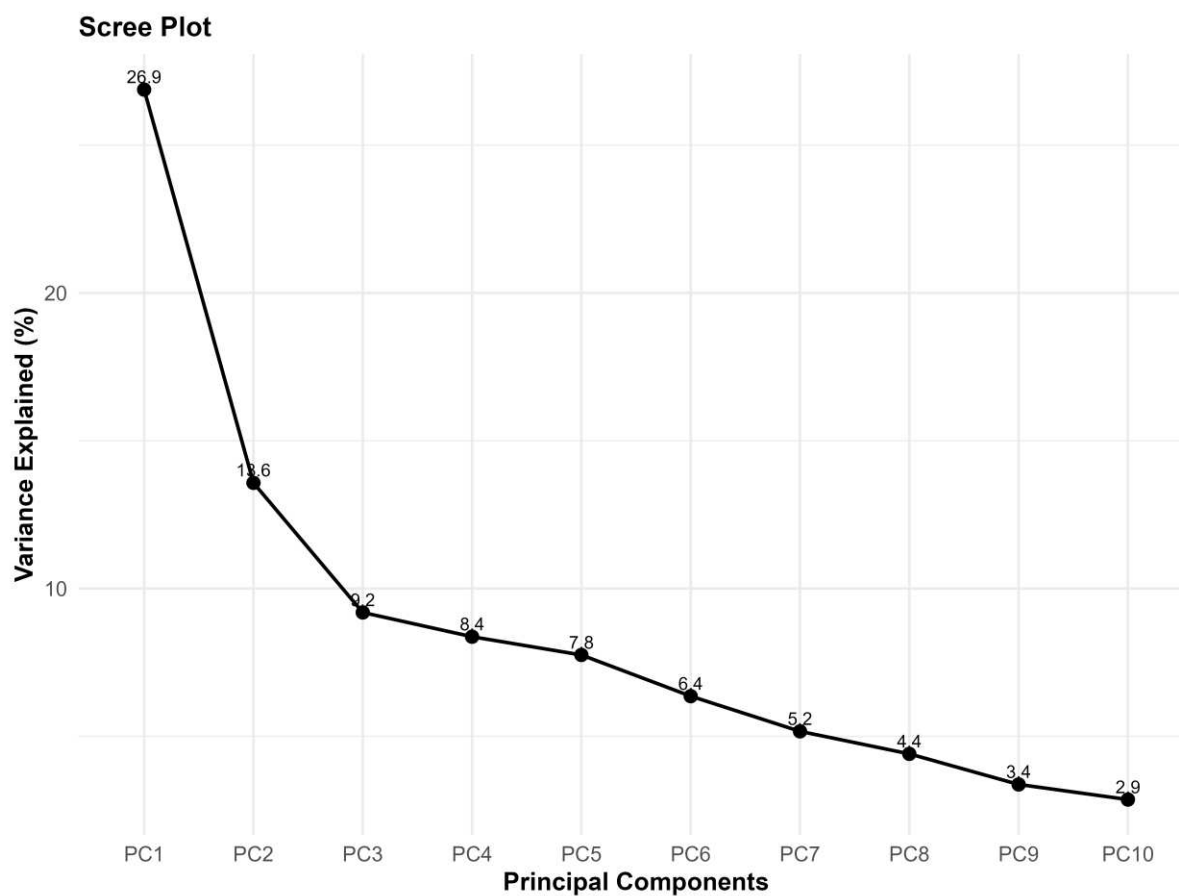


Fig. 8 Scree plot analysis derived from the studied morpho-biochemical parameters in hybrid progenies and their parents on the basis of the first two principal components, which accounted for 26.9% (PC1) and 13.6% (PC2) of the total variance.

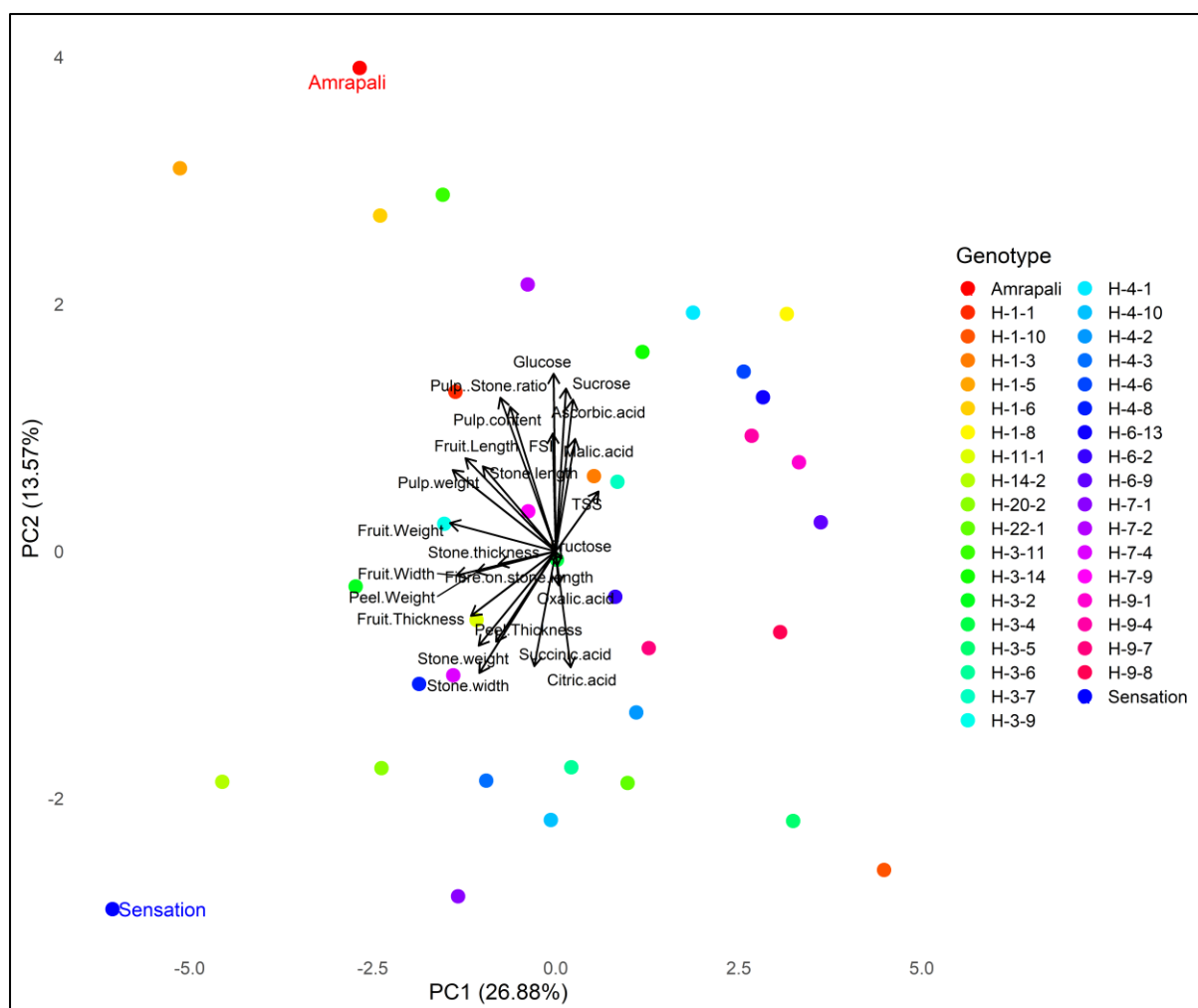


Fig. 9. PCA biplots based on evaluated morpho-biochemical parameters among the hybrid progenies and their parents. Genotypes are represented by labels, and trait vectors indicate the direction and magnitude of each trait's contribution.

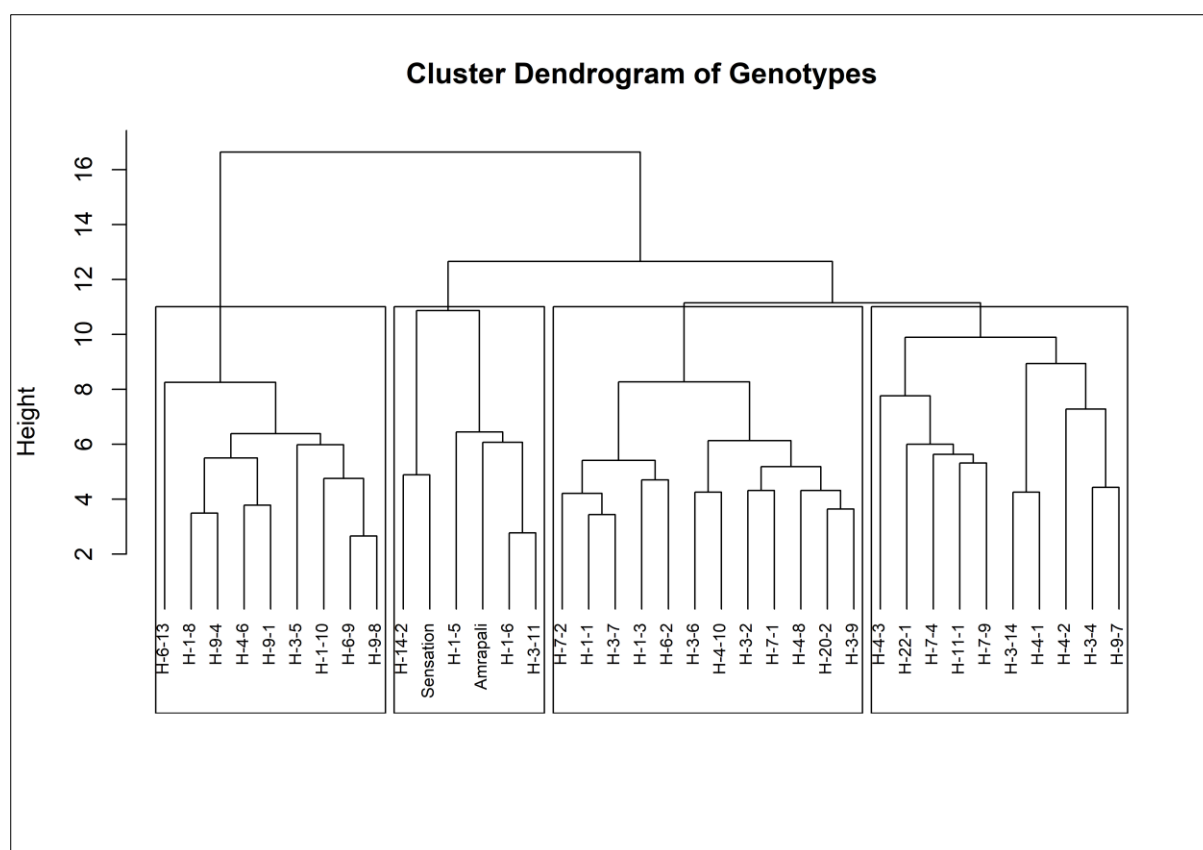


Fig. 10. Clustering patterns of hybrid progenies and their parents on the basis of morpho-biochemical traits.

Table 1 Descriptive statistics for the morphological and biochemical characteristics of newly developed mango hybrid progenies and parental hybrids.

Trait	Mean	SD	CV (%)	Max	Min
Fruit length (mm)	96.17	2.53	4.55	121.25	63.70
Fruit width (mm)	57.81	0.92	2.74	77.11	40.67
Fruit weight (mm)	178.10	9.42	9.16	324.69	70.48
Fruit shape index FSI (mm)	1.67	0.05	4.95	2.22	1.16
Fruit thickness (mm)	53.28	0.92	2.99	66.75	37.35
Stone length (mm)	80.15	3.22	6.96	109.77	53.10
Stone width (mm)	32.27	1.21	6.51	44.37	24.17
Stone thickness (mm)	17.73	0.80	7.79	22.89	10.54
Stone weight (mm)	26.55	1.99	13.01	51.17	17.36
Stone fiber length (cm)	1.43	0.01	1.31	3.27	0.32
Pulp weight (g)	110.98	8.49	13.26	232.64	32.79
Pulp content (%)	61.49	1.75	4.94	75.63	33.19
Pulp stone ratio	4.34	0.41	16.47	9.28	1.64
Peel weight (g)	33.18	2.50	13.04	71.19	15.51
Peel thickness (mm)	1.10	0.01	1.33	1.49	0.66
TSS	18.02	0.22	2.11	22.03	12.63
Oxalic acid (mg/g)	0.08	0.01	19.85	0.18	0.03
Citric acid (mg/g)	4.88	0.64	22.87	11.74	1.03
Ascorbic acid (mg/g)	4.91	0.24	8.40	9.71	1.79
Succinic acid (mg/g)	16.27	1.39	14.79	122.79	1.22
Malic acid (mg/g)	1.72	0.58	58.71	11.94	0.09
Sucrose (mg/g)	43.79	0.94	3.71	74.46	16.01
Glucose (mg/g)	13.67	1.02	12.95	24.78	4.55
Fructose (mg/g)	11.18	0.75	11.56	25.41	5.00

Max Maximum, Minimum, SD Standard Deviation, CV Coefficient of Variation

Table 2. Variations in fruit physical parameters among the newly developed mango hybrid progenies and parental hybrids.

Genotype	Fruit length (mm)	Fruit width (mm)	Fruit weight (g)	FSI	Fruit thickness (mm)	Stone length (mm)	Stone width (mm)	Stone weight (g)
H-1-1	101.40 ± 0.02	63.46 ± 0.43	208.38 ± 2.88	1.60 ± 0.01	63.91 ± 0.79	80.08 ± 7.85	36.61 ± 2.57	28.15 ± 3.49
H-1-10	73.31 ± 1.58	46.36 ± 1.58	70.48 ± 1.58	1.58 ± 0.02	44.75 ± 0.14	61.36 ± 0.21	27.04 ± 0.41	19.79 ± 0.14
H-1-3	99.38 ± 7.50	61.70 ± 4.48	182.03 ± 24.30	1.61 ± 0.01	56.90 ± 4.89	66.40 ± 7.95	25.05 ± 1.28	24.26 ± 3.24
H-1-5	119.14 ± 0.04	65.66 ± 0.63	324.69 ± 0.03	1.80 ± 0.00	61.46 ± 0.85	100.90 ± 1.94	28.41 ± 0.32	24.79 ± 0.03
H-1-6	121.45 ± 0.31	60.56 ± 2.26	215.54 ± 17.46	2.01 ± 0.07	56.29 ± 3.18	99.50 ± 6.68	30.87 ± 1.68	27.48 ± 2.82
H-1-8	82.11 ± 3.44	54.22 ± 2.94	127.78 ± 15.61	1.52 ± 0.02	50.32 ± 2.94	67.78 ± 6.67	25.25 ± 2.30	17.51 ± 6.01
H-11-1	106.84 ± 0.65	55.16 ± 0.51	163.78 ± 0.72	1.94 ± 0.03	54.45 ± 0.62	109.13 ± 15.28	36.70 ± 5.56	33.55 ± 11.45
H-14-2	108.59 ± 0.99	72.50 ± 1.39	278.77 ± 0.77	1.45 ± 0.01	64.49 ± 0.26	91.20 ± 0.67	42.10 ± 0.04	51.17 ± 0.31
H-20-2	94.77 ± 1.48	64.14 ± 2.49	206.04 ± 15.88	1.48 ± 0.03	66.75 ± 4.40	76.44 ± 1.01	38.99 ± 4.99	27.33 ± 0.00
H-22-1	98.99 ± 1.07	49.34 ± 1.08	232.89 ± 1.08	2.01 ± 0.02	52.19 ± 0.40	83.06 ± 0.02	32.70 ± 0.24	26.14 ± 0.17
H-3-11	118.24 ± 4.86	57.03 ± 1.17	198.50 ± 8.84	2.08 ± 0.13	48.56 ± 0.70	109.77 ± 9.16	29.94 ± 1.16	28.55 ± 0.22
H-3-14	95.39 ± 8.25	57.29 ± 0.57	161.07 ± 19.43	1.66 ± 0.13	49.14 ± 0.84	79.96 ± 5.19	30.80 ± 1.27	25.74 ± 1.00
H-3-2	116.25 ± 0.79	68.56 ± 0.27	229.23 ± 3.94	1.70 ± 0.02	63.00 ± 1.03	93.36 ± 2.66	32.55 ± 0.54	27.07 ± 0.90
H-3-4	110.17 ± 1.04	54.09 ± 1.03	185.01 ± 0.47	1.97 ± 0.01	51.15 ± 0.21	94.88 ± 0.74	26.30 ± 0.03	26.98 ± 0.22
H-3-5	63.71 ± 0.50	55.03 ± 0.49	127.62 ± 0.11	1.16 ± 0.01	50.93 ± 0.15	53.10 ± 0.35	27.26 ± 0.19	30.27 ± 0.36
H-3-6	87.40 ± 0.75	58.97 ± 0.53	155.53 ± 0.14	1.47 ± 0.02	56.52 ± 0.21	70.42 ± 0.52	39.02 ± 0.24	34.65 ± 0.42
H-3-7	85.30 ± 1.54	59.65 ± 1.49	168.87 ± 17.46	1.43 ± 0.01	57.93 ± 1.30	69.80 ± 2.14	27.86 ± 2.72	25.00 ± 3.50
H-3-9	101.74 ± 0.28	56.94 ± 2.81	188.50 ± 24.67	1.79 ± 0.08	59.45 ± 2.67	86.40 ± 0.54	31.16 ± 0.64	28.66 ± 2.33
H-4-1	100.63 ± 1.88	55.66 ± 0.03	133.39 ± 2.10	1.77 ± 0.00	40.93 ± 0.15	86.59 ± 0.43	30.89 ± 0.38	21.66 ± 0.17
H-4-10	90.31 ± 0.16	56.04 ± 0.32	159.52 ± 1.68	1.59 ± 0.01	55.15 ± 0.37	74.89 ± 0.66	33.76 ± 0.35	32.82 ± 0.31
H-4-2	99.55 ± 0.01	55.03 ± 0.01	134.75 ± 1.41	1.83 ± 0.01	41.36 ± 0.25	86.67 ± 0.17	30.66 ± 0.41	21.74 ± 0.26
H-4-3	89.10 ± 0.02	63.45 ± 0.07	230.92 ± 2.10	1.41 ± 0.01	57.53 ± 0.38	74.94 ± 0.11	38.71 ± 0.51	28.41 ± 0.34
H-4-6	70.34 ± 0.18	45.03 ± 0.48	145.32 ± 0.99	1.59 ± 0.01	42.92 ± 0.46	59.45 ± 0.71	28.87 ± 0.22	18.16 ± 0.15
H-4-8	96.52 ± 0.30	65.76 ± 0.70	194.11 ± 1.35	1.49 ± 0.01	58.73 ± 0.63	80.73 ± 0.95	39.75 ± 0.30	26.90 ± 0.24
H-6-13	90.69 ± 16.55	40.67 ± 1.51	142.84 ± 55.11	2.22 ± 0.33	37.35 ± 0.40	78.36 ± 15.94	24.17 ± 3.23	17.36 ± 4.36
H-6-2	79.64 ± 4.23	61.49 ± 3.02	150.39 ± 24.06	1.29 ± 0.01	59.30 ± 2.68	62.83 ± 2.68	31.41 ± 5.93	17.44 ± 9.44
H-6-9	79.69 ± 2.09	46.88 ± 0.04	97.65 ± 3.65	1.70 ± 0.04	43.38 ± 0.43	69.74 ± 0.88	25.76 ± 0.26	19.11 ± 0.29
H-7-1	92.37 ± 4.31	62.50 ± 0.98	194.71 ± 22.71	1.48 ± 0.10	59.05 ± 0.66	75.01 ± 5.15	40.66 ± 0.04	25.88 ± 3.07
H-7-2	100.27 ± 1.87	57.82 ± 0.76	181.28 ± 3.95	1.71 ± 0.03	53.83 ± 0.08	76.22 ± 0.05	37.04 ± 0.11	18.10 ± 0.04
H-7-4	96.88 ± 0.01	58.56 ± 0.37	195.61 ± 1.11	1.65 ± 0.01	56.77 ± 0.07	77.51 ± 0.48	37.59 ± 0.28	32.48 ± 0.35
H-7-9	108.05 ± 11.03	59.25 ± 2.71	164.63 ± 14.54	1.84 ± 0.27	41.33 ± 0.10	97.78 ± 11.44	38.93 ± 1.19	34.13 ± 1.13
H-9-1	74.53 ± 9.56	51.65 ± 2.80	106.00 ± 19.50	1.44 ± 0.11	49.69 ± 2.61	61.10 ± 7.55	29.72 ± 2.73	24.65 ± 4.68
H-9-4	90.37 ± 0.00	51.36 ± 0.53	126.44 ± 0.08	1.74 ± 0.00	50.82 ± 0.66	74.17 ± 1.43	25.75 ± 0.28	22.63 ± 0.00
H-9-7	97.91 ± 0.80	53.20 ± 0.52	156.84 ± 0.32	1.84 ± 0.01	51.94 ± 0.24	86.10 ± 0.55	29.16 ± 0.17	20.50 ± 0.34
H-9-8	82.85 ± 0.60	48.17 ± 0.23	94.61 ± 2.39	1.72 ± 0.02	45.20 ± 0.49	70.80 ± 1.67	27.07 ± 0.24	19.91 ± 0.57
Amrapali	120.10 ± 5.10	68.88 ± 1.53	271.84 ± 28.51	1.75 ± 0.03	53.42 ± 0.58	93.25 ± 10.44	31.03 ± 5.32	30.89 ± 4.12
Sensation	114.36 ± 1.53	77.11 ± 0.69	284.09 ± 41.24	1.48 ± 0.01	64.65 ± 0.57	85.75 ± 10.45	44.37 ± 0.97	42.52 ± 7.48

Table 2. Variations in fruit physical parameters among the newly developed mango hybrid progenies and parental hybrids.

Genotype	Stone thickness (mm)	Stone fiber length (cm)	Pulp weight (g)	Pulp content (%)	Pulp stone ratio	Peel thickness (mm)	Peel weight (g)
H-1-1	17.71 ± 0.68	1.46 ± 0.01	139.73 ± 15.32	66.92 ± 7.58	5.06 ± 1.11	1.02 ± 0.00	30.46 ± 4.67
H-1-10	18.36 ± 0.01	0.39 ± 0.06	32.79 ± 0.39	47.26 ± 1.67	1.64 ± 0.07	1.02 ± 0.00	15.51 ± 0.06
H-1-3	10.54 ± 6.52	0.51 ± 0.01	121.09 ± 14.20	66.64 ± 1.14	5.11 ± 0.18	1.22 ± 0.01	34.22 ± 9.32
H-1-5	18.89 ± 0.05	1.29 ± 0.01	232.64 ± 3.97	70.27 ± 0.03	9.28 ± 0.09	1.28 ± 0.00	71.19 ± 0.01
H-1-6	18.99 ± 0.01	2.22 ± 0.01	149.07 ± 18.81	68.55 ± 2.80	5.61 ± 1.28	1.39 ± 0.01	35.29 ± 5.16
H-1-8	15.58 ± 0.33	0.65 ± 0.03	70.45 ± 7.70	55.32 ± 0.47	4.44 ± 1.11	0.66 ± 0.01	31.94 ± 5.98
H-11-1	20.36 ± 1.67	1.15 ± 0.00	101.36 ± 2.14	61.89 ± 1.57	3.45 ± 1.25	1.28 ± 0.00	26.66 ± 6.39
H-14-2	21.62 ± 0.08	1.47 ± 0.01	165.73 ± 2.38	59.87 ± 0.28	3.34 ± 0.01	1.16 ± 0.02	45.49 ± 0.70
H-20-2	18.57 ± 0.00	0.32 ± 0.01	135.17 ± 1.50	66.06 ± 4.24	4.98 ± 0.06	1.44 ± 0.03	34.48 ± 5.32
H-22-1	17.48 ± 0.25	1.56 ± 0.00	77.30 ± 0.19	33.19 ± 0.07	3.01 ± 0.01	1.07 ± 0.02	36.31 ± 0.08
H-3-11	18.59 ± 0.43	1.19 ± 0.01	140.70 ± 14.20	70.76 ± 4.01	4.95 ± 0.55	1.10 ± 0.02	32.30 ± 0.63
H-3-14	16.45 ± 0.40	3.27 ± 0.02	93.74 ± 17.77	57.79 ± 4.00	3.63 ± 0.54	1.21 ± 0.01	34.04 ± 8.21
H-3-2	17.10 ± 0.22	0.97 ± 0.03	148.22 ± 7.14	64.62 ± 2.01	5.50 ± 0.43	1.15 ± 0.00	47.41 ± 4.22
H-3-4	18.45 ± 0.08	1.86 ± 0.01	105.53 ± 1.50	57.44 ± 0.26	4.02 ± 0.01	0.98 ± 0.02	38.54 ± 0.60
H-3-5	14.64 ± 0.08	1.99 ± 0.03	68.60 ± 0.20	53.16 ± 0.74	2.32 ± 0.00	0.91 ± 0.01	25.99 ± 0.27
H-3-6	15.75 ± 0.09	2.02 ± 0.03	100.14 ± 0.19	63.59 ± 0.88	2.93 ± 0.00	1.08 ± 0.02	21.37 ± 0.27
H-3-7	18.61 ± 0.76	1.69 ± 0.03	105.14 ± 18.03	61.81 ± 4.27	4.22 ± 0.10	0.87 ± 0.00	29.15 ± 5.51
H-3-9	20.68 ± 0.11	0.86 ± 0.01	124.77 ± 20.97	65.61 ± 2.01	4.46 ± 1.09	1.49 ± 0.00	33.53 ± 7.57
H-4-1	16.70 ± 0.40	1.50 ± 0.00	85.06 ± 0.41	64.24 ± 0.67	3.99 ± 0.02	1.03 ± 0.00	24.71 ± 0.01
H-4-10	17.81 ± 0.12	1.08 ± 0.01	85.47 ± 0.13	54.36 ± 0.32	2.65 ± 0.03	1.42 ± 0.01	40.39 ± 0.40
H-4-2	16.50 ± 0.04	1.48 ± 0.01	86.35 ± 0.08	64.48 ± 0.68	3.87 ± 0.06	1.03 ± 0.01	25.22 ± 0.31
H-4-3	16.15 ± 0.04	3.11 ± 0.02	143.20 ± 0.53	63.44 ± 0.68	4.99 ± 0.06	0.96 ± 0.01	39.05 ± 0.51
H-4-6	18.11 ± 0.26	0.90 ± 0.01	104.87 ± 0.37	72.77 ± 0.38	5.64 ± 0.07	1.03 ± 0.02	21.88 ± 0.36
H-4-8	20.57 ± 0.29	0.44 ± 0.00	127.82 ± 0.44	66.51 ± 0.37	4.70 ± 0.06	1.10 ± 0.02	31.18 ± 0.51
H-6-13	15.53 ± 0.52	0.84 ± 0.00	102.85 ± 50.16	68.68 ± 8.64	5.57 ± 1.47	0.98 ± 0.05	20.17 ± 3.06
H-6-2	14.14 ± 4.73	2.18 ± 0.04	94.42 ± 17.82	62.51 ± 1.84	6.89 ± 2.70	1.10 ± 0.00	35.34 ± 6.38
H-6-9	18.21 ± 0.19	2.13 ± 0.02	58.78 ± 1.11	59.86 ± 0.77	3.08 ± 0.12	1.01 ± 0.00	16.75 ± 0.18
H-7-1	17.31 ± 0.00	1.09 ± 0.00	121.29 ± 0.78	63.28 ± 7.73	4.84 ± 0.56	1.47 ± 0.01	29.75 ± 2.63
H-7-2	16.21 ± 0.11	1.97 ± 0.02	126.38 ± 1.95	71.96 ± 0.33	7.05 ± 0.01	0.90 ± 0.00	31.14 ± 0.27
H-7-4	22.89 ± 0.24	1.88 ± 0.02	104.30 ± 0.70	53.82 ± 0.16	3.21 ± 0.00	1.39 ± 0.02	56.94 ± 0.27
H-7-9	20.82 ± 0.04	1.31 ± 0.02	89.69 ± 12.45	54.29 ± 2.70	2.66 ± 0.43	1.06 ± 0.01	37.17 ± 6.86
H-9-1	16.66 ± 0.38	0.92 ± 0.01	65.28 ± 11.30	61.76 ± 0.69	2.68 ± 0.07	0.96 ± 0.00	17.51 ± 2.08
H-9-4	17.89 ± 0.04	1.48 ± 0.01	72.54 ± 1.23	56.46 ± 0.03	3.23 ± 0.03	0.82 ± 0.00	22.76 ± 0.01
H-9-7	12.52 ± 0.08	2.38 ± 0.00	82.19 ± 0.19	52.18 ± 0.02	3.95 ± 0.00	1.04 ± 0.01	54.49 ± 0.16
H-9-8	17.95 ± 0.27	1.16 ± 0.01	51.43 ± 1.98	54.34 ± 0.57	2.61 ± 0.17	1.15 ± 0.02	21.31 ± 2.96
Amrapali	19.99 ± 0.26	0.45 ± 0.02	205.75 ± 19.77	75.63 ± 0.48	6.86 ± 1.56	0.79 ± 0.00	21.85 ± 0.51
Sensation	21.60 ± 0.08	1.70 ± 0.01	186.24 ± 56.87	63.99 ± 10.72	4.28 ± 0.59	1.35 ± 0.03	56.18 ± 15.99

Table 4. Various sugars and organic acid fractions were identified in fresh pulp via HPLC.

S No.	Compound	RT (Minute)
1	Oxalic acid	7.566
2	Citric acid	8.925
3	Ascorbic acid	10.684
4	Succinic acid	12.259
5	L-Malic acid	14.061
6	Sucrose	8.592
7	Glucose	9.852
8	Fructose	10.548

Table 3. Variations in biochemical parameters among the newly developed mango hybrid progenies and parental hybrids.

Genotype	TSS (°Brix)	Oxalic acid (mg/g)	Citric acid (mg/g)	Ascorbic acid (mg/g)	Succinic acid (mg/g)	Malic acid (mg/g)	Glucose (mg/g)	Fructose (mg/g)	Sucrose (mg/g)
H-1-1	21.76 ± 0.14	0.07 ± 0.01	1.68 ± 1.55	4.96 ± 0.34	3.62 ± 1.74	1.94 ± 0.49	24.78 ± 4.51	11.85 ± 2.58	62.18 ± 1.42
H-1-10	20.08 ± 0.15	0.07 ± 0.01	1.68 ± 0.42	5.75 ± 0.75	3.34 ± 0.03	0.39 ± 0.22	20.32 ± 0.18	12.66 ± 2.03	56.88 ± 0.76
H-1-3	19.18 ± 0.49	0.03 ± 0.00	9.00 ± 0.12	2.77 ± 0.01	24.17 ± 0.95	0.09 ± 0.01	7.50 ± 2.42	9.19 ± 1.61	33.81 ± 1.22
H-1-5	19.60 ± 0.13	0.08 ± 0.01	4.44 ± 1.55	4.98 ± 0.00	8.37 ± 0.08	1.12 ± 0.76	12.10 ± 0.92	12.26 ± 1.16	46.51 ± 0.72
H-1-6	17.45 ± 0.05	0.04 ± 0.01	4.45 ± 0.06	5.87 ± 0.00	10.98 ± 0.39	1.26 ± 0.03	18.62 ± 1.11	10.15 ± 0.67	52.85 ± 1.61
H-1-8	16.29 ± 0.05	0.07 ± 0.02	2.18 ± 0.76	6.56 ± 0.18	6.38 ± 3.60	2.02 ± 0.58	19.56 ± 0.82	9.62 ± 1.53	69.56 ± 0.43
H-11-1	19.55 ± 0.32	0.11 ± 0.01	1.94 ± 0.27	9.71 ± 0.08	3.19 ± 0.41	0.66 ± 0.48	18.22 ± 1.11	14.00 ± 1.23	61.45 ± 2.53
H-14-2	20.12 ± 0.05	0.09 ± 0.01	1.57 ± 0.39	4.48 ± 0.37	12.08 ± 10.50	0.61 ± 0.10	7.75 ± 0.56	16.25 ± 1.33	24.80 ± 3.01
H-20-2	18.23 ± 0.00	0.06 ± 0.01	9.00 ± 0.16	5.40 ± 0.01	49.14 ± 1.42	0.24 ± 0.04	17.00 ± 2.48	12.08 ± 1.58	39.82 ± 1.00
H-22-1	14.64 ± 0.93	0.08 ± 0.01	1.27 ± 0.86	4.43 ± 0.69	15.38 ± 6.74	0.50 ± 0.24	6.19 ± 0.57	10.79 ± 0.36	20.70 ± 0.77
H-3-11	19.72 ± 0.62	0.18 ± 0.01	6.69 ± 0.09	3.56 ± 0.05	16.51 ± 0.69	0.28 ± 0.00	11.88 ± 2.42	17.11 ± 1.61	28.09 ± 1.38
H-3-14	15.26 ± 0.23	0.09 ± 0.02	2.76 ± 0.15	5.61 ± 0.70	4.85 ± 2.74	1.44 ± 1.22	17.01 ± 2.03	10.02 ± 0.52	74.46 ± 2.44
H-3-2	21.39 ± 1.13	0.09 ± 0.02	2.77 ± 1.04	5.39 ± 0.51	1.22 ± 0.29	11.63 ± 4.18	19.42 ± 0.23	7.09 ± 1.17	54.53 ± 0.96
H-3-4	16.95 ± 0.05	0.06 ± 0.03	9.14 ± 3.89	4.52 ± 0.06	3.01 ± 0.97	0.22 ± 0.12	8.41 ± 1.33	11.98 ± 0.66	32.12 ± 2.20
H-3-5	19.73 ± 0.01	0.03 ± 0.00	4.54 ± 0.23	3.43 ± 0.16	5.39 ± 0.12	1.09 ± 0.06	4.60 ± 0.42	7.45 ± 0.95	26.66 ± 1.53
H-3-6	16.15 ± 0.19	0.06 ± 0.00	11.17 ± 0.28	6.62 ± 0.33	17.09 ± 0.49	0.75 ± 0.15	10.73 ± 2.44	14.76 ± 1.32	50.21 ± 0.92
H-3-7	17.24 ± 0.19	0.11 ± 0.02	2.16 ± 0.00	3.36 ± 0.47	9.45 ± 1.01	0.54 ± 0.11	11.03 ± 0.26	7.71 ± 0.49	36.62 ± 1.12
H-3-9	18.00 ± 0.53	0.08 ± 0.04	4.73 ± 2.42	4.38 ± 1.17	5.20 ± 1.37	2.13 ± 1.44	20.70 ± 0.70	9.54 ± 0.60	55.97 ± 2.48
H-4-1	14.91 ± 0.10	0.08 ± 0.00	2.14 ± 1.04	5.05 ± 0.80	4.35 ± 1.55	2.80 ± 2.57	11.98 ± 1.14	13.68 ± 2.88	45.19 ± 0.63
H-4-10	20.74 ± 0.23	0.13 ± 0.00	3.71 ± 0.01	6.74 ± 0.04	7.81 ± 0.16	11.94 ± 0.02	19.63 ± 2.39	9.68 ± 1.45	19.15 ± 1.26
H-4-2	18.32 ± 0.15	0.04 ± 0.00	5.87 ± 0.04	2.61 ± 0.35	41.76 ± 1.38	0.15 ± 0.02	15.40 ± 1.07	10.19 ± 1.12	41.91 ± 1.81
H-4-3	20.23 ± 0.10	0.15 ± 0.01	1.44 ± 0.02	1.79 ± 0.02	122.79 ± 1.38	1.30 ± 0.00	5.65 ± 0.76	5.00 ± 0.82	34.90 ± 0.24
H-4-6	18.31 ± 0.10	0.18 ± 0.01	11.41 ± 0.05	4.09 ± 0.03	13.26 ± 0.33	0.38 ± 0.04	7.83 ± 2.49	25.41 ± 1.50	34.90 ± 1.18
H-4-8	19.48 ± 0.05	0.06 ± 0.01	2.08 ± 0.04	4.28 ± 0.00	25.10 ± 0.88	2.49 ± 0.13	19.99 ± 0.54	12.89 ± 1.13	52.31 ± 1.59
H-6-13	12.63 ± 0.03	0.12 ± 0.01	4.30 ± 0.11	2.85 ± 0.01	3.96 ± 0.02	0.32 ± 0.00	5.85 ± 0.68	8.54 ± 1.54	61.66 ± 1.21
H-6-2	15.43 ± 0.08	0.03 ± 0.00	10.84 ± 0.05	8.99 ± 0.09	10.26 ± 0.09	0.45 ± 0.02	5.00 ± 0.51	17.28 ± 1.33	20.52 ± 1.06
H-6-9	17.44 ± 0.17	0.13 ± 0.03	3.82 ± 2.07	3.64 ± 0.58	4.80 ± 1.12	1.78 ± 0.49	13.79 ± 5.59	6.06 ± 0.18	41.19 ± 0.37
H-7-1	18.69 ± 1.02	0.10 ± 0.01	3.04 ± 1.40	5.33 ± 0.47	4.58 ± 0.83	1.42 ± 0.64	12.72 ± 1.11	11.54 ± 0.83	46.79 ± 0.74
H-7-2	15.87 ± 0.53	0.06 ± 0.01	11.74 ± 0.48	2.91 ± 0.00	3.19 ± 0.04	0.13 ± 0.01	4.55 ± 0.93	6.26 ± 1.42	21.95 ± 1.42
H-7-4	14.62 ± 0.01	0.07 ± 0.00	2.57 ± 0.05	6.16 ± 0.04	4.78 ± 0.03	3.27 ± 0.10	19.48 ± 0.74	11.12 ± 1.02	49.34 ± 1.01
H-7-9	18.59 ± 0.05	0.11 ± 0.01	8.46 ± 0.14	8.05 ± 0.04	12.05 ± 0.49	1.01 ± 0.05	20.09 ± 2.29	16.25 ± 1.25	34.67 ± 1.10
H-9-1	17.25 ± 0.51	0.18 ± 0.04	3.78 ± 0.49	5.65 ± 0.49	7.58 ± 0.89	3.43 ± 0.49	15.76 ± 2.91	8.45 ± 2.24	63.14 ± 2.56
H-9-4	21.02 ± 0.62	0.05 ± 0.00	4.23 ± 3.07	4.72 ± 0.03	3.62 ± 3.06	4.04 ± 2.84	21.90 ± 0.62	9.34 ± 0.43	68.37 ± 4.35
H-9-7	19.94 ± 0.07	0.06 ± 0.01	5.73 ± 0.13	7.74 ± 0.36	10.19 ± 0.57	0.29 ± 0.02	14.38 ± 2.44	8.84 ± 1.63	58.27 ± 1.51
H-9-8	22.03 ± 0.20	0.04 ± 0.01	11.00 ± 1.02	3.24 ± 0.67	30.58 ± 0.51	0.29 ± 0.07	10.34 ± 0.08	7.78 ± 0.09	44.56 ± 1.16
Amrapali	16.16 ± 0.08	0.07 ± 0.05	2.33 ± 0.70	3.49 ± 0.69	2.61 ± 0.65	0.68 ± 0.36	15.38 ± 3.06	13.74 ± 0.95	38.07 ± 1.04
Sensation	13.84 ± 0.10	0.06 ± 0.01	1.03 ± 0.01	2.74 ± 0.09	89.17 ± 1.59	0.56 ± 0.01	10.32 ± 2.49	7.29 ± 1.55	16.01 ± 1.07

