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Integrated Multidimensional Evaluation of Postharvest Quality and Physiopathologies in Seasonal Tropical Fruits: Linking Physicochemical, Sensorial, and Economic Loss Parameters

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ABSTRACT

Tropical regions exhibit remarkable environmental variability, resulting in high biodiversity and numerous fruit species with considerable nutritional and commercial potential. Despite this richness, many tropical fruits remain underexplored, particularly regarding their postharvest quality, phytosanitary status, and consumer perception. This study aimed to characterize and analyze five seasonal tropical fruit species that lack comprehensive evaluation: mamoncillo (*Melicoccus bijugatus*), yellow sapote (*Quararibea cordata*), red dragon fruit (*Hylocereus undatus*), chontaduro (*Bactris gasipaes*), and cherimoya (*Annona cherimola*). Samples were collected from commercial distribution centers in Colombia during the 2024–2025 harvest seasons. Physicochemical traits and postharvest diseases and disorders were evaluated using fruits at commercial maturity, while economic losses and physiopathological impacts were assessed in the main marketing centers of Antioquia, Cundinamarca, and Valle del Cauca, Colombia. Additionally, a consumer perception survey was analyzed using natural language processing techniques to prioritize quality attributes such as color, aroma, flavor, and texture. Results revealed high variability in physical, chemical, and physiological parameters among species and between species by season (2024 vs. 2025). The most frequent disorders included epidermal browning, dehydration, senescence, and sunburn, while anthracnose and stem-end rot were the predominant pathological conditions. These issues caused a 40%–70% reduction in market value and fruit losses ranging from 25% to 80%. Highly perishable fruits, such as cherimoya, and high-cost products, like red dragon fruit, exhibited particularly elevated waste rates. Our research provides an integrated perspective on the postharvest behavior, economic implications of postharvest physiopathologies, and consumer acceptance of seasonal tropical fruits, emphasizing the need to improve pre- and postharvest handling and establish strategies for export-oriented quality and phytosanitary assurance.

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1 | Introduction

The increase in the consumption of fruits and vegetables worldwide has become a topic of great relevance in the promotion of healthy foods. This is because the consumption of a wide variety of fruits and vegetables provides an aromatic, colorful, delicious diet that is low in calories and rich in micronutrients [1, 2]. Furthermore, fruits are rich in essential nutrients, fiber, vitamins, and antioxidants, which are essential to improve human health and prevent diseases [3–5]. Additionally, fruit production and consumption contribute to diversifying food sources and reducing dependence on traditional cereal crops [6]. For these reasons, the increase in consumption and therefore in the area planted with tropical fruits has a large impact on the economies of the producing countries, many of which are considered undeveloped or in development [7].

The tropics are geographically situated between latitudes 23°N and 26°S of the equator and are characterized by climatic conditions that allow 80% of the world's biologically diverse fauna and flora to thrive [8]. Colombia, one of the countries that are part of the intertropical zone, is considered one of the most biodiverse countries on the planet [9]. The climatic and edaphic conditions of tropical countries have made them prominent agricultural producers, especially of fruits [10].

The fruit production sector has grown in most tropical countries, due to the increase in international demand for so-called exotic fruits that are generally native and grown in the tropics [11]. In this sense, Colombia has been one of the most dynamic countries worldwide in terms of growth area and high commercial value export volumes [12]. These fruits include avocado, banana, baby banana, Tahiti acid lime, cape gooseberry, purple passion fruit, sweet passion fruit, yellow passion fruit, mango, yellow dragon fruit, and pineapple, among others [12].

Furthermore, due to the high edaphoclimatic variability of tropical areas, there are multiple conditions for the growth and development of many species with high potential for human consumption [13]. Important tropical fruits grown in Colombia include mamoncillo (*Melicoccus bijugatus* Jacq.), yellow sapote (*Quararibea cordata* Bonpl.), red pitaya or dragon fruit (*Hylocereus undatus* Haw.), chontaduro or peach palm fruit (*Bactris gasipaes* Kunth.), and cherimoya (*Annona cherimola* Mill.). Unique conditions that allow the development of exotic fruits are not present in other areas of the planet, conferring export potential from the tropics to other parts of the world. An example is the Canadian market, where climatic seasonality limits the production of fruits in terms of both variety and quantity, so domestic demand is greater than the country's production rate [14].

Many fruit plants cultivated or naturally distributed in tropical regions exhibit high seasonal production patterns [15], presenting challenges for their marketing and resulting in low prices for producers or collectors. Furthermore, these fruits often face numerous limitations in their quality and storage life after harvest [16, 17]. These limitations are due to various factors, including oversupply, inadequate pre- and postharvest practices to improve quality and minimize losses, and the absence of standardized quality criteria throughout the value chain [16–18]. The consequent lack of consistent quality standards exacerbates the difficulties associated with the marketing of these tropical fruits, further perpetuating the low-price cycle and limited

profitability for growers. Addressing these challenges requires a comprehensive understanding and implementation of effective pre- and postharvest strategies, as well as the establishment of quality criteria and standards throughout the value chain. Such efforts may be essential to improve the marketability and economic viability of tropical fruit production, thus benefiting both growers and consumers alike.

The challenges associated with seasonal fruits highlight the pressing need for a complete characterization of multidimensional quality (MQ) parameters. The MQ criteria cover various aspects, such as physicochemical and sensory characteristics, nutritional composition, and postharvest characteristics [19–21]. Understanding and evaluating these diverse quality dimensions is vital to improving the marketability and consumer acceptance of seasonal fruits. Furthermore, integrating consumer perceptions and preferences into quality criteria is vital, as they play an important role in shaping purchasing decisions and overall market demand [22]. Therefore, incorporating consumer feedback into quality assessments ensures alignment with market preferences and increases the likelihood of successful commercialization.

Many processes aimed at characterizing MQ can be costly and often rely on advanced, less accessible methods such as expert sensory panels [21, 23]. Therefore, it is essential to seek innovative alternatives that allow sensory profiling to be assessed directly by consumers, the true judges of product acceptance [23–25]. Their perception of sensory value is highly meaningful for understanding market preferences [23–25]. In this context, natural language processing (NLP) offers a valuable analytical tool to extract and interpret consumer opinions from textual, audio, or video data, providing deeper insights into sensory attributes and acceptance levels [23–25]. Unlike traditional tests, this approach emphasizes the richness of language rather than the number of participants [23–25]. Furthermore, NLP-based evaluations can be integrated with quality characterization techniques, such as Likert-type scales, enabling the prioritization of sensory and quality factors in an ordered scale while transforming descriptive information into quantitative, analyzable data [23–25].

This study presents a baseline postharvest characterization of five nonconventional tropical fruits with export potential *M. bijugatus* (mamoncillo), *Q. cordata* (yellow sapote), *H. undatus* (red dragon fruit), *B. gasipaes* (chontaduro or peach palm), and *A. cherimola* (cherimoya). The main objective was to describe their MQ profiles, integrating physicochemical attributes, postharvest pathologies and physiological disorders, and consumer perception during the commercial maturity stage.

Rather than comparing production systems or origins, the study focused on generating reference information that captures the intrinsic quality variability and postharvest behavior of these seasonal fruits. Through the evaluation of each species over two consecutive production seasons (2024–2025), the research provides insights into temporal changes in MQ traits, forming the basis for the development of standardization tools and predictive models that promote quality consistency and export readiness. Additionally, the study offers the first integrated assessment of postharvest pathologies and physiological disorders in these fruits, emphasizing their economic implications related to quality degradation, price reduction, and waste generation. The

findings contribute to the design of integrated pre- and post-harvest management strategies, supporting agricultural diversification, improving market competitiveness, and strengthening Colombia's role as a producer of high-quality tropical fruits for export.

2 | Materials and Methods

2.1 | Description of the Methodological Approach and Origin of the Fruits

The methodology of this study was structured into three sequential and complementary phases, each designed to address a specific analytical dimension of the research objectives and to generate integrated information on the MQ of nonconventional tropical fruits with export potential (Figure 1). The specific procedures, analytical methods, and criteria applied within each phase are described in greater detail in the following sections to ensure methodological transparency and reproducibility.

2.1.1 | Phase I

Selection of fruit species and MQ assessment: In the first phase, five fruit species were selected (*H. undatus*, *Q. cordata*, *M. bijugatus*, *B. gasipaes*, and *A. cherimola*) based on the limited availability of scientific data on their MQ parameters under tropical postharvest conditions. These fruits are known for their short shelf life, restricted commercial value, and limited export positioning. This phase focused on the quantification of MQ parameters, encompassing physical (size, weight, firmness, color), chemical (soluble solids, titratable acidity, pH, and other compositional traits), and physiological indicators (respiration rate, senescence onset, and dehydration) (Figure 1). The objective was to establish baseline reference values that reflect the intrinsic quality variability of each species.

2.1.2 | Phase II

Characterization of postharvest diseases, physiological disorders, and economic implications: The second phase involved the identification and characterization of postharvest pathologies and physiological disorders observed in fruits during commercialization and under simulated market conditions (Figure 1). The aim was to determine their incidence, visual manifestation, and progression, as well as their economic impact in terms of quality loss, price depreciation, and waste generation. This analysis provided an applied perspective on how biological deterioration affects both the commercial value and market sustainability of these seasonal tropical fruits.

2.1.3 | Phase III

Consumer perception and sensory acceptance: The third phase focused on assessing consumer-perceived quality attributes through sensory evaluation and acceptance testing (Figure 1). Commercially mature fruits were harvested during their natural growing seasons from representative production areas across Colombia. Consumer responses were analyzed using Likert-scale evaluations and NLP techniques applied to open-ended feedback. This phase aimed to understand consumer preferences, perceived quality cues, and acceptance thresholds, linking sensory perception with measurable quality attributes and marketability potential.

2.1.4 | Origin of the Plant Material and Design of the Evaluations

The fruits selected for this study represent species produced under diverse agroecological and management conditions across multiple Colombian regions and throughout different periods of the year. These systems range from low-input commercial production and companion or shaded cropping systems to backyard cultivation and naturalized growth in mixed landscapes. Such heterogeneity in

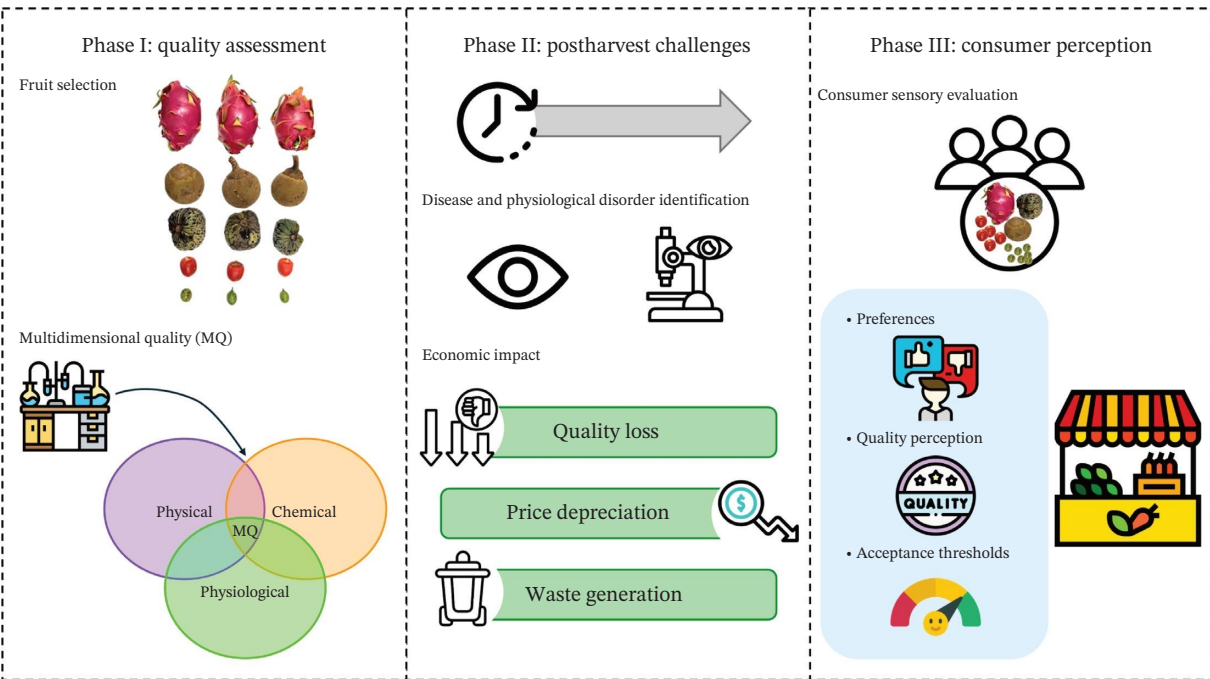


FIGURE 1 | Graphical description of the methodological approach using physicochemical and sensorial approaches to the multidimensional postharvest quality assessment of seasonal tropical fruits.

production environments has limited the development of standardized harvest and postharvest protocols, leading farmers to rely primarily on empirical and traditional knowledge to determine physiological maturity based on visual and tactile indicators such as color, firmness, or aroma. In addition, fruits are then sold to urban markets, where traders also guided by experience determine commercial maturity for distribution.

During their seasonal harvest peaks, fruits are typically collected in bulk and transported to major distribution centers, from where they are distributed through different commercial channels, including wholesale markets, supermarkets, and neighborhood stores. Considering the seasonal fruiting patterns and regional availability, sampling was carried out during the second semester of each year (2024 and 2025), which corresponds to the period of highest production under Colombian edaphoclimatic conditions. This approach ensured that fruit collection reflected the natural variability of nonconventional tropical fruit systems, capturing their commercial, physiological, and quality characteristics as they appear in real marketing contexts.

Fruits from each of the five species (*H. undatus*, *Q. cordata*, *M. bijugatus*, *B. gasipaes*, and *A. cherimola*) selected for this study were purchased at commercial maturity, e.g., completely ripe and ready for consumption and each seasonal (2024 and 2025) (1 kg for chontaduro [approximately 15-20 fruits] and mamoncillo [approximately 40-50 fruits] and six units of fruits for the remaining three) from local markets in Paipa, Boyacá, for cherimoya fruit and Bogotá “Corabastos” and “Paloquemado” for the others, and brought to the Laboratory of Calidad y Poscosecha de Productos Agrícolas, Universidad Nacional de Colombia, Bogotá. Furthermore, based on the previous evaluation criteria at fruit commerce sources and their ripeness state, we ensured that the ten selected samples included the greatest possible variability.

On arrival in the laboratory, the physicochemical characteristics and presence of diseases and disorders were evaluated. The fruits purchased were preselected to ensure homogeneity to minimize the number of samples to analyze, given the high economic, time, and logistic costs of this process. Cherimoya fruits were purchased the day before the laboratory analysis due to the distance between markets and the laboratory (189 km), and the samples were transported in a box and stored at room temperature. The other fruits were purchased and analyzed on the same day and transported in separate bags (about 11 km).

2.2 | Phase I: Characterization of Physicochemical and Physiological Parameters of Selected Fruits Harvested at Commercial Maturity

2.2.1 | Physical Attributes

Physicochemical analyses were carried out using the range of 6-20 fruits depending on the size of the fruit (described in detail above) for each selected species and in each season (2024 and 2025). For volume, an Erlenmeyer flask with 400 and 250 mL of water was used for large and small fruits, respectively. Fresh weight was measured on a precision balance scale (Ohaus, Ohio, OH) to the nearest 0.01 g. With these weights, the epidermis/pulp and pulp/seed(s) ratios were determined. Based on the measured weight and volume, the density of each fruit was established. Two perpendicular axial measurements were taken with a caliper

(Mitutoyo, Andover), corresponding to the polar and equatorial axes [26].

The firmness (N) of the fruit and the epidermal extensibility (mm) were measured according to the methodology of Africano et al. [27] using an LS1 texturometer (Lloyd LS1, Bognor Regis, UK), with a tip 3 mm in diameter, coupled with Nexygen Plus™ software. Measurements were taken at the intersection of the polar and equatorial axes of the fruit.

Fruits were cut in half, and epidermal thickness was measured using a 150-mm digital vernier caliper with an accuracy of 0.05 mm (Mitutoyo, Andover). Epicarp and pulp color were measured according to the methodology of González et al. [28] and González-Bonilla and Marín-Arroyo [29]; L^* , a^* , b^* , chroma, and hue were measured with a digital colorimeter (Konica Minolta, CR-400). With the parameters of the CIELab system, the color index (CI) was determined [28, 29]. The corresponding colors were determined from the L^* , a^* , and b^* values in the CIELab color space to visually represent the color ranges observed in the fruits, for both the epidermis and the pulp. The epidermis, pulp, and seeds were then manually separated for all fruits except chontaduro, where a peeler was used, and weighed.

2.2.2 | Chemical Composition

The pulp separated from the physical analysis as described above was processed using a 1 mm to extract 3 mL of juice. Total soluble solids (TSSs, °Brix) were determined with a digital refractometer, 0-85°Brix (Hanna, HI 96841). The total titratable acidity (TTA, %) was measured by titration with 0.1 N NaOH using a titrator (Metrohm 916 Food Ti-Touch). For this procedure, 2 mL of juice was dissolved in 20 mL of distilled water. The pH was determined using a digital potentiometric device. The maturity index (MI) was determined using the TSS/TTA ratio.

2.2.3 | Physiological Characteristics

For the respiratory rate and ethylene production, the closed system method described by Castellanos et al. [30] and Rojas-Rodríguez et al. [31] was used. Approximately 129 g (15-20 fruits) of mamoncillo, 152 g (15-20 fruits) of chontaduro, and 770 g (six fruits) of cherimoya fruit were placed in a 450-mL hermetic glass chamber. Approximately 710 g (seven fruits) of yellow sapote and 750 g (six fruits) of red dragon fruit were placed inside a 2300-mL hermetic glass chamber, at a temperature of 19°C. For each fruit, 4 glasses were used.

For the respiratory rate, after 2-5 h, depending on the fruit, the concentration reading of CO₂ and O₂ generated by the respiration of the fruit was measured with a portable gas analyzer (Check Point 3, Mocon). Subsequently, the respiratory rates were determined with the equations used by Castellanos et al. [30]. Readings were taken for ethylene measurement at 3, 7, and 9 h for *A. cherimola*, *Q. cordata*, *M. bijugatus*, and *B. gasipaes*, respectively. One mL of chamber gas sample was taken and injected into an Agilent Technologies 7890A gas chromatograph (GC) equipped with an HP-PLOT column (30 m × 0.55 mm × 40 μm), a flame ionization detector (FID), and helium as carrier gas with a flow rate of 7.0 mL·min⁻¹. Each measurement was carried out with four replications [30].

2.2.4 | Statistical Analysis of Physicochemical and Physiological Parameters

For each fruit species and evaluated variable, a two-stage statistical framework was implemented to ensure analytical robustness, transparency, and full reproducibility of results. Given the distinct biological nature of the studied species each exhibiting unique physical, chemical, physiological, and phytosanitary traits, the analysis was designed to focus on intraspecies variability between seasons, rather than interspecies comparisons.

Initially, a comprehensive descriptive analysis was conducted independently for each season (2024 and 2025). For every variable, measures of central tendency (mean and median), dispersion (standard deviation and coefficient of variation), and distribution (minimum, maximum, and quartiles) were computed. Data visualization was performed using boxplots generated with the Seaborn library under Python v3.13.1, allowing the identification of distributional patterns, data asymmetries, and potential outliers across replicates.

Prior to inferential comparison, assumptions of normality and homoscedasticity were evaluated. Shapiro–Wilk tests ($\alpha = 0.05$) were applied to assess normality, and Levene's tests were used to evaluate variance homogeneity. When both assumptions were satisfied, parametric inference was conducted using the Student's *t* test for independent samples, comparing mean values of each variable between the 2024 and 2025 seasons. For datasets violating one or both assumptions, nonparametric inference was performed via the Mann–Whitney *U* test, providing a distribution-free comparison of medians. All analyses were executed at a 95% confidence level ($\alpha = 0.05$). The results were expressed as mean $\pm$ standard deviation, and significance levels (*p* values) were explicitly reported for each comparison. This analytical workflow ensures a statistically sound evaluation of seasonal effects on fruit quality parameters, supporting the reproducibility and scientific reliability of the findings.

2.3 | Phase II: Identification, Characterization, and Determination of the Economic Impact, Loss, and Waste Associated With Postharvest Pathologies and Disorders in Seasonal Fruits

As previously described, many postharvest characteristics of these fruits remain largely unknown. In particular, information on pathological symptoms and physiological disorders is limited. The fruits available in markets often show multiple types of damage, mechanical injuries, deterioration due to microbial activity, pest infestations, and other forms of degradation. Therefore, the objective of this part of the study was to conduct a basic characterization of the main postharvest physiopathologies and their potential causal agents, economic losses (loss of commercial value due to the presence of damage), implications for waste generation (fruit discarded due to damage) under marketing conditions, and its corroboration under simulated marketing conditions in the laboratory. Detailed analyses such as pathogenicity tests or in-depth identification of causal agents were beyond the scope of this work. In line with the evaluation of other quality traits, fruit samples were randomly collected from commercial distribution points to ensure that the widest possible variability was represented.

2.3.1 | Characterization of Postharvest Diseases and Disorders Under Simulation of Duration and Marketing Conditions

Seasonal tropical fruits were selected from different commercialization centers in an apparently healthy condition, with no visible symptoms of external damage and at a commercial maturity stage according to the corresponding market system. Each fruit species was monitored individually under laboratory-controlled conditions to evaluate the onset and progression of postharvest physiological and pathological disorders. Ten fruits per species and per season (2024–2025) were stored under ambient conditions representative of retail environments ($18^{\circ}\text{C} \pm 2$ and $75\% \pm 5$ relative humidity) for variable postharvest durations, defined according to the average shelf life estimated by retailers for consumer use after purchase: mamoncillo: 10 days; yellow sapote: 15 days; red dragon fruit: 25 days; chontaduro: 30 days; and cherimoya: 5 days.

During storage, each fruit was inspected daily for the appearance of symptoms and signs associated with physiological disorders (dehydration, senescence, browning, tissue softening) and pathological infections. Observations were performed by stereomicroscopy (10–40 $\times$) to detect surface mycelia, lenticel colonization, or subepidermal necrosis. Morphological traits and color changes were photographically documented and compared with specialized literature and reference atlases for tropical fruit pathology.

The analysis prioritized the characterization and temporal sequence of symptom development, focusing on the differentiation between primary physiological deterioration (e.g., dehydration and senescence) and secondary pathogen-associated decay that manifested during the simulated shelf life period. We focused on the basic characterization of symptoms and the description of the damage, rather than in the in-depth identification and causal determination of the agent as a polyphasic specific process [32], linking them to the estimated postharvest life and the market-relevant quality degradation observed in each fruit. For each fruit species, the incidence of every detected pathology and physiological disorder was quantified and expressed as the mean value $\pm$ confidence interval. This statistical representation allowed for an accurate estimation of the variability and consistency of symptom occurrence within each group. In parallel, high-resolution photographic documentation was obtained for each pathological and physiological condition, serving as a visual reference for record-keeping, comparative analysis, and temporal monitoring of symptom progression throughout the postharvest evaluation period.

2.3.2 | Characterization and Consequences of Postharvest Pathologies and Disorders in Tropical Seasonal Fruits: Quality Degradation, Market Economic Loss, and Waste Production

To determine the impact of postharvest diseases and disorders on seasonal tropical fruits described previously, a monitoring study was conducted across different commercialization systems, including large retail chains, medium-scale distributors, and small neighborhood markets. The survey encompassed approximately 30 commercialization sites, distributed among major urban

centers such as Bogotá, Medellín, and Cali; intermediate municipalities such as Rionegro, La Ceja, La Unión, El Santuario, and Donmatías in Antioquia; Fusagasugá, Mosquera, Facatativá, Ubaté, and Chía in Cundinamarca; and Palmira, Buga, and La Unión in Valle del Cauca.

All monitored locations exhibited similar sales and storage infrastructure conditions (average temperature of $18 \pm 5^\circ\text{C}$ and relative humidity of $80 \pm 15\%$), comparable fruit supply sources, and analogous postharvest management practices. These included fruit selection based on quality attributes, periodic turnover of produce, and price adjustments according to fruit quality and visual condition. Such standardization allowed for consistent evaluation of postharvest quality degradation and its implications across diverse marketing environments and socio-economic contexts.

In this study, and following the methodological framework of Castaño-Tarazona et al. [23], with specific adjustments to the context of tropical seasonal fruits, a comprehensive quality classification system was developed to evaluate the post-harvest impact of pathological and physiological disorders across multiple commercialization environments. The classification was primarily based on visible epidermal and sub-epidermal alterations detected during the retail monitoring stages. Two main quality categories were defined: (i) standard quality fruits exhibiting an intact epidermis without visible pathological lesions or physiological disorders, a characteristic size consistent with commercial standards for the species, and appropriate physiological maturity at the consumption stage; and (ii) low quality fruits showing limited or incipient deterioration that did not compromise overall marketability. This category included fruits with a maximum of 20% of the epidermal area affected by superficial symptoms (e.g., minor rots, lenticel damage, or discoloration), mechanical injury below 10%, normal external coloration, and no signs of over-ripening or fungal colonization.

From this classification, two critical parameters were quantified for each commercialization system (large-scale, intermediate, and small retailers): (i) discarded or waste fruit, corresponding to the proportion of fruit that, due to visual deterioration or consumer rejection, was withdrawn from sale and considered unsellable by the market operators. This parameter reflects the functional threshold of acceptability beyond which fruit no longer meets commercial or sensory standards. (ii) Economic impact of quality loss and waste, calculated as the relative decrease in commercial value associated with the transition from standard to low quality, or from low quality to waste. This was determined by comparing the weighted average selling price of fruits in each quality category with the reference price of standard quality, multiplied by the proportion of downgraded or discarded fruit within each market. This metric expresses the monetary value lost per commercialization unit due to post-harvest deterioration.

Considering the variability in fruit turnover rates, sale volumes, and price structures across different regions and commercialization scales, all estimations were normalized to relative values per 100 kg of fruit. This standardization enabled direct and comparable assessment of economic losses, quality degradation, and waste generation among distinct distribution systems and temporal sampling periods.

2.4 | Phase III: Analysis of Consumer Perception of Consumption of Selected Fruits at Commercial Maturity

In the analysis of perceived quality factors for a product, consumer surveys were used [33]. Our decision was guided by the need to achieve a more accurate representation of consumers' perceptions regarding quality and sensory attributes [23–25]. Ultimately, consumers are the final arbiters of product acceptance, making choices not only based on measurable parameters such as flavor, texture, and appearance but also on subjective and contextual factors, including personal preference, cultural background, and product origin [23–25]. Understanding these multidimensional drivers of perception is essential for aligning objective quality assessments with real consumer behavior and expectations.

The five species of fruits selected for this study are seasonally available in stores and markets and even on the street and can be purchased at low prices during different harvest periods, depending on where they are produced and the environmental conditions that regulate the phenological cycles of the producing trees. In this way, there is no purchase bias by socioeconomic status, age, location, culture, gender, and cost, and each person has the same probability of buying and consuming the fruit during the season. Based on the above assumptions, we selected the consumer population based on the nonprobability sampling of convenience type based on the selection of a population composed of students, professors, administrators, and staff from the Universidad Nacional de Colombia, campus Bogotá. The selected population ensured similar gender, social strata, origin (regions of the country), and age propensities.

In total, 62 surveys were conducted, given the logistical challenges of evaluating a large quantity of fruits and aiming for the surveyed unit to consume the different fruits in a “fresh” state according to the degree of ripeness for commercial consumption. For each fruit studied, fresh samples in commercial ripeness were taken, except for the chontaduro samples, which were cooked with unrefined sugarcane for 1.5 h, as this is the most common form of consumption. The samples were arranged in individual trays: whole fruits for mamoncillo and chontaduro and a portion (around 10 g) of the fruit for the remaining three due to their size.

A sensory profile test was performed based on a descriptive analysis through a survey in which price, smell, visual appearance, texture, color, size, and maturity perception of the fruits were characterized. Fruit flavors were neutralized with soda crackers. The survey structure was implemented using Google Forms; the survey was conducted for academic research purposes only, with a commitment to noncommercial use of the data collected. Participants were informed of the nature of the study and gave their consent before proceeding.

Each question was designed with a Likert-scale format, offering respondents five discrete response options to accurately gauge their perceptions and preferences [34]. Additionally, open questions were incorporated to allow participants to provide qualitative feedback. This approach (open and closed questions) was designed to capture the textual elements of the sensations and feelings evoked by the consumption of each fruit. This methodology facilitated a comprehensive understanding of the

perceptions and experiences of participants with the fruits under investigation [35]. Furthermore, the inclusion of NLP techniques allowed for a nuanced analysis of qualitative data, enriching the study findings with insights into consumer sentiments and preferences [36]. Additionally, by using the NLP approach, robust analysis was ensured, as it not only utilizes the number of respondents, but also analyzes each word of open questions [37, 38], making it a robust tool for this type of analysis where the sample size is not as high due to logistical challenges explained in the previous paragraphs.

2.4.1 | Analysis of Sensory Perception Data

Sensory perception analysis was developed using (i) Likert package using R programming language, where consumer preference patterns were identified in relation to quality aspects described in the literature [39]. (ii) WordCloud libraries and the Sentiment Intensity Analyzer tool from the *nlTK* library using Python-free programming environments. The survey carried out included open questions about the sensorial characteristics of fruits. WordCloud is based on the word frequency used by all interviewed, so the most repeated words are graphs in high font size. The sentiment analyzer involves lexical and syntactic rules to identify if the phrase is positive, negative, or neutral [40].

3 | Results

3.1 | Phase I: Characterization of Harvest Quality

3.1.1 | Physicochemical and Physiological Characterization of Fruits in Commercial Maturity

3.1.1.1 | Mamoncillo. Mamoncillo in 2024 presented a coloration in the epidermis with green and yellow tones, with a CI of 9.48 ± 0.93 (Figure 2, Table 1), while in the pulp, beige tones were found (Figure 2) with a CI of 4.26 ± 0.44 (Table 1). In the epidermis, h of 114 and chroma of 32.76 were found (Table 1). In contrast, during 2025, the epidermis showed an increase of 11.4 units in lightness (L), indicating brighter surfaces. In contrast, the hue angle (h) and chroma decreased by 76.6 and 33.9 units, respectively, reflecting a loss of hue and saturation. The CI increased by 2.8 units, suggesting that the epidermis became less green in 2025.

In the pulp, lightness decreased by 10.4 units, indicating darker internal tissues. The hue angle decreased by 51.2 units, pointing to a shift toward warmer tones. Chroma (C) decreased by 22.2 units, showing a lower color intensity. However, the CI did not show significant differences (Table 1).

Figure 3 shows the characteristics of mamoncillo fruits, rounded to oval in shape, since the relation polar and equatorial diameters tend to be 1, and the thickness of the epidermis is 1 mm, homogeneous throughout the fruit. The pulp corresponds to ~50% of the total fruit, between 3.3 and 3.6 times the mass of the seed, and its relationship with the epidermis is between 0.4 and 0.44. It has an approximate weight of 10.5 g, a volume of $8.5\text{--}10.5\text{ cm}^3$, and a density of $1.1\text{--}1.2\text{ g}\cdot\text{cm}^{-3}$. Similarly, the firmness of the fruit is high and has a low variation. Compared to 2025, significant differences were found only in variables such as fruit weight, which was higher, reaching values below 16 g but with equatorial

diameters up to 0.5 cm smaller on average. The increase in fruit weight is due to the epidermis, which shows weights up to 4 g higher than the fruits from 2024, also increasing the epidermis/pulp ratio, which averages 0.7. Another physical variable that shows changes is firmness, which tends to be lower, with values around 9 N.

Regarding the chemical characteristics (Figure 3), obtained TSS between 14 and 16°Brix, a pH of approximately 3, and a TTA with values indicating high acidity. Furthermore, it presents a MI of 7.6–8.5, a respiratory rate of approximately $30\text{ mL CO}_2\text{ kg}^{-1}\cdot\text{h}^{-1}$, and an ethylene production rate between 0.22 and $0.27\text{ }\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ (Figure 3). With the exception of respiratory rate, all chemical variables show differences between the two evaluated periods: pH values up to 3.75, soluble solids up to 3°Brix higher, and TTA up to 5% lower. These last two characteristics result in a maturity ratio of up to 20, which is up to 2.5 times higher than in the previous period. Likewise, the ethylene production rate was higher, reaching values from 0.40 to $0.73\text{ }\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$.

3.1.1.2 | Yellow Sapote. Regarding color, a coloration was presented with a tendency to brown and ocher tones in the epidermis (Figure 2) with a CI of 3.68 ± 1.43 (Table 1), while the pulp shows orange shades (Figure 2) with a CI of 6.46 ± 1.19 (Table 1). The darker tones match with advanced state of fruit maturation (Figure 2). In 2025, in the epidermis, lightness increased by 0.8 units, indicating slightly brighter surfaces. The hue angle decreased by 6.1 units, and chroma decreased by 35.9 units, reflecting a shift toward less defined tones and a marked loss of color saturation. In the pulp, lightness decreased by 23.3 units, indicating darker internal tissues as found in 2024. The hue angle decreased by 74.2 units, revealing a strong shift toward warmer tones.

The physical characteristics of this fruit (Figure 3) indicate a rounded shape, due to the very close polar and equatorial diameters. The thickness of the epidermis was above 4 mm, being wider in the lower parts of the fruit. It presented approximately 45% pulp, between two and three times the mass of the seeds, and the ratio to the epidermis is 0.8. It has a weight that fluctuates between 300 and 330 g, a volume greater than 300 cm^3 , and a density of approximately $1\text{ g}\cdot\text{cm}^{-3}$. It presents a low deformation of the fruit, as it has an extensibility between 33 and 35 mm; however, the firmness of the fruit had a high variation, between 35 and 43 N. For 2025, differences were only observed in characteristics such as the polar diameter, which tended to be 2 cm larger, and the epidermis weight reached 250 g, which is 100 g higher than the fruits in 2024, resulting in an increase in the epidermis/pulp ratio.

The chemical characteristics obtained for the yellow sapote fruit (Figure 3) were as follows: TSS content between 10 and 11°Brix; pH between 6.6 and 6.8 and a low TTA; a high MI from 210 to 250; and a respiration rate of $40\text{--}60\text{ mL CO}_2\text{ kg}^{-1}\cdot\text{h}^{-1}$. The pH and TTA also showed changes during 2025, with pH values reaching up to 8.5, and titratable acidity up to four times higher, exceeding 0.4%. Despite this, no significant changes were observed in the maturity ratio.

3.1.1.3 | Dragon Fruit. In the physical characteristics (Figure 4), dragon fruits are described as oval-shaped, with

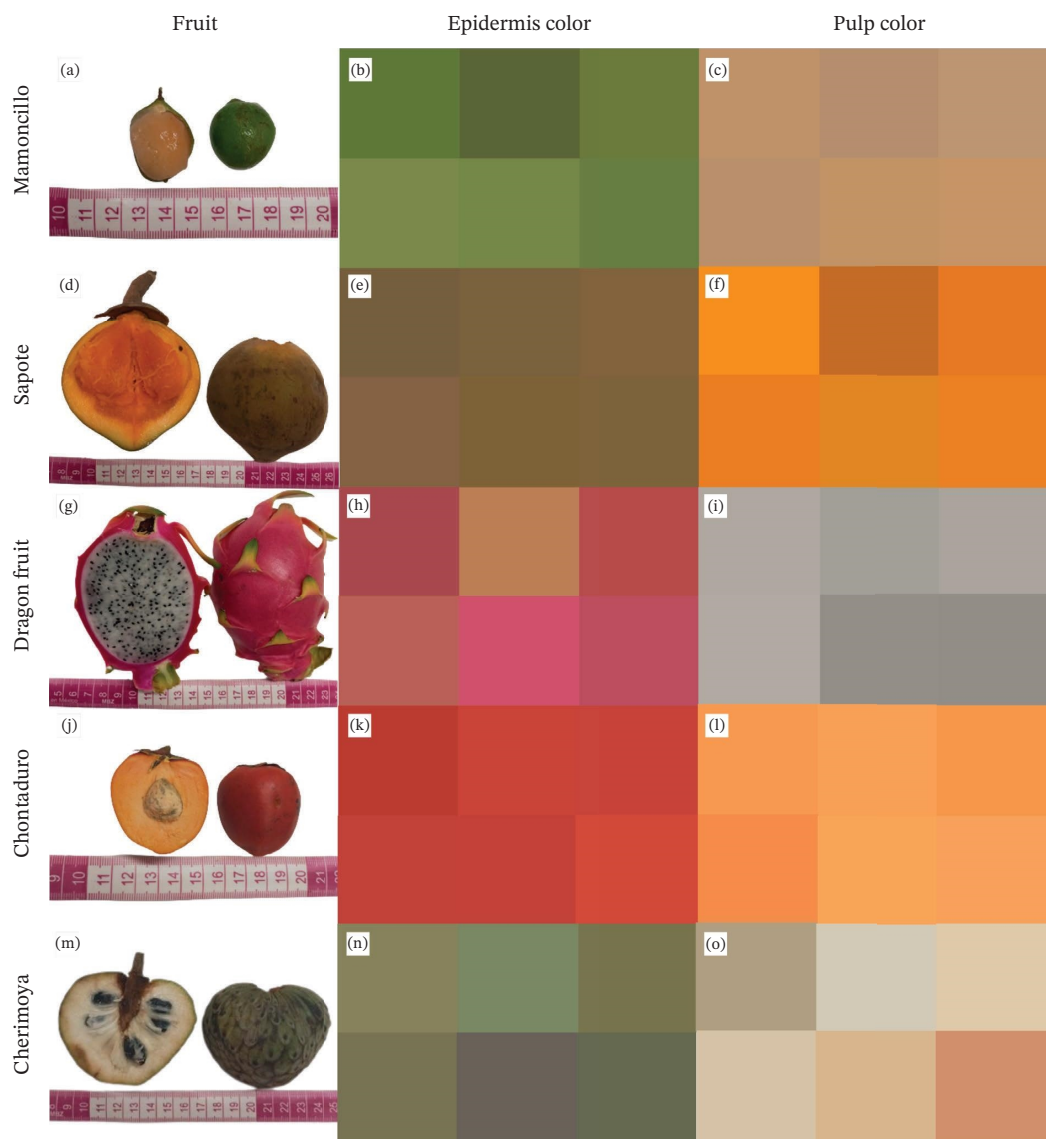


FIGURE 2 | Color of the epidermis and pulp of different native fruits at commercial maturity. Measurements were performed with a digital colorimeter. Colors correspond to the CIE L^*C^*h scale per sample ($n = 6-20$). On each fruit, the top part shows the fruits for 2024 and the bottom part shows those for 2025.

a polar diameter about 3 cm longer than the equatorial diameter. The mean thickness of the epidermis was 3 mm, being wider at the base up to 6 mm. The fruits have more than 5500 seeds dispersed in the pulp. Compared to the other fruits studied, they are large fruits with weights that oscillate between 400 and 530 g, average volumes of 335 cm³, and densities of approximately 1.2 g·cm⁻³. The pulp is 2.5 times the weight of the epidermis and 7 to 12 times that of the seeds. The deformation of the fruit due to extensibility varies from 5 mm to 25 mm after the perforation reaches between 10 and 19 N. During 2025, the fruits exhibited smaller dimensions, with volumes close to 200 mL and polar and equatorial diameters 3-4 cm smaller. Although total weight showed no differences, pulp and epidermis weights tended to be 200 g and 100 g lower, respectively. Likewise, the number of seeds decreased fivefold. This led to changes in the epidermis/pulp and pulp/seed ratios, reaching values of up to 1.25 and 5, respectively. The epidermis also showed greater resistance to penetration, with extensibility values of up to 60 mm.

The color of the epidermis color (Figure 2) tends to be red with some yellow zones, especially associated with the basal area in the bracts along the fruit (Figure 2). The pulp colors (Figure 2) tend to gray due to the black seeds within the white pulp. Meanwhile, the L^* values, hue, chroma, and CI were 47.27, 28, 36.26, and 60.24, respectively, for the epidermis and 64.64, 86.79, 3.74, and 0.91, respectively, for pulp; and L^* and hue were greater than epidermis, but not chroma (Table 1). In contrast, in 2025, the epidermis lightness increased by 0.8 units, indicating slightly brighter surfaces. Hue decreased by 6.1 units, and color saturation decreased by 35.9 units, reflecting a shift toward less defined tones and a marked loss of saturation. While in the pulp, lightness decreased by 23.3 units, indicating darker internal tissues. Hue decreased by 74.2 units, revealing a strong shift toward warmer tones.

Concerning chemical characteristics (Figure 4), we obtained TSS levels ranging from 8.7°Brix to 12.2°Brix, pH values below 4.5, low total acidity, and a MI of 30. The respiration rate is between

TABLE 1 | Color of the epidermis and pulp of different native fruits at commercial maturity.

Fruit	Year	Epidermis				Pulp				Pulp color index
		L^*	h°	C	color index	L^*	h°	C	color index	
Mamoncillo	2024	49.40 ± 4.65***	114.98 ± 2.00***	32.76 ± 3.02***	-9.48 ± 0.93***	62.30 ± 1.06**	75.15 ± 1.42***	26.30 ± 2.85***	4.26 ± 0.44	
	2025	60.83 ± 3.00***	38.40 ± 1.74***	-1.19 ± 0.03***	-6.65 ± 0.54***	51.93 ± 7.07***	23.92 ± 4.39***	4.13 ± 1.68***	5.44 ± 1.99	
Yellow sapote	2024	42.84 ± 1.05	81.06 ± 3.47***	23.25 ± 2.32***	3.68 ± 1.43	60.22 ± 4.80***	68.98 ± 2.40*	66.37 ± 6.33***	6.46 ± 1.19**	
	2025	43.04 ± 3.05	23.87 ± 2.71***	1.21 ± 0.74***	3.86 ± 2.03	38.95 ± 6.55***	49.05 ± 15.04*	3.84 ± 5.63***	13.63 ± 6.65**	
Dragon fruit	2024	47.27 ± 5.17	28.00 ± 20.13*	36.26 ± 4.11***	60.24 ± 40.51	64.64 ± 4.85***	86.79 ± 5.88***	3.74 ± 0.46**	0.91 ± 1.60	
	2025	48.05 ± 1.25	41.91 ± 4.67*	0.35 ± 0.06***	59.33 ± 11.31	41.38 ± 4.28***	12.62 ± 10.00***	-12.55 ± 68.87**	16.67 ± 18.49	
Chontaduro	2024	43.41 ± 1.92*	34.78 ± 1.51***	50.29 ± 2.16***	33.30 ± 2.77***	71.60 ± 2.82***	64.85 ± 2.53*	58.25 ± 2.36***	6.60 ± 0.95**	
	2025	47.38 ± 3.60*	46.60 ± 5.39***	0.86 ± 0.10***	18.54 ± 4.45***	50.84 ± 4.57***	58.15 ± 5.50*	4.41 ± 1.21***	4.74 ± 1.12**	
Cherimoya	2024	47.66 ± 4.60	103.27 ± 13.58***	17.01 ± 6.44***	-4.92 ± 5.45	74.10 ± 8.08**	83.95 ± 10.97***	19.75 ± 7.27	1.71 ± 3.23	
	2025	47.92 ± 6.83	26.01 ± 6.10***	-1.09 ± 0.69***	-6.15 ± 3.08	55.80 ± 11.36**	10.19 ± 1.95***	69.73 ± 133.80	0.77 ± 0.88	

Note: The values shown refer to mean ± standard deviation ($n = 6$ in 2024 and $n = 16$ in 2025). *shows the significant differences based on the Mann-Whitney U test at a 95% confidence level ($\alpha = 0.05$) comparing both years. ** p value < 0.05, *** p value < 0.01, **** p value < 0.001. CIE L^*C^*h scale (lightness, chroma, and hue) with a digital colorimeter. The values shown refer to mean ± standard deviation ($n = 6$).

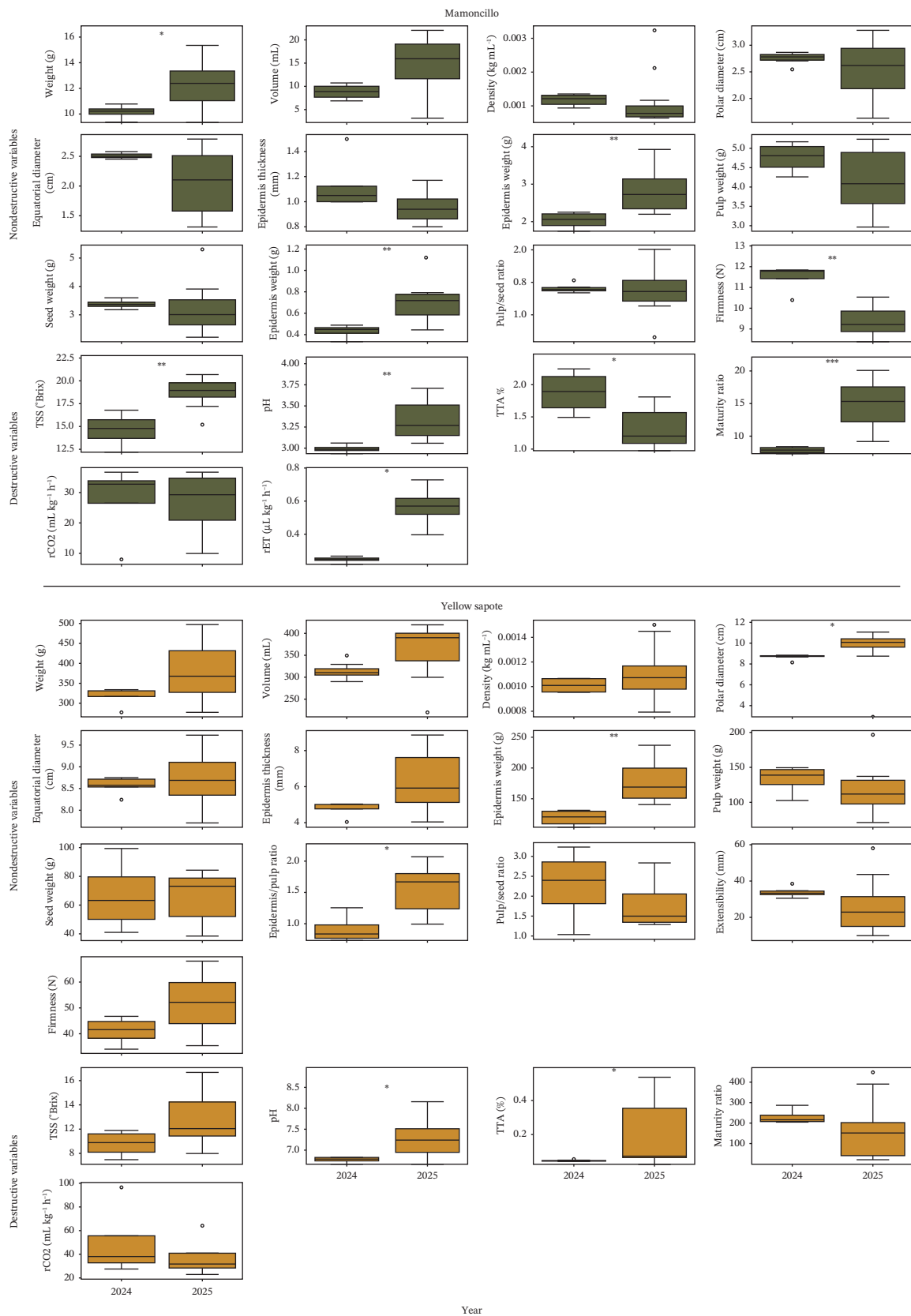


FIGURE 3 | Box plot with results of the physicochemical characteristics of the commercial maturity of the mamoncillo and yellow sapote fruits. Sample $n = 6$ to 20. rCO₂, respiratory rate; rET, ethylene measure; TSS, total soluble solids; TTA, total titratable acidity. *Significant differences based on the Mann–Whitney U test at a 95% confidence level ($\alpha = 0.05$) comparing both years: * p value < 0.05 , ** p value < 0.01 , and *** p value < 0.001 . For each variable, the values for 2024 and 2025 are on the left and right, respectively.

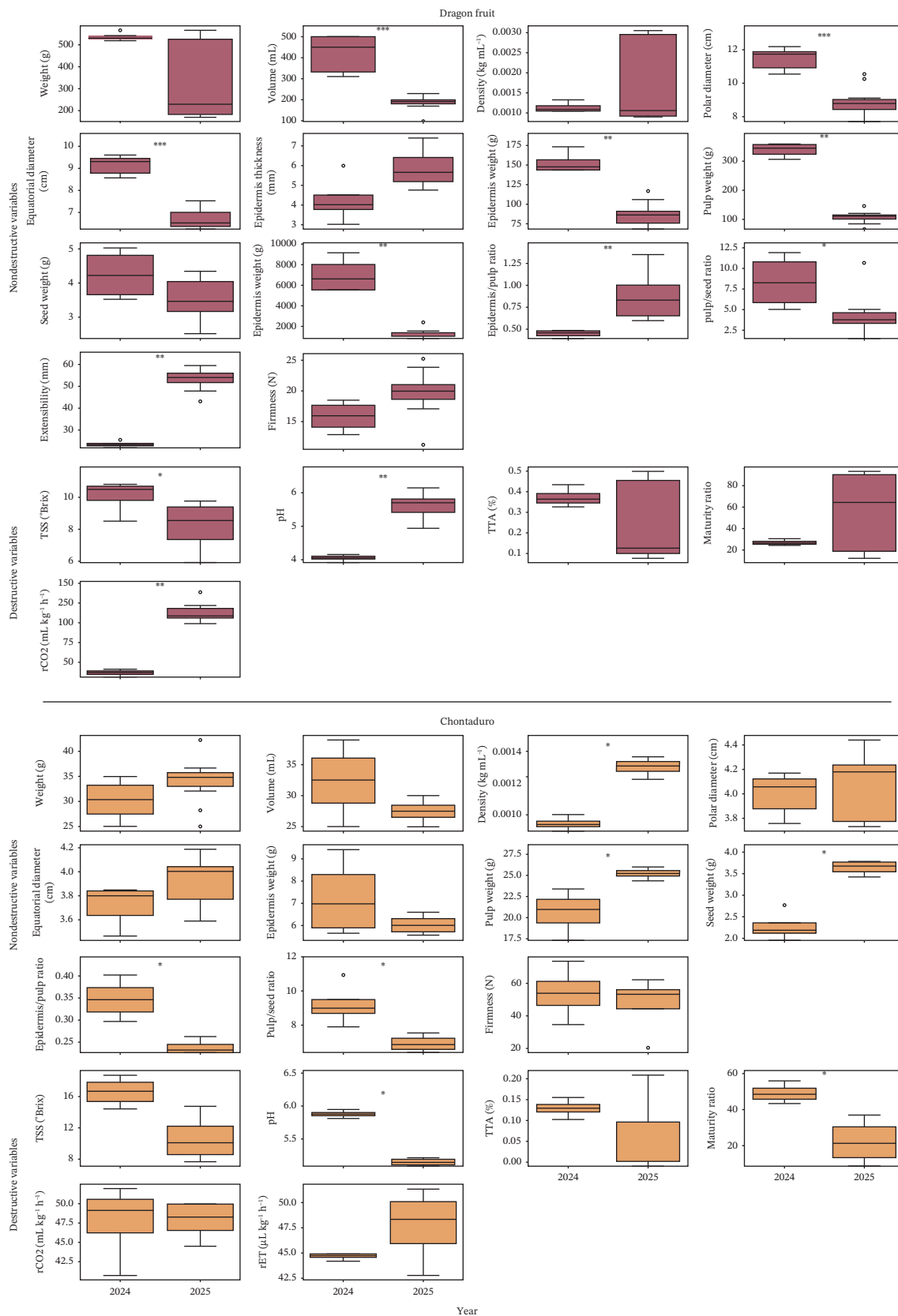


FIGURE 4 | Box plot with results of the physicochemical characteristics of the dragon fruit and chontaduro fruit at commercial maturity. Sample $n = 6$ to 20. rCO₂, respiratory rate; rET, ethylene measure; TSS, total soluble solids; TTA, total titratable acidity. *Significant differences based on the Mann–Whitney U test at a 95% confidence level ($\alpha = 0.05$) comparing both years: * p value < 0.05, ** p value < 0.01, and *** p value < 0.001. For each variable, the values for 2024 and 2025 are on the left and right, respectively.

30 mL·kg⁻¹·h⁻¹ and 42.5 mL·kg⁻¹·h⁻¹. Under study conditions, the dragon fruits did not emit ethylene. For 2025, the fruits had lower soluble solids, with values between 6 and 10°Brix, and higher pH values up to 6. No differences were observed in titratable acidity or the maturity ratio. The fruits also showed higher respiration rates, around 112.5 mL·kg⁻¹·h⁻¹.

3.1.1.4 | Chontaduro. Regarding coloration, reddish tones were presented in the epidermis (Figure 2), with an IC of 33.3 ± 2.77 (Table 1), while orange tones were presented in the pulp (Figure 2) with an IC of 6.6 ± 0.95 (Table 1). In 2025, the epidermis lightness increased by 4.0 units, indicating a brighter surface. Hue increased by 11.8 units, suggesting a shift toward greener tones. In contrast, color saturation decreased by 49.4 units, indicating a loss of intensity. The pulp lightness decreased by 20.8 units, revealing darker tissues. Hue decreased by 6.7 units, indicating a shift toward warmer tones. Color saturation decreased by 53.8 units, reflecting a reduced internal intensity. The CI of the pulp decreased by 1.9 units, suggesting a slightly less warm internal tone in 2025.

About physical characteristics (Figure 4), a round-to-oval shape was presented, since the polar and equatorial diameters tend to be 1. Regarding pulp, this corresponds to approximately 60%, between 9 and 12 times the mass of seeds, and its relationship to the epidermis is approximately 0.3. It has an approximate weight of 30-35 g, with a volume of 30-35 cm³ and a density of 0.9-1 g cm³. A very high firmness of the fruit was presented at 15 N. In 2025, the fruits showed a tendency toward a higher density, with values reaching up to 0.0014 kg·mL⁻¹. Likewise, an increase in pulp and seed weight was observed, reaching up to 27.5 g and 4 g, respectively, which caused a decrease in both the epidermis-to-pulp and pulp-to-seed ratios.

In chemical characteristics (Figure 4), TSS was approximately 6° Brix, and pH was 5.9–6, slightly acidic. Furthermore, the MI obtained was 47-60, the respiratory rate ranged between 47 and 50 mL CO₂ kg⁻¹·h⁻¹, and the ethylene production rate showed values around 0.19 μL·kg⁻¹·h⁻¹. Both pH (below 5.5) and the maturity ratio (around 20) showed significant differences during 2025, with decreasing trends. For this second period, the ethylene production rate showed a wider range with values between 0.11 and 0.45 μL·kg⁻¹·h⁻¹.

3.1.1.5 | Cherimoya. The pulp (Figure 2) shows gray colors due to mixing with the black seeds dispersed in it. However, some fruits showed tissue browning. *L** values, hue, chroma, and CI range from 47.66, 103.27, 17.01, and 4.92 for the epidermis, and 74.1, 83.95, 19.75, and 1.71 for pulp, respectively (Table 1). The coloration of the epidermis (Figure 2) tends to green and dark gray in some cases. The epidermis hue in 2025 decreased by 77.3 units, indicating a notable shift in color tone. Color saturation decreased by 18.1 units, reflecting a lower surface color intensity. The pulp lightness decreased by 15.8 units, showing darker internal tissues. Hue decreased by 73.8 units, indicating a strong shift toward warmer tones. Color saturation increased by 50.3 units, indicating a greater internal color intensity compared to 2024 (Table 1).

Meanwhile, the physical characterization of the cherimoya fruits (Figure 5) shows that it is a fruit with round to oval shapes, since the equatorial axis tends to be 1 cm longer. In

most fruits, the pulp is equivalent to one or two times the weight of the epidermis. In some cases, the epidermis was three times the weight of the pulp due to the hardening of the tissue. In the same way, the pulp was two to nine times the weight of the seed, with an average count of 18-40 per fruit. It is classified as a medium fruit, with average weights, volumes, and densities of 170 g, 180 cm³, and 0.93 g·cm³, respectively. When the fruits were cut, hardening of the subepidermal tissue was observed, causing an increase in the thickness of the shell of up to 6 mm. Cherimoya has low fruit deformation, with firmness between 10 and 42 N. In 2025, the fruits showed greater weight, reaching up to 300 g, with volumes of up to 250 mL, which in turn led to increases in the density. Pulp weight also increased, by up to 50 g compared to the previous year, along with a lower number of seeds, resulting in an increase in the pulp-to-seed ratio of up to four times. The fruits also showed lower firmness, with values around 3 N.

Chemical characteristics show a TSS content ranging from 4 to 12°Brix and a TTA of 0.25% (Figure 5). Based on that, the MI of cherimoya commercialized in Colombia varies between 25 and 40. The average pH was 4.8. Of all the fruits evaluated, cherimoya had the highest respiratory rate, with 80 mL·kg⁻¹·h⁻¹. For the second time period, the fruits had higher soluble solids, reaching up to 30°Brix above 2024, causing increases in the maturity ratio. The respiration rate also showed significant changes but with lower values than those observed in 2024, with a maximum of 60 mL·kg⁻¹·h⁻¹.

3.2 | Phase II: Identification, Characterization, and Determination of the Economic Impact and Loss Generation Associated With Postharvest Pathologies and Disorders in Seasonal Fruits

3.2.1 | Postharvest Disease and Disorder Problems

Figure 6 summarizes the incidence of latent physiological disorders and pathogenic activity identified under controlled laboratory simulation of commercialization conditions. Fruits that appeared visually sound at the time of sampling often developed symptoms of dehydration, senescence, and superficial browning after 3-21 days of simulated storage. The laboratory assessment revealed that these symptoms were not only progressive but also highly dependent on the fruit's inherent respiration rate and epidermal resistance. Dehydration was particularly accentuated in species with low cuticular thickness or high surface-to-volume ratios, whereas senescence symptoms predominated in fruits with elevated ethylene sensitivity. Fungal colonization was detected in a smaller subset of samples, usually following pre-existing mechanical injuries or microcracks.

The mamoncillo fruits showed browning in some areas of the epidermis (Figure 6B2), characterized by ocher tones. In addition, after spending 5 days, 8 days, and 13 days at rest at room temperature, the fruit showed signs of sunburn damage on the surface of the epidermis and at the mesocarp level, associated with possible effects of the sun (sunburn) (Figure 6B3) and the fruit showed signs of dehydration (Figure 6B4). To a lesser extent, but no less important, the following were found mechanical damage (rupture of the epidermis) (Figure 6B5) and other damage associated with the presence of a scab-like spot on the epidermis (Figure 6B6).

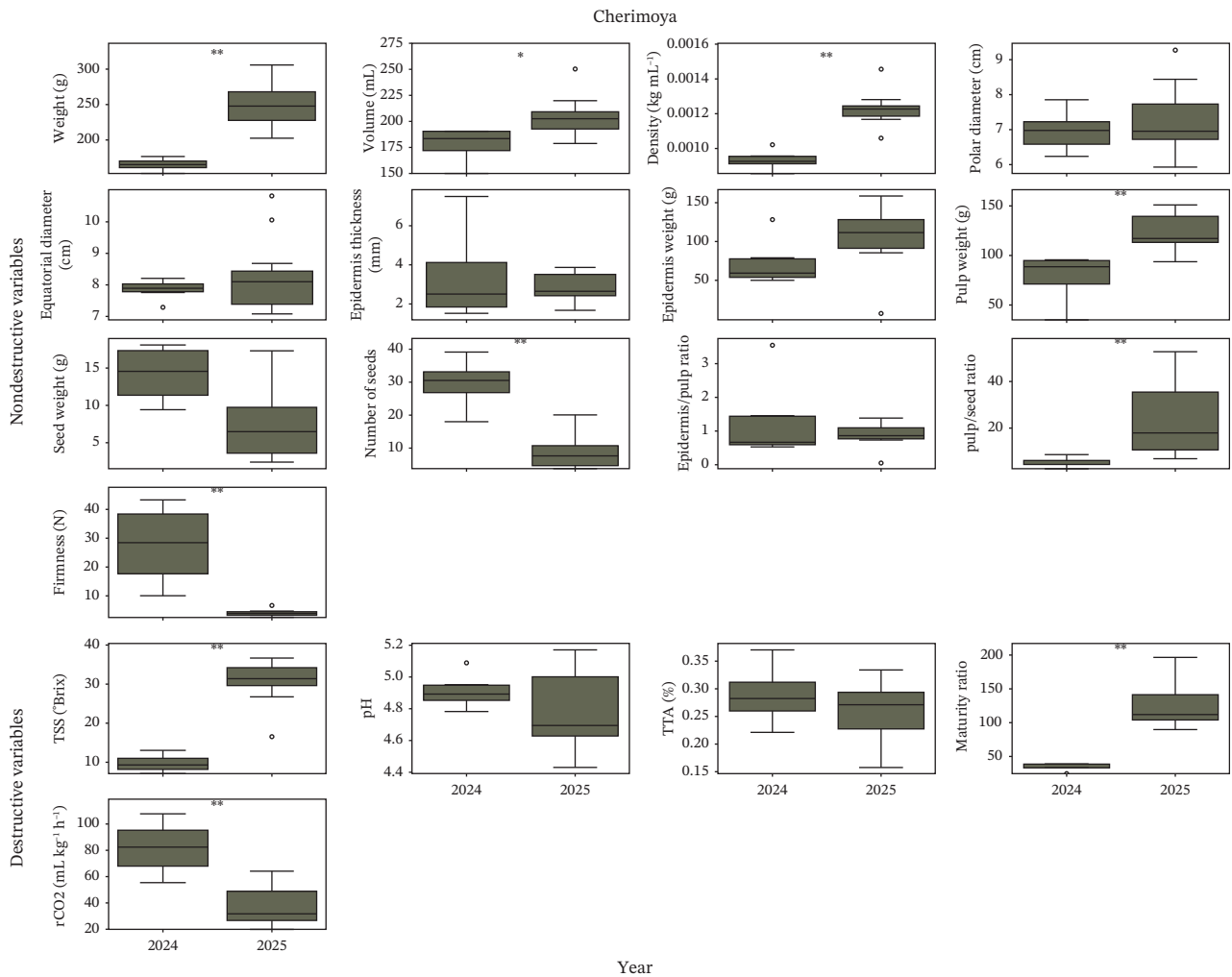


FIGURE 5 | Box plot with results of the physicochemical characteristics of the cherimoya fruit at commercial maturity. Sample $n = 6$ to 20. rCO_2 , respiratory rate; rET: ethylene measure; TSS, total soluble solids; TTA, total titratable acidity. *Significant differences based on the Mann–Whitney U test at a 95% confidence level ($\alpha = 0.05$) comparing both years: * p value < 0.05 , ** p value < 0.01 , and *** p value < 0.001 . For each variable, the values for 2024 and 2025 are on the left and right, respectively.

In the yellow sapote fruits, a series of damages associated with senescence were identified that affect visual quality in especially the signs of nonpathogenic fungus in the epidermis of the fruit (Figure 6B1) with white and green sporulation of the pathogen, formation of other pink tones, and mycelial growth with black ends (Figure 6C2). Between 8 and 13 days after leaving under room temperature conditions showed dehydration (Figure 6C3). Also at this stage, and of lesser importance, was the presence of fruit flies, a phytosanitary problem that greatly affects fruit quality by causing mesocarp rot (Figure 6C4). Thus, in our presence, unidentified mechanical damage was reported, as well as damage to the epidermis due to cuts (Figure 6C5) and damage to the seed due to possible pollination problems or seed development due to other causes (Figure 6C6).

The red dragon fruits had mechanical damage to the epidermis, presenting as yellow clefts and, in some cases, dark colors in the center, and this continued in the evaluations of Day 5. Then, 8 days after being stored at room temperature, the bracts looked dehydrated and changed color to brown (Figure 6C1). The change in the color also began to become evident around the initial wounds, in addition to the changes in texture and smell

associated with tissue rot (Figure 6C2). These stains had a radial advance until they covered almost all fruits on Day 13 of evaluation, where it was evident that the tissue had become more fragile and susceptible to damage, with a strong odor (Figure 6D2). This fruit also showed sunburn damage from the sun, albeit to a lesser extent, appearing as a round, brown spot (Figure 6D3). There was also a loss of intense pink color, shifting to pale pink tones with a loss of texture and softening (Figure 6D4), as well as mechanical damage to the surface (Figure 6D5).

The chontaduro fruits showed after 8 days under room dehydration (Figure 6E2) temperature mechanical damage of unknown origin and sunburn damage (Figures 6E3 and 6E4). On Day 28, when the fruit was opened, a gray and white sporulation was observed that begins under the bract and continues to develop inside the fruit a symptom known as mesocarp black rot, in which micro-organisms with a high probability of being pathogenic were observed, identified as *Ceratocystis* spp. and/or *Lasiodiplodia theobromae* (Pat.) Griffon and Maubl (Figures 6D4 and 6D5). Damage of unknown origin has also been reported, which is associated with a stain on the skin from the base of the

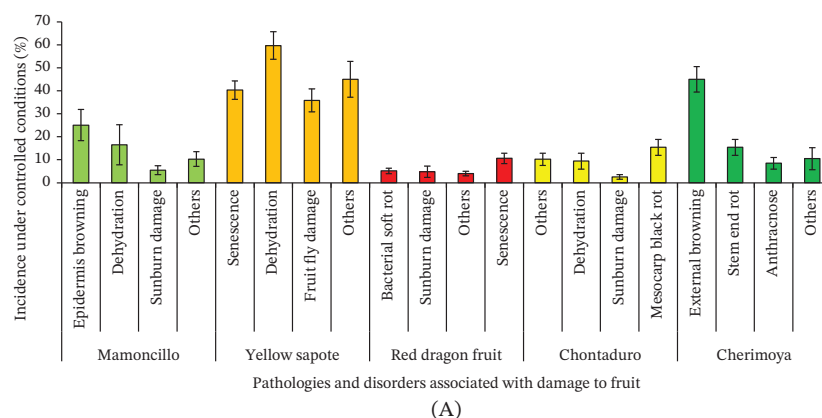


FIGURE 6 | Characteristics of postharvest diseases and disorders of the different native fruits, beginning at the time of purchase up to 5–29 days of rest under room temperature conditions. A: Incidence of phytopathologies found in seasonal tropical fruits. The bars represent the confidence interval of the mean. B1: Healthy mamoncillo; B2: epidermal browning; B3: sunburn damage; B4: dehydration; B5: mechanical damage; B6: scab-like spot. C1: healthy yellow sapote; C2: senescence; C3: dehydration; C4: fruit flies; C5: mechanical damage. C6: possible pollination problems; D1: healthy red dragon fruit. D2: temporal advance of symptoms of symptoms of symptoms of symptoms of bacterial disease symptoms; D3: sunburn damage; D4: senescence; D5: mechanical damage. E1: Healthy chontaduro; E2: external dehydration; E3: sunburn damage; E4: temperature mechanical damage of unknown origin; E5: mesocarp black rot, in which micro-organisms with a high probability of being pathogenic were observed, identified as *Ceratocystis* spp. and/or *Lasiodiplodia theobromae*; E6: damage of unknown origin has also been reported, which is associated with a stain on the skin from the base of the fruit to the apex. F1: Healthy cherimoya; F2–F3: external browning; F4: stem-end rot associated with *L. theobromae*; F5: Anthracnose associated with *Colletotrichum* spp.; F6: mechanical damage.

fruit to the apex, with a slight impact on the epidermis, without affecting the mesocarp.

The cherimoya fruits showed hardening of the epidermal and subepidermal tissue and browning of the pulp. Damage characterized as external browning, with a significant impact on the quality of this fruit, given that in a short time, the epidermal surface turns completely black and the inside becomes very soft (Figures 6F2 and 6F3). In addition, some fruits had tissue degradation with black discolorations. Later, at 5 days, the fruits had white and pink growths on the surface, with black globose structures (Figure 6E4), and this continued in the evaluations of Days 8 and 13. This damage was associated with stem-end rot, from which the micro-organisms *L. theobromae* were consistently isolated. On the other hand, and to a lesser extent, symptoms of intense black spots were observed, which over time become covered with a pink hue associated with the spores of their causal agent, a problem known as anthracnose and its associated micro-organism *Colletotrichum gloeosporioides sensu lato*. Similarly, a series of mechanical damages with a high impact on the visual quality of the product were also found.

3.2.2 | Characterization and Consequences of Postharvest Pathologies and Disorders in Tropical Seasonal Fruits: Quality Degradation, Market Economic Loss, and Waste Production

The results highlight that physiological disorders such as dehydration and senescence constitute the primary drivers of visible deterioration and economic loss in seasonal tropical fruits. These conditions accelerate the transition from commercial acceptability to rejection, thereby influencing the rate of waste generation and the cumulative market value loss. The integration of field and laboratory observations confirms that many of the postharvest disorders observed in retail environments originate from latent physiological processes initiated prior to commercialization, which subsequently manifest as quality decline, color alteration, and tissue breakdown under ambient market conditions (Figure 7).

Figure 7(a) depicts the relative frequency of postharvest disorders and pathological symptoms recorded across the surveyed tropical seasonal fruits in different commercialization environments. The distribution shows a heterogeneous pattern among fruit types, with dehydration, senescence, and external browning emerging as the most recurrent issues. Fruits such as mamoncillo, chontaduro, and cherimola exhibited a higher proportion of dehydration symptoms. In contrast, red dragon fruit and yellow sapote displayed a predominance of senescence-related deterioration, manifested through peel discoloration, loss of firmness, and surface wrinkling. A moderate but consistent presence of external browning and lenticel darkening was observed, particularly in fruits with naturally thin or porous epidermis. These findings indicate that physiological breakdown processes, rather than infectious diseases, accounted for the majority of visible deterioration under commercial handling.

Figure 7(b) illustrates the relative quality status of the fruits reaching commercialization points and the consequent economic implications of quality loss and waste generation. Markets receiving fruits with advanced dehydration or senescence symptoms presented a clear decline in overall quality index values,

resulting in increased rejection rates and price reductions. In high-turnover urban centers, losses were mainly expressed as price depreciation, with fruits sold at discounts of 40%-70% compared with standard-quality produce. In addition, the rapid product senescence led to direct waste generation, with a significant proportion of fruit (up to 25%-80%) being discarded as nonsellable. The data collectively demonstrate that quality deterioration directly translated into measurable commercial losses, through both the depreciation of low-quality fruit and physical disposal of unsold produce.

3.3 | Phase III: Analysis of Sensory Perception by Consumers of Selected Fruits at Commercially Mature

The Likert analysis showed that appearance and price are two of the most important factors for the purchase and preferences of the five fruits evaluated (Figure 8). Other important factors that may influence the purchase and consumption of these fruits were smell for mamoncillo, yellow sapote, and cherimoya (Figures 8(a), 8(b), and 8(e)); maturity stage for mamoncillo, yellow sapote, and chontaduro (Figures 8(a), 8(b), 8(d)); fruit texture for red dragon fruit and cherimoya (Figures 8(c) and 8(e)); and the color for red dragon fruit and chontaduro (Figures 8(c) and 8(d)). On the other hand, the factors of least importance for all fruits were fruit size and product origin, which refers to whether the product comes from clean, organic, or nonorganic agricultural processes (Figure 8). Texture was also of little importance for fruits such as mamoncillo and yellow sapote, which also shows little importance with color (Figures 8(a) and 8(b)).

The highest positive perception was found for the mamoncillo and cherimoya fruits (Figures 9(b)–9(j)) with approximately 150 positive words, followed by the yellow sapote with 120 (Figure 8(d)). Both dragon fruit and chontaduro had less than 100 positive words and the highest proportion of negative sentiments (Figures 9(f)–9(h)). For mamoncillo, consumers agree that it is a soft, juicy, and rich fruit, although it can also be considered hard because of the presence of the seed that occupies a large part of the fruit. With respect to its physical characteristics, it is a small fruit, with a rough and opaque epidermis and a gelatinous, fibrous, shiny, and attractive pulp. For some people, it reminds them of childhood. Some people mention that they consider it a perfect fruit associated with happiness. Despite this, some consumers consider it an acid fruit similar in taste to a lemon, or flavorless, possibly associated with the degree of ripening, with undesirable physical characteristics associated with damage in the form of spots on the epidermis of the fruit (Figure 9(a)).

Some people associate yellow sapote with fruits such as mango and papaya, possibly due to the texture of the pulp or its sweetness, while others associate it with tubers such as potatoes. The results highlight the aroma and physical appearance of the fruit, making it an attractive fruit. However, some people consider it an ugly fruit, which is marketed with imperfections and incidences of phytosanitary problems mainly associated with fungi (Figure 8(c)).

In the red dragon fruit, one of the most notable physical characteristics of this fruit is its pink epidermis, although a few people mentioned the colors purple, yellow, red, and fuchsia. Some

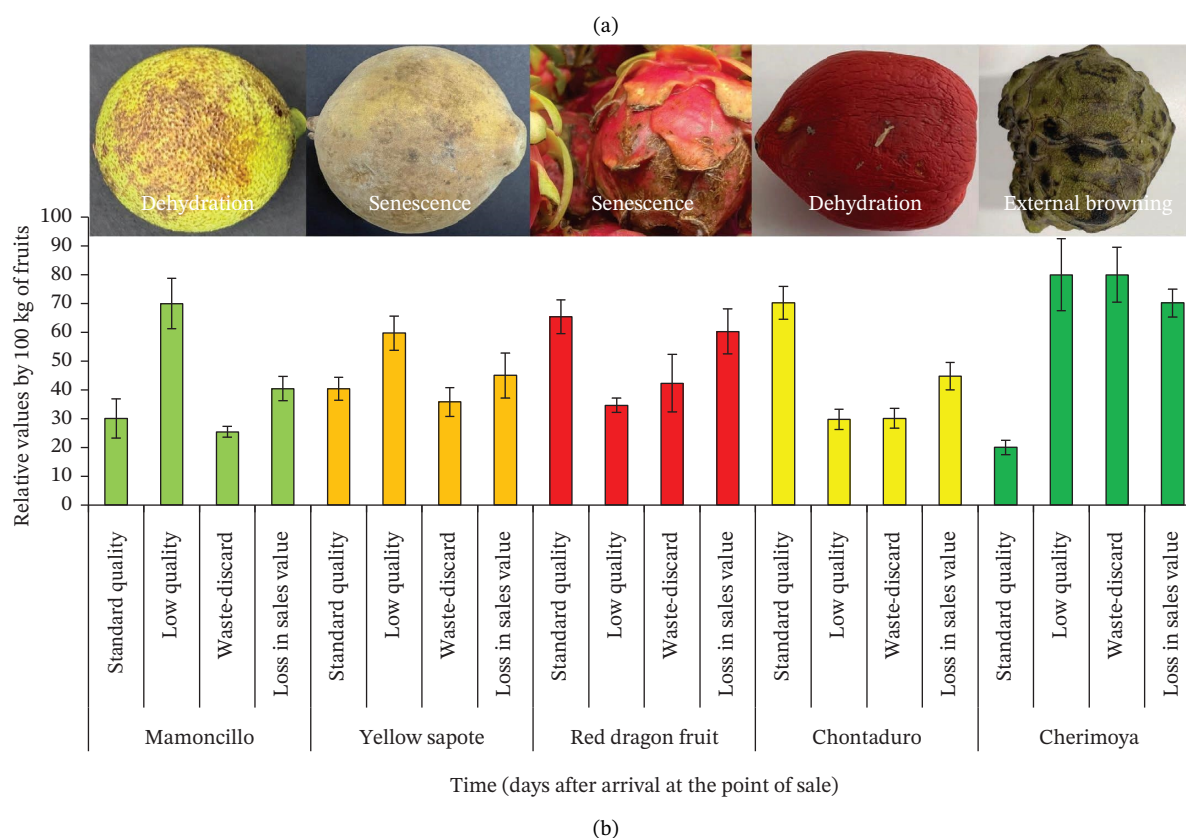
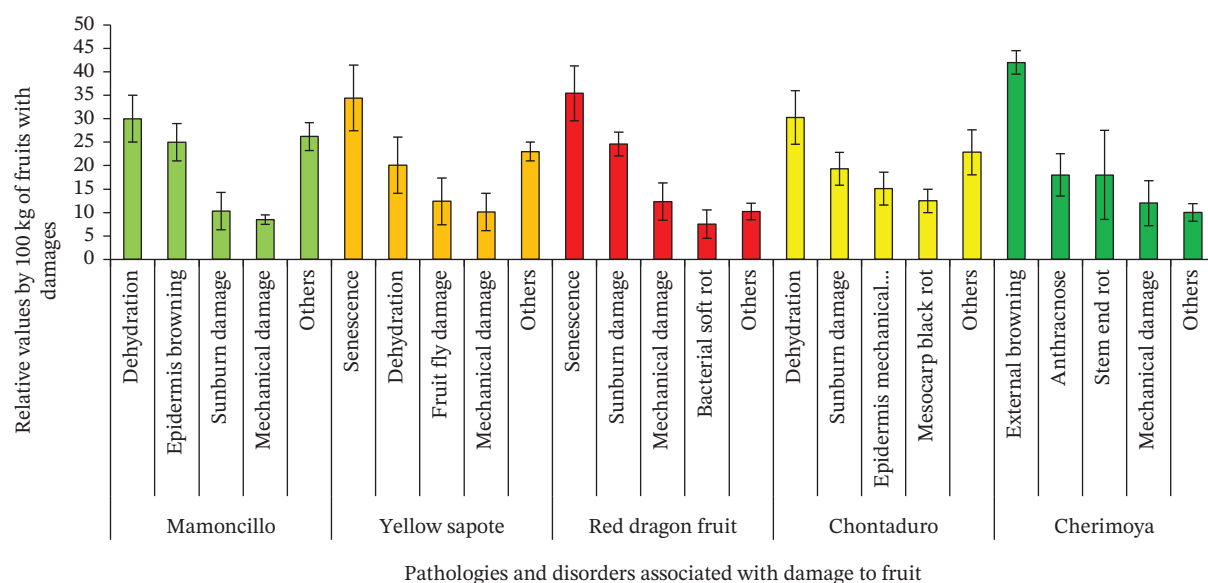


FIGURE 7 | Multidimensional assessment of postharvest quality deterioration in seasonal tropical fruits: prevalence and visual evidence of physiopathological damage. (a) Incidence (%) of postharvest physiopathologies observed in five seasonal tropical fruit specie from Colombian commercial distribution centers during the 2024–2025 harvests. (b) Representative images illustrating predominant postharvest disorders identified in the evaluated species, including dehydration, senescence, and external browning. These symptoms were the most frequently associated with reduced commercial quality and higher rejection rates in marketing centers.

people associate its flavor with kiwi, with gelatinous textures such as aloe vera. Some not very positive characteristics are attributed to the taste of the fruit, which they mention is very tasteless. However, with respect to the physical component, some mentioned that the fruits were not in good condition because they showed bruising and other damage to the epidermis, in addition to opaque colors (Figure 9(e)).

Chontaduro showed mixed consumer perceptions, reflecting both positive and negative evaluations. In some cases, they really like the fruit, mentioning that they are healthy and bring back memories specifically of the Colombian Pacific or cities like Cali in Valle del Cauca, with very striking colors and pleasant flavors. In other cases, they did not like the fruit because it was salty or had woody notes (Figure 9(g)).

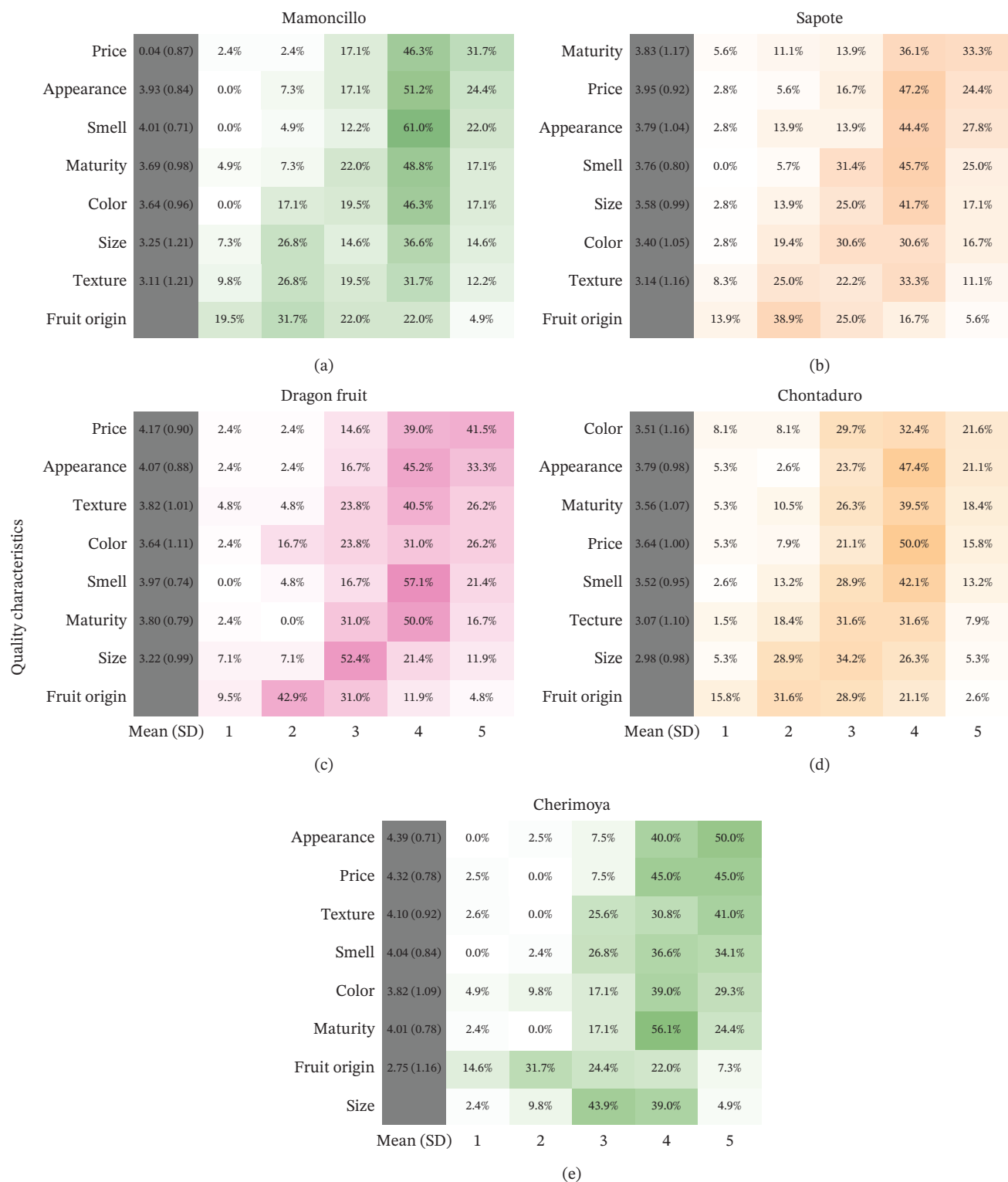


FIGURE 8 | Results of the Likert analysis for the identification of preferences for quality characteristics in the purchase and consumption of (a) mamoncillo; (b) yellow sapote; (c) red dragon fruit; (d) chontaduro; (e) cherimoya. The vertical axis shows the quality factors obtained from literature, and the horizontal axis shows the responses on a nominal scale where 1 is Unimportant and 5 is Very Important. The percentages are the proportion of people who answered each response.

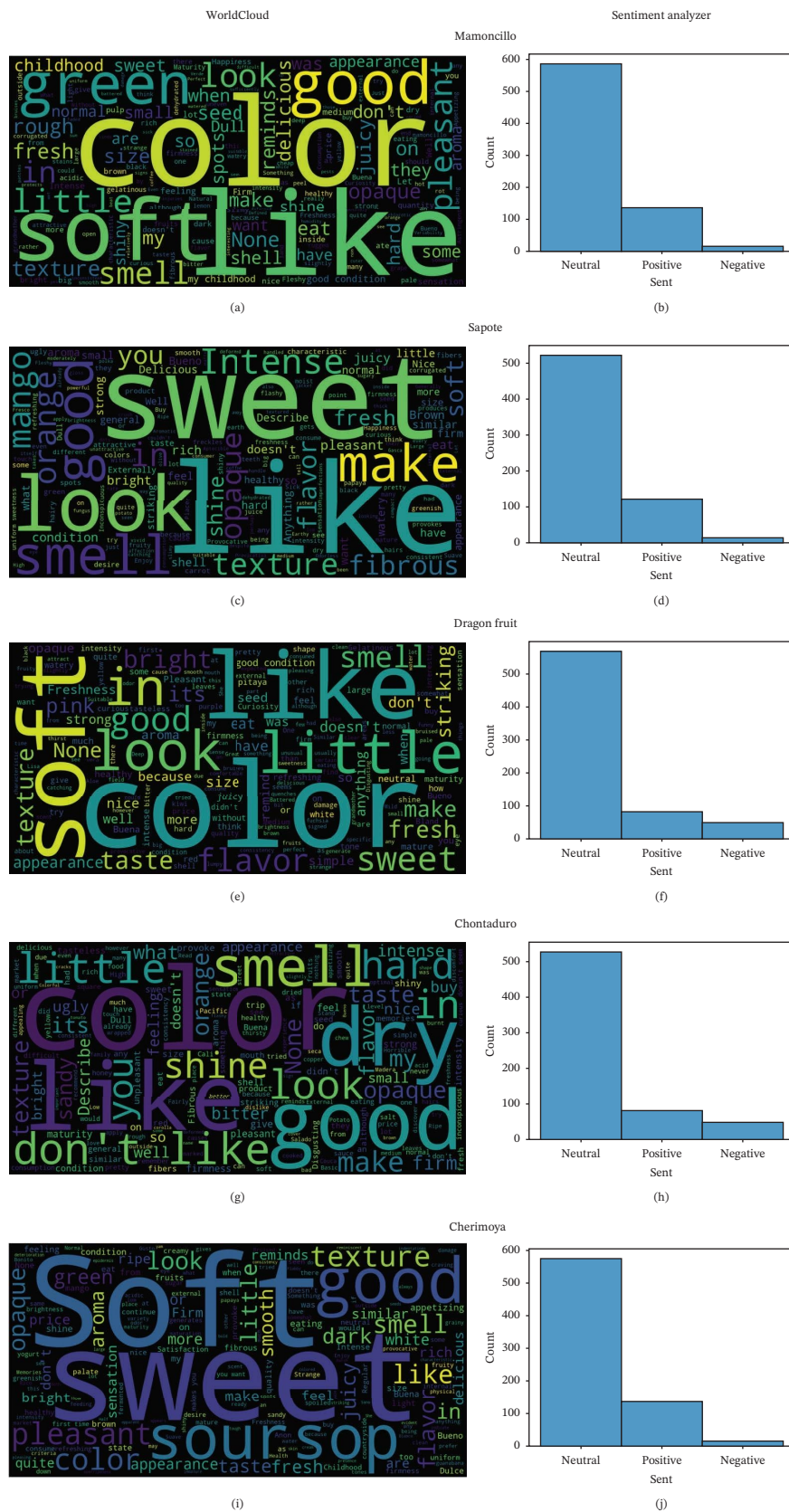


FIGURE 9 | Results of the sensory analysis of the different native fruits at commercial maturity. Text analysis was done using WordCloud Sentiment analyzer. The text analysis is presented (a, c, e, g, and i), where the word size is proportional to its importance. The frequency distribution indicates whether the consumer's perception was neutral, positive, or negative (b, d, f, h, and j).

Most of the respondents for cherimoya fruits, it resembles the taste of soursop, and others associate it with other foods such as yogurt, papaya, and anon. Like mamoncillo, it is a fruit that some associate with childhood and the countryside. One of the negative feelings was associated with it, as some people indicated that it had strong fermented flavors, as well as a deteriorated appearance that was not very pleasant (Figure 9(i)).

4 | Discussion

In tropical conditions, there is a wide variety of fruits with high nutritional value and good sensory acceptance by consumers, as evidenced by our study. Through the MQ characterization [19–21] of five selected seasonal fruits, this research advances understanding of their potential uses and suggests areas for improvement, contributing to the sustainable and high value use of tropical biodiversity. In this context, our study demonstrates that under current production conditions, the five tropical fruits evaluated exhibit a high degree of heterogeneity in their quality attributes across both seasons (2024 vs. 2025). This variability represents a major challenge if these fruits are to be positioned in the future as a viable alternative for Colombia's current export portfolio. The findings highlight the need to improve numerous practices across the production chain preharvest, harvest, and postharvest to ensure greater consistency and exportability. Critically, this includes the adoption of stable genotypes, validated agronomic management practices, appropriate harvest indices, and postharvest technologies that enhance fruit performance, particularly by reducing the impact of physiopathologies and addressing the inherently short shelf life that characterizes these tropical fruits.

In addition, our study significantly enhances the characterization of quality factors in tropical fruits, offering a general analysis of their physical and chemical properties under both optimal and suboptimal postharvest conditions. Unlike previous studies that focus on isolated quality parameters [41], our research integrates a multidimensional approach, examining the combined effects of factors such as pulp and seed weight, epidermis thickness, respiration rate, ethylene production, and consumer perceptions across multiple fruit species. This holistic perspective provides a more complete understanding of fruit quality. As such, our findings are highly relevant to improve postharvest management strategies, with implications for the commercialization and preservation of tropical fruits [42]. Within the scope of our contribution, we conducted a MQ characterization of five seasonal fruits produced under tropical conditions. This analysis allowed us to perform a basic characterization of these high-potential genetic resources, paving the way for the development of these fruits under commercial production systems.

The findings of this study highlight that when fruits are harvested and commercialized under suboptimal conditions, they exhibit uneven ripening processes and low quality in key parameters such as size, color, shape, and taste, which is characteristic of local markets [43]. Furthermore, multiple pathologies and disorders contribute to a reduction in their overall MQ. We found disorders such as sunburn damage in chontaduro and browning in mamoncillo fruits that are mainly due to variations in the water regime [44, 45], indicating that the fruits were acquired under conditions of dehydration generated by postharvest

processes or high-temperature conditions in the crop [44, 46, 47]. In this regard, the browning of cherimoya has been reported to be the result of cold storage below 7°C [48]. These are significant causes of the increase in postharvest losses [47].

On the other hand, postharvest pathologies found in this study are mainly attributed to causal agents from bacteria and fungi. Chontaduro and cherimoya fruits show symptoms associated with fungi rots. During postharvest chontaduro processes, the main effects have been determined to be black rot, the causal agent of which has been associated with *Ceratocystis* spp. and *L. theobromae* [49]. While cherimoya symptoms were associated with stem-end rot and anthracnose. Some pathogens reported in the literature that can be associated with the structures found are *L. theobromae*, *Colletotrichum* spp., and *Rhizopus stolonifer* (Vuillemin). [50, 51].

These issues significantly impact consumer perception, which fluctuates depending on the level of quality encountered. This variability undermines the ability to promote a consistent and reliable consumption culture [52]. Addressing these quality deficiencies is crucial to ensure that consumers receive fruits that meet acceptable standards, fostering long-term market stability and trust. Furthermore, the information collected from our study can be used to refine harvest and postharvest practices. For example, data on firmness, weight distribution, and sugar content can guide the development of specific handling protocols to reduce postharvest losses, even for packaging design. Farmers and distributors could benefit from this by implementing targeted interventions based on fruit maturity stages and identified quality thresholds.

Our results show that epidermal damage, although it does not necessarily compromise the internal quality of the fruit, has a decisive effect on consumer perception and commercial acceptance [23–25]. Across the five tropical routes evaluated, we found a high degree of heterogeneity in quality attributes between the 2024 and 2025 seasons, revealing a critical challenge for positioning these fruits as competitive alternatives within Colombia's export portfolio. The sensitivity of these fruits to inadequate agronomic management, harvest, and postharvest practices exacerbates the occurrence of superficial defects, which in practice translate into discard rates ranging from 25% to 80%. These losses not only represent a significant economic impact for producers and marketers but also pose a serious environmental problem due to the increase in organic waste and the inefficient use of resources.

Our study introduced and validated innovative data analytics tools, particularly NLP, specifically tailored to capture consumer sensations and perceptions during fruit taste tests. This method provided valuable insights into consumer preferences and demonstrated its potential for broader applications involving nonnumeric data, such as text or audio [36–38]. This approach allowed us to capture detailed and subtle insights into how consumers assess fruit quality, offering actionable data that can inform marketing strategies and improve consumer engagement. NLP analysis identified critical patterns in feedback, highlighting the important role of visual and textural attributes in shaping purchasing decisions [53].

It is important to state that our approach focused on a basic characterization of MQ factors, which should be enhanced in

various aspects to gain a better understanding of these genetic resources. Based on our findings, we suggest that future studies include the following aspects: (i) characterize fruits at different stages of ripeness and during their shelf life, as well as of different origins, to determine the effect of edaphoclimatic conditions on quality factors. (ii) Pursue new analyses aimed at functional characterization, which is currently essential for defining the added value of foods. (iii) Increase the number of participants in perception tests and include expert panels to describe the sensory quality criteria of these fruits. (iv) Include some genetic variations in these fruits to incorporate all possible variability from the perspective of MQ factors. (v) It is important to improve and use both preharvest and postharvest aspects. Specifically, and related to the topic addressed in this study, future work should focus on determining harvest indicators to enhance postharvest and commercialization stages. (vi) We also suggest evaluating different postharvest technologies for these fruits.

5 | Conclusions

This study allows the exploration of the market potential of five native tropical fruits in Colombia: mamoncillo, sapote, red dragon fruit, chontaduro, and cherimoya. We have provided a first approach to understanding the quality parameters and potential challenges associated with these fruits, by conducting comprehensive analyses that include physical–chemical attributes, post–harvest diseases and disorder problems, and consumer sensory evaluations. Our study represents a significant step forward in comprehensively characterizing the MQ attributes of native fruits grown under tropical conditions.

Author Contributions

Laura A. Valbuena-Gaona: conceptualization, methodology, investigation, data curation, writing–original draft, validation, and writing–review and editing. Ana María Orjuela-Rodríguez: methodology, investigation, data collection, validation, and writing. Helber Enrique Balaguera-López: conceptualization, supervision, writing–original draft, and writing–review and editing. Joaquín Guillermo Ramírez-Gil: conceptualization, validation, supervision, project administration, methodology, data curation, writing–original draft, and writing–review and editing.

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Disclosure

All authors have read and agreed to the published version of the manuscript.

Ethics Statement

In this study, during both the generation and validation of consumer perception, a preliminary engagement was conducted with the participants (consumers). They were provided with a detailed explanation of the study, including its objectives, the nature of the questions, and the intended use of the collected information.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Multidimensional-Quality-of-Seasonal-Tropical-Fruits at <https://github.com/agrocompuepidemlab/Multidimensional-Quality-of-Seasonal-Tropical-Fruits>.

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