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Sensory profile, visual and aromatic instrumental analysis of African tamarillo (*Solanum betaceum* L.) fruit drinks

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A R T I C L E I N F O

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A B S T R A C T

Tamarillo (*Solanum betaceum* L.), also known as “tree tomato”, is a subtropical plant native of the Andean regions, also found in Southern Europe and Africa. These fruits are of great interest in some regions of the world as they can also be processed into juice or wine and contain functional compounds such as phenolic molecules, vitamins, minerals, and carotenoids. The objective of this study was to characterize, through sensory and instrumental analyses, two tamarillo fruit drinks produced in Kenya, named TJ and BTJ (the latter a variant of the first one through enrichment with mulberry leaf extract), formulated without added sugars and two common Italian juices (a red fruit juice and an orange juice), these last used for a comparison. The sensory analysis (Flash Profile) identified 23 distinctive sensory descriptors. TJ was characterized by bitter, herbal, and moldy notes, while BTJ exhibited turbidity, exotic fruit aroma, and balsamic notes. The volatile profile (SPME-GC-MS) revealed the presence of terpenic compounds, namely, limonene, linalool, and terpinen-4-ol. Furthermore, image analysis (IRIS electronic eye) identified the specific red tones of the tamarillo fruit drinks. The combined analysis of sensory and instrumental data (Multiple Factor Analysis) highlighted relationships between specific volatile molecules and olfactory descriptors, as well as registered red tones and visual descriptors. This work provides elements for the characterization of tamarillo fruit drinks, useful for improving their formulation, acceptability and enhancing their commercial potential at a global level, or considering specific needs of sugar reduction and dietary food fortification.

1. Introduction

Tamarillo (*Solanum betaceum Cav., syn. Cyphomandra betacea Sendt.*), also known as “tree tomato”, is a perennial specie belonging to the Solanaceae family, genus Solanum (Diep et al., 2022; S. Wang & Zhu, 2020). It is a subtropical plant native of the Andean regions of South America, from Peru to Argentina; however today it is grown worldwide (Bakshi et al., 2016; García et al., 2016; Nowak et al., 2023; S. Wang & Zhu, 2020). Tamarillo fruits have an ovoid shape, pointed at both ends, they are covered with a thick, smooth, and shiny exocarp and they can vary in size (length from 4 to 10 cm) and diameter (from 3 to 5 cm). Tamarillo varieties are distinguished by the colour of the exocarp, which can be yellow, orange, red or purple. Also, the pulp can vary in colour ranges from yellow to deep red or purple. Its texture is firm and juicy, with a sweet and sour flavour and a potential astringent sensation. At the fruit’s core the flat seeds are arranged in two longitudinal compartments and they are covered in a purple or red mucilage (García et al., 2016; S. Wang & Zhu, 2020). Studies on the chemical composition of tamarillo fruits are limited. The composition can vary depending on the variety, geographical and environmental factors, and the fruit’s ripeness (Nowak et al., 2023). The tamarillo fruit has a low calories content (Bakshi et al., 2016) and, on a dry matter basis, it contains 4.89–9.58 % proteins, 28.1–52.0 % total sugars, and small amounts of lipids (0.1–0.7 %), in its pulp, which is the edible part of the fruit (Nowak et al., 2023). Tamarillo

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fruit is rich in minerals (i.e., potassium, phosphorus, magnesium, calcium, copper, iron, and zinc) and it contains vitamin C, provitamin A, vitamin E, and vitamin B (X. Chen, Fedrizzi, Kilmartin, & Quek, 2021a; Diep et al., 2022; Nowak et al., 2023). Additionally, tamarillo contains organic acids, mainly citric acid and a lower amount of malic acid, which, along with soluble sugars (glucose, fructose and sucrose) contribute greatly to the characteristic flavour of the fruit (Nowak et al., 2023; S. Wang & Zhu, 2020). The pulp is particularly rich in antioxidant substances, including phenolic compounds, ascorbic acid, and carotenoids (Orqueda et al., 2021). The phenolic compounds present in tamarillo include derivatives of rosmarinic acid, 3-O-caffeoylquinic acid (chlorogenic acid), and hydroxycinnamic acids. The presence of anthocyanins, carotenoids, and chlorophylls collectively determines the colour of tamarillo fruits (Correa Uriburu et al., 2023; Yahia, 2011; S. Wang & Zhu, 2020). In addition to its antioxidant properties, tamarillo is rich in pectin and contains a specific lectin in the cell walls of the fruit tissues and the seed coat (Bakshi et al., 2016). The primary volatile compounds contributing to the fruit's aroma have been identified as *trans*-3-hexenal, *cis*-3-hexenol, methyl hexanoate, 3-hydroxybutanoates and 3-hydroxyhexanoates which impart fruity notes, along with eugenol and 4-allyl-2,6-dimethoxyphenol, responsible for spicy notes (Bakshi et al., 2016). The tamarillo fruit can be consumed both raw and cooked, it can be used as a vegetable, and it is also frequently incorporated into sweet preparations (Diep et al., 2022). Fresh tamarillo fruit is the most popular form (Orqueda et al., 2021), but it is exceptionally well-suited for processing after removing the peel and seeds, which can impart a bitter taste. This versatile fruit can be used in a wide range of products, including jams, pulps, purees, chutneys, juices and alcoholic beverages, like wines and liqueurs. Additionally, there is significant potential for combining tamarillo with dairy products such as yogurt (Diep et al., 2022; S. Wang & Zhu, 2020; Yahia, 2011). In South America, this fruit is processed into juice or wine. Generally, fruits harvested for juice production must reach a certain ripeness level to ensure efficient extraction. As the fruit ripens, its texture and acidity typically decrease, while juice yield and total soluble solids may decline (Mwithiga et al., 2007). Fruit juice often experiences clouding, to prevent colloidal particle precipitation during storage, stabilizing agents are added: CMC (carboxymethylcellulose) is an effective stabilizer for maintaining fruit juice quality over time (Zaidar & Hidayanti, 2023). Additionally, there is significant interest in developing functional ingredients from tamarillo. For example, tamarillin, a unique serine protease found in tamarillo fruit extracts, can be used as a natural coagulant similar to rennet, of interest for vegetarian and vegan production. Moreover, hydrocolloids extracted from tamarillo pulp demonstrate significant oil and water binding capacities, suggesting their potential applications as food emulsifiers (Diep et al., 2022). Furthermore, phenolic compounds from tamarillo seeds, peel, and fruit pulp exhibit notable antioxidant activity and can inhibit key enzymes involved in carbohydrate and lipid metabolism, such as α-glucosidase, α-amylase, and lipase. Inhibiting these enzymes could contribute to managing diabetes and obesity. This evidence suggests the potential of tamarillo fruits as functional ingredient for foods or supplements (Orqueda et al., 2021).

Descriptive sensory methods are useful tools applied to describe the sensory characteristics perceived in a food product and to quantify sensory differences between products (UNI EN ISO 13299 2016). Among them, Flash Profile (FP) is a method that allows description of the sensory properties of a product more quickly (Sinesio, Monteleone, & Spinelli, 2012) as it is based on the fact that it is easier and more natural to compare products, rather than evaluate them on an absolute scale (Valentin et al., 2012). FP combines the generation of individual vocabularies by each judge and, for each single attribute generated, evaluates, by ordering, the entire set of products presented simultaneously. The FP method is designed to quickly and reliably establish a sensory profile for a set of products based on their key sensory differences. It utilizes individual vocabularies and comparative evaluations to reduce the time required for analysis (Delarue, 2014). FP has been successfully applied for the description of different beverages, such as Yacon juice (Marques et al., 2024), passion fruit juice (Fonseca et al., 2022), goji berry juice (Liu et al., 2022) as well as foods, such as jam (Dairou & Sieffermann, 2002), tortillas (Rodríguez-Noriega et al., 2021), pepper (Wang et al., 2022), sweet pumpkin porridge (Kim et al., 2023), cream cheese and their plant-based analogues (Silva et al., 2024).

Given the numerous variables involved in defining the sensory profile of a food product, a combined instrumental and sensory approach can effectively highlight differences between the studied samples. This integrated approach allows for a more comprehensive assessment of a food product characteristics, as well as its distinctiveness. Thus, a combined instrumental and sensory approach could contribute to a more thorough evaluation of the characteristics of a food product, as well as its typicality (Valli et al., 2022). Similarly, Bendini et al. (2017) investigated the volatile and sensory profiles of Italian and Spanish commercial tomato sauces for pasta dressing by applying FP and solid-phase microextraction-gas chromatography-mass spectrometry methods. The authors found interesting agreement among sensory and instrumental data, highlighting the presence of volatile compounds linked with specific sensory notes.

Therefore, the aim of this work was to characterize using a combined approach, through sensory analysis, volatile compounds and the chromatic profile, of two tamarillo drinks produced in Kenya, one of them enriched with a plant extract (mulberry leaf extract) and two Italian fruit drinks, and their blends in a 1:1 (v/v) ratio, to operate a comparison. To the best of the authors' knowledge, studies on tamarillo juice in the existing literature remain limited. The study presented herein provides a comprehensive assessment of the aromatic profile of tamarillo juice, as data were obtained through both instrumental and sensory evaluations and they were elaborated to identify potential relationships between them. This approach not only allowed the identification of specific sensory descriptors for tamarillo juices but also enabled the evaluation of the key volatile compounds responsible for the aromatic profile and related specific attributes. Thus, this study offers valuable insights into the specific characteristics of tamarillo fruit drink, laying a foundation for refining their formulation and increasing their appeal in the marketplace. This research is particularly relevant in dietary contexts that demand reduced sugar content and targeted nutritional fortification, making tamarillo fruit drink a promising candidate for health-conscious and specialized diets. Ultimately, these findings support the development of tamarillo fruit drink as an innovative product with strong commercial potential in a competitive and health-oriented market.

2. Materials and methods

2.1. Samples

The analysis was conducted on two tamarillo drinks formulated without added sugars and pasteurized: specifically, a 100 % tamarillo drink and a blend of tamarillo drink and mulberry leaf extract. Their labels are shown in Figs. S1 and S2, respectively. Researchers from the University of Nairobi formulated the products in the context of the European project H2020-FoodLAND (https://foodland-africa.eu/project/).

The 100 % tamarillo drink formulation contained tree tomato pulp, lemon juice and preservatives (E202 & E203) while the tamarillo drink and mulberry leaf extract blend had tree tomato pulp, mulberry leaf extract, lemon juice, stabilizers and preservatives (E202 & E203).

Considering the limited familiarity of the Italian population with this type of product, it was decided to evaluate, in addition to the two samples of tamarillo drinks, also two samples of fruit drinks purchased from the Italian market: a blood orange drink (100 %) and a red fruit drink without added sugars. For this experimental study, six blends were formulated, each combining four types of drink in a 1:1 (v/v) ratio and these were also analyzed. The composition of the six blends, depicted in Fig. S3, is as follows: a 1:1 ratio of tamarillo drink (TJ) and tamarillo drink enriched with mulberry leaf extract (BTJ), a 1:1 ratio of tamarillo drink (TJ) and blood orange drink (OJ), a 1:1 ratio of tamarillo drink (TJ) and red fruit drink (RFJ), a 1:1 ratio of tamarillo drink enriched with mulberry leaf extract (BTJ) and red fruit drink (RFJ), a 1:1 ratio of tamarillo drink enriched with mulberry leaf extract (BTJ) and blood orange drink (OJ), a 1:1 ratio of red fruit drink (RFJ) and blood orange drink (OJ). Prior to analysis, the samples were stored at refrigeration temperature (4 °C).

2.2. Rapid descriptive sensory analysis: Flash Profile

To determine the sensory profile of fruit drink samples and their blends, a rapid descriptive sensory test was done, using the Flash Profile method.

2.2.1. Ethical authorization

The study was authorized by the Bioethics Committee of the Alma Mater Studiorum, University of Bologna which, with exclusive reference to bioethical profiles, expressed a unanimous favourable opinion regarding the research project "Evaluation of the sensory profile of tamarillo fruit drink" (Prot. n. 0101255 del April 09, 2024).

2.2.2. Assessors

The Flash Profile test engaged ten subjects, six females and four males aged between 18 and 60 years who prior experience in the sensory description analysis of different food products. All were recruited from among employees of the Campus of Food Science of the University of Bologna.

2.2.3. Method

The fruit drinks and their mixtures, previously shaken, were presented simultaneously to the judges in white disposable plastic cups, in quantities of approximately 15 mL at a temperature of around 4 °C. The samples were identified by a three-digit code. The evaluation was conducted at room temperature, inside the tasting booths of the sensory room.

The judges participated in a total of three tasting sessions. During the first session, all the samples were evaluated for each sensory modality (appearance, aroma, flavour and texture) by the assessors. Each assessor created their own list of sensory attributes perceived, based on what they considered relevant for discriminating between the samples, while avoiding the use of hedonic terms. At the end of the session, a brief collective discussion on the sensory characteristics perceived and the lexicon used to describe them was conducted. Each assessor had the possibility of modifying their list, even adding or eliminating one or more descriptors. During the second and third tasting sessions, the assessors ordered the samples according to the increasing intensities of their selected sensory attributes (Pagliarini, 2021; Sinesio et al., 2012). The second and third tasting sessions were two replications of the same phase of the test, in order to verify that the tasters produced replicable data. The data processing considered the average of the resulting data from the second and third tasting sessions.

2.3. Determination of the volatile compound profile by SPME-GC-MS

The analysis of the volatile fraction of fruit drink samples and their blends was conducted using a SPME fiber (DVB/CAR/PDMS) (50/30 μm film thickness) and a GC model 2010 (Shimadzu, Milan, Italy) equipped with an autosampler HT2850T (HTA, Brescia, Italy).

An aliquot of 2 mL of each sample was placed into a 20 mL vial, closed with a silicone septum. Then, the sample was conditioned at 40 °C for 15 min, with shaking; the fiber was exposed at the same temperature for 60 min. The desorption of the volatile fraction was performed at 250 °C for 15 min, and the method included the following temperature program: 40 °C for 10 min, 3 °C/min up to 200 °C, 20 °C/min up to 250 °C, using an Rtx®-Wax capillary column (30 m x 0.25 mmID x 0.25 μm df). The carrier gas used was helium with a flow rate of 1 mL/min.

Peak identification was based on the comparison of mass spectrum data with spectra present in the NIST17.1 library and only identifications that matched by more than 90 % were taken into account.

Due to the difficulty in solubilizing a standard molecule in a thick semi-liquid sample, a semi-quantitative evaluation was applied and expressed as the area of each peak. Three replicates for each sample were performed.

2.4. Image analysis

Image analysis of the fruit drink samples and their mixtures was carried out using an "electronic eye" (Visual Analyzer VA400 IRIS, Alpha MOS, Toulouse, France), or a high-resolution (2592 × 1944 p) charge-coupled camera equipped with a specific data processing system (Alphasoft, version 14.0, Alpha MOS, Toulouse, France) and a photo camera (16 million colors). The instrument is furnished with two lights (2 × 2 fluorescent tubes) with a color temperature of 6700 K. An aliquot of 20 mL of each sample was inserted into a Petri dish, placed on a white plastic tray, diffusing a uniform light inside the device's closable light chamber, and the CCD camera took the picture. Both image analyses (RGB scale or CIE L*a*b*) and statistical analyses were carried out. The data processing software (Alphasoft, version 14.0, Alpha MOS, Toulouse, France) extracts color parameters from the picture.

Samples were analyzed in triplicate.

2.5. Statistical analysis

XLSTAT (version 2023.3.0 (1415), 2024, Lumivero, Denver, CO, USA) was used to elaborate the sensory and instrumental results by analysis of variance and multivariate approaches such as Generalized Procrustes Analysis (GPA) and Multiple Factor Analysis (MFA), in order to investigate the relationships between volatile compounds and aroma sensory attributes as well as the relationships between color index and appearance sensory attributes.

3. Results and discussion

3.1. The sensory profile

A rapid descriptive sensory test was conducted, applying the Flash Profile (FP) method (Delarue & Sieffermann, 2004), to determine the sensory profile of fruit drink samples and their blends. FP was originally developed as a versatile method designed to quickly assess the relative sensory positioning of a set of products. To optimize efficiency, the stages of familiarization with the product space, attribute generation, and rating were combined into a single step (Delarue & Sieffermann, 2004). During the first session, the judges were asked to individually generate attributes that would be sufficiently distinct to allow for ranking the samples. The number of descriptors resulting from the first FP session was 23. In fact, since each judge used their own list of attributes, not all subjects assessed the full set of descriptors in second and third sessions, as the vocabulary is individual. This approach removed the time-consuming requirements of reaching consensus and aligning concepts, thereby reducing the need for a trained panel (Delarue & Sieffermann, 2004). The 23 descriptors elicitated by the assessors are presented, highlighted in red, in Fig. 1.

In the second and third tasting sessions, a score was assigned to each attribute, calculated based on ranks derived from ordering the samples according to the perceived intensity of each descriptor. The mean data resulting from the second and third tasting sessions, which constitute two replicates of the same phase of the test, were elaborated using Generalized Procrustes Analysis (GPA). This analysis employs the Commandeur algorithm to achieve a consensus configuration among the

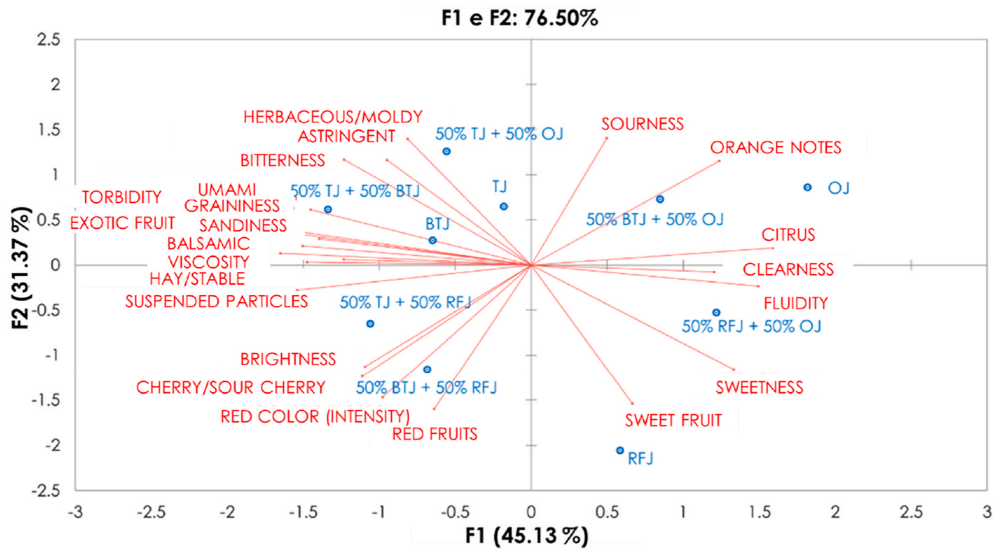

Fig. 1. Sensory attributes identified in the samples, processed using Generalized Procrustes Analysis (GPA).

product descriptions provided by different judges. This analysis allows for the identification of common patterns among the samples and their sensory characteristics.

The results of the GPA analysis are presented in Fig. 1 that has on a two-dimensional plane the samples (the fruit juices and their blends), in blue, and the variables (the sensory attributes), in red. The axes of the graph represent the first two principal components, which explain the majority of the variance in the data (76.50 %).

The samples are positioned in space based on the similarity of their sensory characteristics. Thus, in relation to the position of the variables, the samples are either correlated or not with these variables and among themselves. When the samples are located close to each other on the graph, it indicates that their sensory profiles are similar concerning the 23 attributes considered, and vice versa. For example, samples such as RFJ and OJ are distantly placed, indicating they possess significantly different sensory characteristics.

Moreover, a potential correlation between the variables themselves can also be evaluated. The attributes “turbidity” and " clearness " are positioned at opposite ends of the graph, as are “viscosity” and “fluidity,” confirming an inverse relationship between them. In contrast, the attributes “acidity,” “orange,” and “citrus” are located in the same region of the graph, indicating that they tend to be perceived simultaneously.

Specifically, the direction of the vectors (related to the variables) indicates the correlation of each sensory attribute with the different samples; the longer the vector, the greater the influence of that attribute in differentiating between the samples. For example, the attribute “citrus” is positively correlated with the sample OJ, while the attribute “sweet fruit” is positively correlated with the sample RFJ.

Juice blends, in some cases, such as 50 % RFJ +50 % OJ, are positioned between the pure samples, RFJ and OJ, indicating that their sensory characteristics are given by the combination of those of the two juices they are composed of. In contrast, for the sample 50 % TJ + 50 % BTJ, the sensory characteristics tend to be more similar to the BTJ sample, which shows these two samples are predominantly influenced by the same vectors, namely those related to the descriptors “umami,” “turbidity,” and “graininess."

The results from the sensory evaluation using Flash Profile, however, revealed a similar profile for the two tamarillo fruit drinks (TJ and BTJ), as well as for their blend (50 % TJ + 50 % BTJ), since they are located in the same quadrant of the graph. As reported in Fig. 1, the TJ sample was primarily characterized by the attributes: astringent, bitter, herbaceous notes, and musty notes, while the BTJ sample was primarily characterized by the attributes: graininess, sandiness, turbidity, umami, exotic fruit aroma, balsamic notes, viscosity, and bitterness.

These results are in agreement with García et al. (2016), who reported some typical sensory attributes of tamarillo fruit, such as herbaceous hints, attributed to the presence of C6 aliphatic compounds, and mint, linked to the presence of terpene compounds. Additionally, it was highlighted that the two distinct flavours typically recognizable in tamarillo fruit are bitterness and umami. As shown by the obtained results, both flavours were characteristic of the two tamarillo fruit drinks (García et al., 2016).

Other authors found different sensory notes in three different tamarillo fruit drinks. In particular, tomato, sweet, herbaceous/woody, green/grassy and fruity notes for a sample of red tamarillo fruit drink from cultivar Laird’s Large. While for a sample of fruit drinks from the Mulligan tamarillo (deep purple red tamarillo) the peculiar notes found were those of green/herbaceous and smoky. Finally, amber tamarillo fruit drinks (yellow tamarillo) were characterized by sweet taste and floral and fruity notes (X. Chen, Kilmartin, Fedrizzi & Quek, 2021b). Some of these attributes were also found in the two fruit drinks evaluated in the present study, in particular herbaceous and fruity notes.

3.2. The volatile profile

To determine the aromatic profile of fruit juice samples and their blends, the analysis of the volatile fraction was performed, using SPME-GC-MS, to identify the volatile molecules. The focus was on compounds associated, according to the literature, with positive olfactory sensory attributes and those considered off-flavours. The results relating to the aromatic profile, for each of the 10 samples, are reported in Fig. 2.

The aromatic profile of the OJ sample revealed the presence of volatile compounds typically found in orange juice, such as α-pinene, octanal and limonene (Ki, Jang & Lee, 2018). The volatile compound profile of the RFJ sample also indicates the presence of compounds characteristic of red fruit juice, such as linalool (Perestrelo et al., 2019). In general, the aromatic profile of fruit juice blends reflected the aromatic profile of pure fruit juices, for example, linalool present in both the OJ and RFJ samples, is also detected in the 50 % OJ + 50 % FRJ sample.

Table 1 summarizes the volatile compounds that were identified in the tamarillo fruit drink (TJ) and the tamarillo fruit drink supplemented with mulberry leaf extract (BTJ); in particular, the volatile profile of these samples highlighted the presence of many terpene compounds, which are related to some olfactory characteristics. As also indicated by

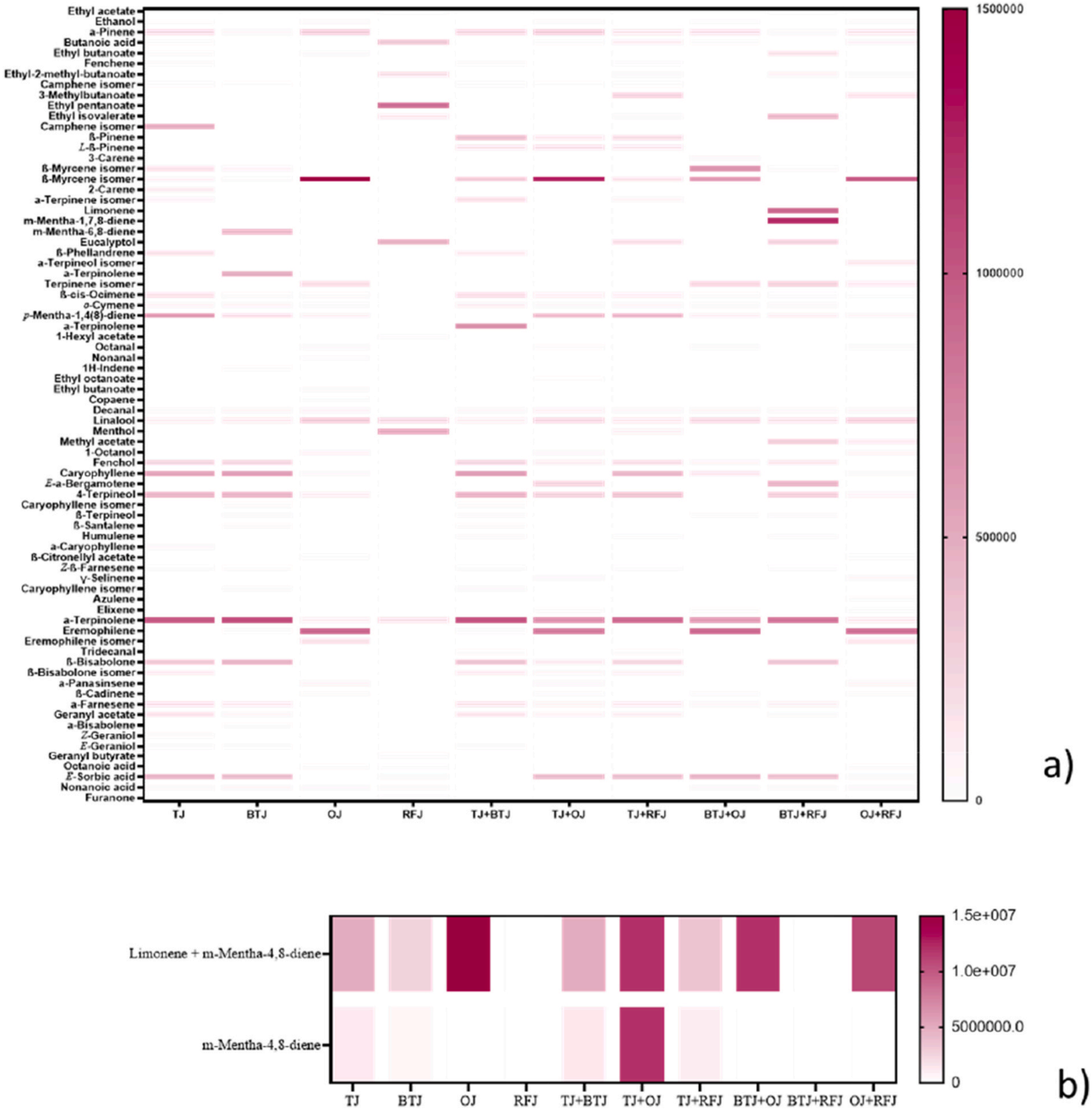

Fig. 2. Heat map comparing the content of the volatile compounds in the ten samples of fruit juice. Figure "a" shows all the volatile compounds except two that presented a high peak area. Figure "b" shows the volatile compounds with the higher peak area.

previous studies (X. Chen, Fedrizzi, Kilmartin & Quek, 2021c; X. Chen, Kilmartin, Fedrizzi & Quek, 2021b; X. Chen, Quek, Fedrizzi & Kilmartin, 2020), limonene, linalool and terpinenol, isomers of *p*-menthadiene are among the main ones. A literature search (X. Chen, Fedrizzi, Kilmartin, & Quek, 2021a; Chen, Kilmartin, Fedrizzi& Quek, 2021b; Flavornet and human) was conducted to identify some olfactory notes associated with each compound identified by gas chromatographic analysis in the samples of tamarillo fruit drink (TJ) and tamarillo fruit drink supplemented with mulberry leaf extract (BTJ); the results of this search are also reported in Table 1.

3.3. Image analysis results

To obtain an objective measurement of the color attributes of fruit juice samples and their blends, a determination of the colorimetric composition was carried out using an electronic eye IRIS (or IRIS image analyzer).

Through image analysis, color parameters were extracted from the acquired image, i.e., color codes were derived from the color spectra detected by the instrument, along with their respective percentage presence (>1 %) for each sample. A selection of the most discriminant variables was performed to improve the separation between the samples and the detected color codes, which are reported in Table 2. The table also shows the corresponding conversion to the CIE L*a*b* color scale and the RGB color scale. The samples were characterized by lightness values (L*) ranging from 38.487 to 60.917, redness index (a* > 0) ranging from 15.400 to 40.335, and yellowness index (b* > 0) ranging from 11.415 to 48.790.

To assess the ability to discriminate between different juice samples, the data collected using the electronic eye were processed using Principal Component Analysis (PCA), as shown in Fig. 3. The different directions and positions of the vectors indicate which variables (colors) contribute to the appearance of the different samples.

Three main clusters of samples can be identified: a cluster located in

Table 1
Volatile compounds in the pure tamarillo fruit drink sample (TJ) and in the tamarillo fruit drink sample fortified with mulberry leaf extract (BTJ) identified and semi-quantified by SPME-GC-MS. Results are expressed as peak area x 10^3. The olfactory notes associated, according to specific references, with each identified compound indicated; nd = not detected.

Compound	Retention Time	TJ (Area x 10^3)	BTJ (Area x 10^3)	Olfactory note (Chen et al., 2021a; Chen et al., 2021b; Flavornet.org)
Ethanol	2.82	10755 ± 6.04	nd	Sweet
α-Pinene	4.30	207584 ± 14.64	46691 ± 11.26	Pine, turpentine
Butanoic acid	4.75	11067 ± 1.02	nd	Rancid, cheese, sudor
Canfene	5.13	10720 ± 13.69	5243 ± 5.55	Camphor
Camphene (isomer 1)	5.32	26565 ± 13.69	11722 ± 10.71	
Camphene (isomer 2)	6.69	482886 ± 8.41	nd	
β-Myrcene (isomer 1)	10.66	172682 ± 19.58	76571 ± 13.35	Balsamic, must, spices
β-Myrcene (isomer 2)	10.86	96120 ± 6.76	34219 ± 6.24	
Carene	11.03	105932 ± 12.41	nd	Orange peel, limon, resina
Carene (isomer 1)	11.24	78277 ± 6.48	nd	
Limonene + m-Mentha-4,8-diene	12.69	4945278 ± 6.12	2550646 ± 0.14	Limon, orange + fresh
β-Phellandrene	12.89	165455 ± 11.87	nd	Mint, turpentine
m-Mentha-4,8-diene	15.42	1243885 ± 7.20	510470 ± 22.99	Fresh
β-cis-Ocimene	16.19	177903 ± 10.42	36477 ± 16.81	Citrus, herb, flower
o-Cymene	16.63	59882 ± 8.06	57835 ± 0.54	Herb
p-Mentha-1,4 (8)-diene	17.43	627870 ± 7.23	201810 ± 13.99	Fresh, phenolic, woody
Decanal	28.32	32410 ± 6.22	69600 ± 0.10	Soap, orange peel, animal fat
Linalool	30.77	102180 ± 2.97	121107 ± 4.11	Floral, lavender
Fenchol	31.77	236588 ± 2.37	230274 ± 4.89	–
α-Bergamotene	31.92	542421 ± 9.92	578128 ± 0.80	Wood, warm, tea
4-Terpineol	32.40	447624 ± 0.28	445246 ± 4.40	Floral, woody-citrus, sweet
β-Terpineol	33.75	nd	24553 ± 3.39	Mold
α-Caryophyllene	34.71	36160 ± 10.75	39980 ± 0.75	Woody
p-Mentha-1-en-8-ol	36.25	1004711 ± 0.62	1064988 ± 1.85	–
β-Bisabolene	37.46	307505 ± 17.68	441772 ± 2.08	Balsamic
β-Bisabolene (isomer 1)	37.55	131366 ± 11.32	nd	
α-Farnesene	38.54	175053 ± 19.29	126895 ± 1.15	Wood, citrus, sweet
Geranyl acetate	38.71	155899 ± 9.57	50363 ± 5.32	Rose
E-Sorbic acid	50.96	445696 ± 32.80	394136 ± 19.71	Sour
Nonanoic acid	52.10	26115 ± 6.62	49299 ± 1.06	Green, fatty

Table 2
Translation of color codes (presence >1 % in the analyzed samples) in CIE L*a*b* color scale and RGB color scale.

Color codes	L*	a*	b*	R	G	B
2115	38.487	26.666	22.278	136	72	56
2116	38.754	27.779	12.824	136	72	72
2132	42.562	18.983	17.872	136	88	72
2370	40.833	32.572	34.965	152	72	40
2371	41.012	33.266	26.042	152	72	56
2372	41.256	34.206	16.681	152	72	72
2389	45.045	27.046	12.035	152	88	88
2404	48.640	17.109	26.114	152	104	72
2405	48.886	18.346	17.206	152	104	88
2626	43.488	38.941	38.675	168	72	40
2627	43.651	39.532	29.929	168	72	56
2628	43.874	40.335	20.680	168	72	72
2641	46.663	30.555	48.790	168	88	24
2642	46.760	30.962	41.889	168	88	40
2643	46.906	31.573	33.657	168	88	56
2644	47.107	32.402	24.771	168	88	72
2659	50.542	23.144	37.701	168	104	56
2660	50.722	23.987	29.226	168	104	72
2661	50.953	25.064	20.382	168	104	88
2662	51.239	26.376	11.415	168	104	104
2676	54.627	15.400	33.904	168	120	72
2677	54.833	16.479	25.386	168	120	88
2678	55.089	17.797	16.653	168	120	104
2899	49.375	37.995	37.214	184	88	56
2900	49.561	38.713	28.447	184	88	72
2932	56.607	22.274	36.810	184	120	72
2950	60.917	15.939	24.752	184	136	104
3187	58.561	28.308	47.696	200	120	56

the right region of the graph, in the second quadrant, consisting of the samples 50 % OJ + 50 % FRJ, 50 % FRJ +50 % BTJ, and the pure sample FRJ; a cluster located in the central region of the graph, in the first quadrant, consisting of the pure sample OJ and the mixture 50 % BTJ + OJ; and the last cluster located in the left region of the graph, in the third and fourth quadrants, consisting of the samples 50 % FRJ +50 % TJ, TJ, 50 % TJ + 50 % BTJ, 50 % OJ + 50 % TJ, and BTJ.

Fig. 3 shows that the first cluster, characterized by brown hues, consisted of samples with a common presence of "red fruit juice" in their composition. The second cluster, characterized by orange hues, consisted of samples with a common presence of "orange juice" in their composition. Finally, the third cluster, characterized by red hues, consisted of samples with a common presence of "tamarillo fruit drink" or "tamarillo fruit drink and mulberry leaf extract ".

3.4. Combined analysis of sensory and instrumental data

Multiple Factor Analysis (MFA) was applied to conduct a joint analysis of sensory and instrumental data, with the aim of highlighting potential relationships between: *i)* specific volatile compounds identified through gas chromatography and aroma attributes identified through sensory analysis (Flash Profile); *ii)* color spectra identified through image analysis (electronic eye) and visual attributes identified through sensory analysis (Flash Profile).

3.4.1. Combined analysis of sensory and instrumental gas chromatographic data

The data obtained from sensory measurements, in terms of ranking of olfactory notes, were jointly processed with the data obtained from gas chromatography measurements (volatile compound profile) (Tura et al., 2025). The result of this processing, carried out using Multiple Factor Analysis (MFA), is shown in Fig. 4, where olfactory notes are shown in red and volatile compounds are shown in green. The axes in the graph represent the first two principal components, which explain most of the data variance (65.56 %).

Through joint analysis, positive correlations were found between

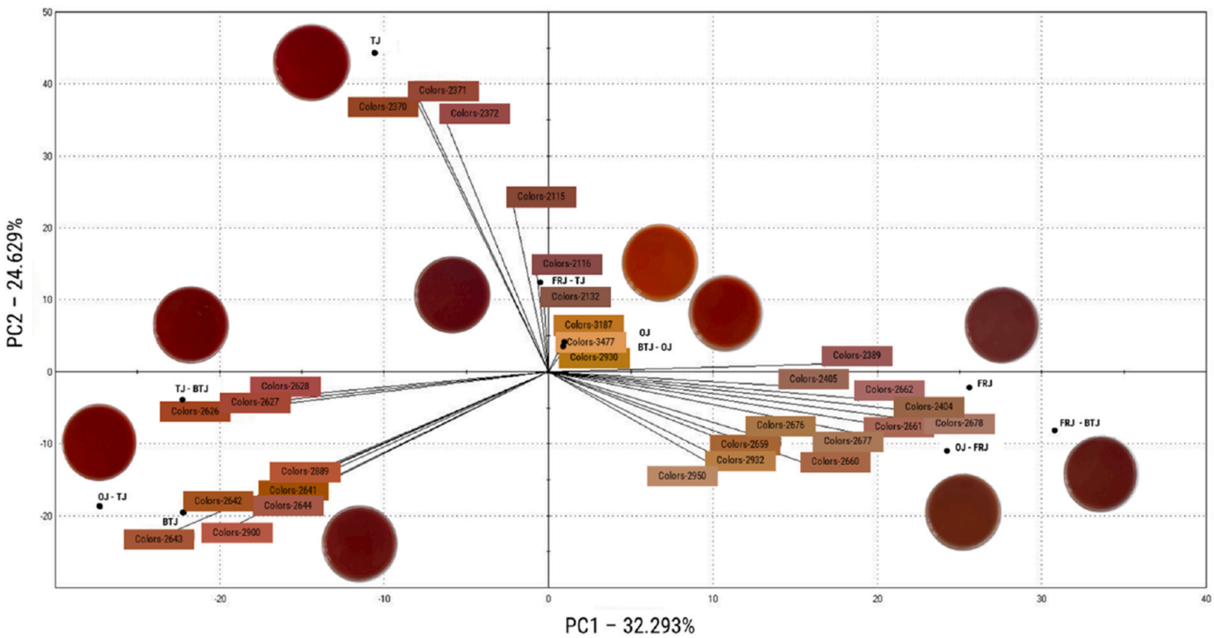

Fig. 3. Color spectra detected by the electronic eye identified in the samples, processed by Principal Component Analysis (PCA).

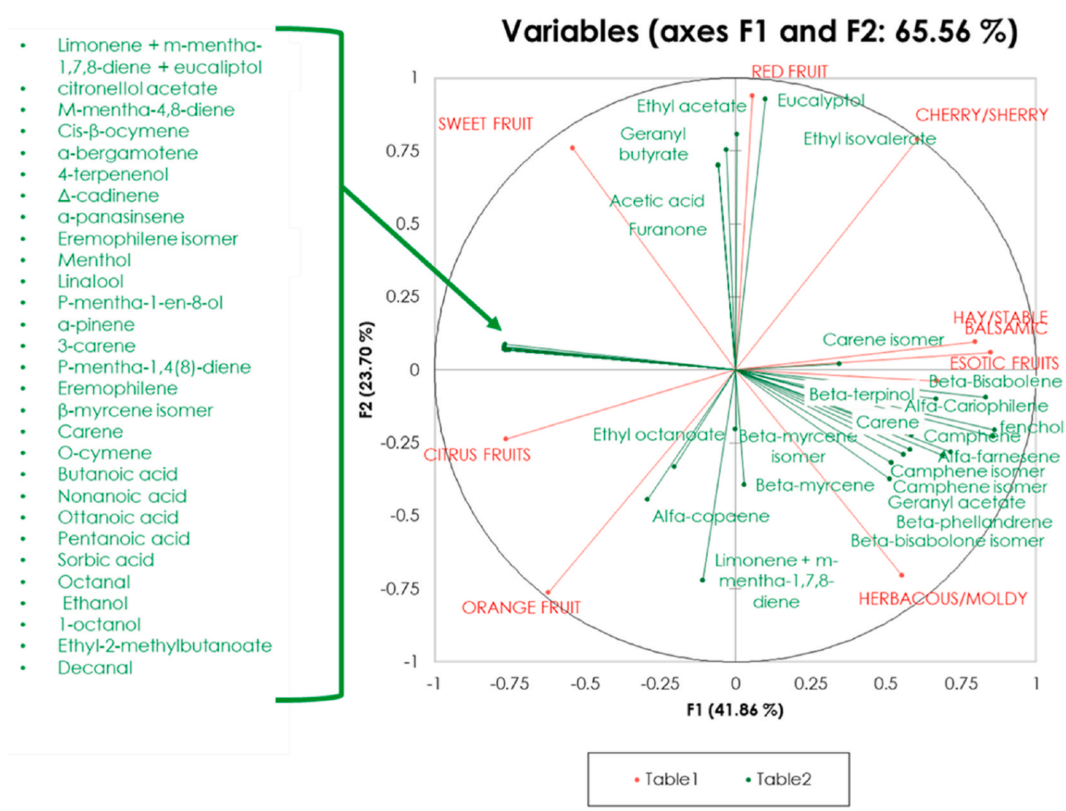

Fig. 4. Correlation map of sensory variables (olfactory notes) and instrumental variables (volatile compounds); the joint analysis of sensory and instrumental data was performed using MFA (Multiple Factor Analysis).

some volatile molecules and some sensory olfactory notes perceived (Flash Profile). The graph highlights a positive correlation between ethyl acetate, generally associated with fruity notes, and the olfactory notes "sweet fruit" and "red fruits" (Xiao et al., 2021). The olfactory note "red fruits" is also positively correlated with the acetyl butyrate, furanone, and acetic acid compounds; the first two molecules are generally also associated with fruity notes (Li et al., 2021), while acetic acid is generally associated with pungent notes similar to vinegar (Cliff & Pickering, 2006). The ethyl octanoate is generally associated with fruity notes (Lillo et al., 2005) and finds a positive correlation with the olfactory note "citrus". A positive correlation is also found between the olfactory note "orange" and limonene, generally associated with citrus, lemon, and orange notes (Pérez-López & Carbonell-Barrachina, 2006; Flavornet.org).

The sensory olfactory notes characterizing the tamarillo fruit drink sample (TJ) were herbaceous and moldy, while those characterizing the tamarillo fruit drink sample supplemented with mulberry leaf extract (BTJ) were exotic fruit, balsamic, hay/stable. The olfactory note "herbaceous/moldy" was found to be positively correlated with the following volatile molecules: camphene (isomer 2), β-bisabolene (isomer 1), and β-fellandrene, which could contribute to the sensory perception of this olfactory note. Specifically, camphene is generally associated with camphor notes (Xiao et al., 2016), β-bisabolene is generally associated with balsamic notes (Durak et al., 2023), β-phellandrene is generally associated with mint and turpentine notes (El-Zaeddi et al., 2016), and β-myrcene is generally associated with balsamic, musty, and spicy notes (Chen et al., 2022).

The olfactory notes "exotic fruit", "balsamic", and "hay/stable" are found in the same area of the graph and are positively correlated with the following volatile molecules: β-bisabolene, α-caryophyllene, and fenchone, which could contribute to the sensory perception of these olfactory notes. Specifically, β-bisabolene is generally associated with balsamic notes, α-caryophyllene is generally associated with woody notes, and carene is generally associated with orange peel, lemon, and resin notes.

3.5. Combined analysis of sensory and instrumental image data

The data obtained from visual sensory measurements (ranking the visual attributes) were jointly processed with the data obtained from measurements made with the electronic eye IRIS (color profile in terms of CIE L*a*b* data). The result of this processing, carried out using Multiple Factor Analysis (MFA), is shown in Fig. 5, where visual attributes are shown in green and color codes are shown in red. The axes in the graph represent the first two principal components, which explain most of the data variance (54.48 %).

Through joint analysis, some positive correlations were found between the identified chromatic characteristics obtained through image analysis and the visual attributes identified through sensory analysis. In particular, the graph shows a positive correlation between the visual attribute "clarity" and color indices 2677 (L = 54.883, a = 16.579, b = 25.386), 2950 (L = 60.917, a = 15.939, b = 24.752), then between the visual attribute "turbidity" and color indices 2370 (L = 40.833, a = 32.572, b = 34.965), 2116 (L = 38.754, a = 27.779, b = 12.824) and 2132 (L = 42.562, a = 18.983, b = 17.872), and finally between the visual attribute "suspended particles" and color indices 2116 and 2132, which it shares with the attribute "turbidity". Furthermore, the visual attributes "color" and "brightness" are located close together on the graph, and are both characterized by color index 2389, characterized by a redness index a = 27.046, in agreement with the first attribute, and a lightness index L = 45.045 in agreement with the second attribute. In fact, the sensory attributes identified through sensory analysis, shown in Fig. 5, are in agreement with the CIE Lab chromatic coordinates of the color indices with which they have a positive correlation.

Multiple Factor Analysis of the data resulted in a plot where samples are positioned on a two-dimensional plane based on both instrumental and sensory variables. Three main clusters of samples can be identified on this plot: a cluster located in the lower right region of the graph, in the fourth quadrant, consisting of samples BTJ, TJ, 50 % TJ + 50 % OJ, 50 % TJ + 50 % BTJ, and 50 % TJ + 50 % RFJ; a cluster located in the central, upper region of the graph, in the first and second quadrants, consisting of the pure sample RFJ and the mixture 50 % BTJ + RFJ; and the last cluster located in the lower left region of the graph, in the third quadrant, consisting of the samples OJ, 50 % OJ + 50 % RFJ, and 50 % BTJ +50 % OJ.

The samples in the first cluster shared the presence of tamarillo fruit drink or tamarillo fruit drink and mulberry leaf extract, in the same quadrant as the visual attributes ("turbidity" and "suspended particles") and color indices characterized by lower lightness (L*) values. The samples in the second cluster shared the presence of red fruit juice, in particular the sample 50 % BTJ+ 50 % FRJ is located in the first quadrant together with the visual attributes as "color" (meaning intensity of red) and "brightness". While the sample RFJ shares the same quadrant as the attribute "clarity" and color codes characterized by higher lightness (L*) values. This data supports the sensory analysis, as the tasters evaluated as clearer a sample positively correlated with color codes characterized by a high degree of lightness (for example, code 2950 is associated with an L* = 60.917). The samples in the third cluster shared the presence of orange juice and none of the sensory visual attributes described by the panel were able to discriminate them; instead, this cluster shares the same quadrant with color codes associated with orange hues.

The sensory visual attributes identified through sensory analysis (Flash Profile) that characterized the tamarillo fruit drink sample (TJ) and the tamarillo fruit drink sample supplemented with mulberry leaf extract (BTJ) were graininess, grittiness, and turbidity; those that characterized the samples 50 % TJ + 50 % RFJ and 50 % BTJ + 50 % RFJ were brightness and red color; finally, those that characterized the

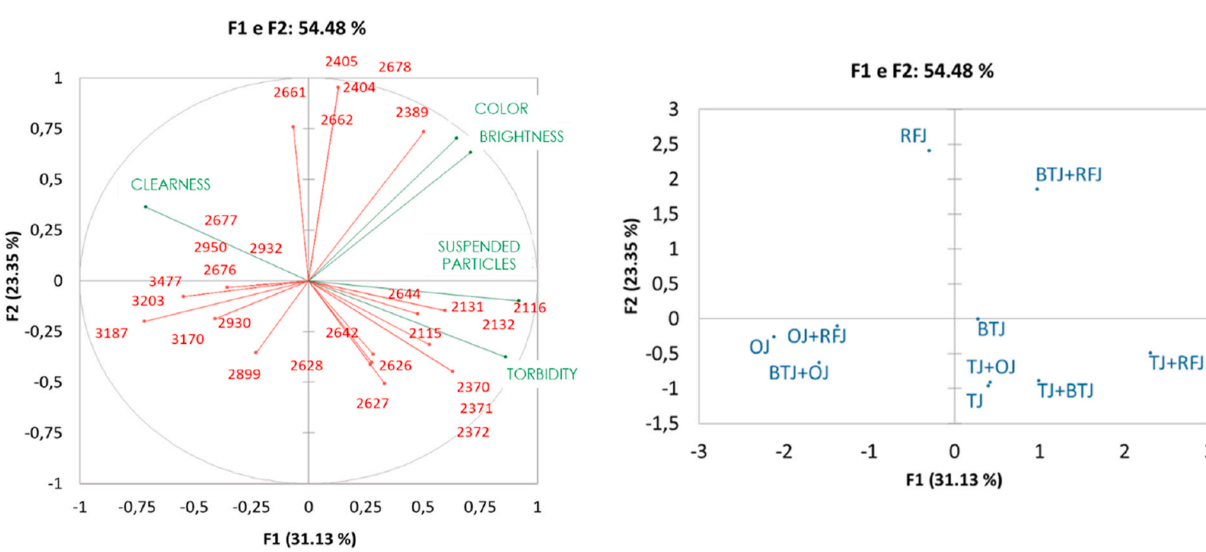

Fig. 5. Correlation map of sensory (visual attributes) and instrumental (color codes) variables on the left and distribution of samples on a two-dimensional plane, based on instrumental variables (color codes) and sensory variables (visual attributes) on the right side; the joint analysis of sensory and instrumental data was performed using MFA (Multiple Factor Analysis).

samples 50 % BTJ and 50 % OJ, OJ, and 50 % RFJ and 50 % OJ were distinguished by the attribute "clarity".

Based on the Principal Component Analysis in Fig. 3., there was a positive correlation between the sample 50 % OJ + 50 % FRJ and the color index 2677, supporting the fact that a sample characterized by higher lightness (L* = 54.883) was described with a higher intensity of the attribute "clarity" by the tasters.

4. Conclusions

The objective of the study was to characterize, the sensory, aromatic, and chromatic profiles of the juice samples, with a particular focus on tamarillo-based samples ("TJ" and "BTJ"), and their 1:1 mixture (50 % "TJ" + 50 % "BTJ"), through descriptive sensory analysis and instrumental investigation. A Flash Profile permitted the identification of 23 sensory descriptors useful to characterize the samples. In particular, the two tamarillo-based fruit drinks (TJ and BTJ), showed similar sensory profiles with TJ being more characterized by astringency, bitterness, herbaceous and musty notes, while BTJ by turbidity, exotic fruit aroma, balsamic notes, umami, and bitterness. Furthermore, the Flash Profile identified some possible defects of the tamarillo-based fruit drink prototypes. In terms of separation of the molecules responsible for the olfactory notes the SPME-GC-MS analysis permitted the identification of 78 compounds and enabled a correlation with sensory olfactory notes. In particular, limonene, linalool, terpineol and the isomers of *p*-menthadiene, found in TJ and BTJ tamarillo-based fruit drinks, can be related with the citrusy perception, while the olfactory note "herbaceous/musty" found in tamarillo fruit drink (TJ), were related with camphene and β-bisabolene molecules that are generally associated with camphor and balsamic notes, respectively. Image analysis, using the electronic eye IRIS, allowed the identification of the chromatic profile of the different drinks, information useful for discrimination, quality control or to assess their visual acceptability. The joint processing of visual and instrumental sensory data, through MFA, allowed an overall characterization of the samples from a visual point of view. Turbidity and suspended particles, as well as low lightness (L*) values were key attributes of tamarillo-based fruit drinks (TJ and BTJ) and, obviously, of some mixtures containing them closely correlated with the visual perceptions of the tasters. The effective integrated approach of combining sensory and instrumental analysis of tamarillo-based fruit drinks allowed their volatile, visual and olfactory characterization to be used as a starting point to ameliorate and optimize their production, from the harvesting of the fruits and their storage, e.g. to avoid the moldy defect, thus enhancing their consumer acceptability, potentiality for fortified or specific dietary formulations and commercial value.

CRediT authorship contribution statement

Matilde Tura: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Patricia Garcia Salas:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation. **Enrico Valli:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Conceptualization. **Wambui Kogi-Makau:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Michael Wandayi Okoth:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Duke Omayio Gekonge:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Dasel Wambua Mulwa Kaindi:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Sophia Ngala:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Erica Bensmail:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Marco Setti:** Writing – review & editing, Project administration, Funding acquisition. **Tullia Gallina Toschi:** Writing – review & editing, Visualization, Supervision, Project administration, Conceptualization.

Research data for this article

The authors have shared the link to the dataset in the references.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2025.117819.

Data availability

The authors will share the link to the dataset in the references as soon as the related doi will be made available.

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