




## Brewing strategy modulates volatile and phenolic extraction, shaping sensory perception in tea and fruit infusions

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### ABSTRACT

This study investigated the impact of brewing strategy on volatile composition, phenolic extraction and sensory perception of tea and fruit infusion beverages. Green tea, dark tea and a fruit infusion were prepared using three extraction methods (Pure Brew, Gaiwan and French Press). Volatile profiles were characterized by HS-SPME-GC-MS, sensory properties were evaluated by descriptive analysis and chemical-sensory relationships were explored using multivariate statistics. Principal component analysis showed that botanical matrix and oxidation degree were the primary drivers of volatile fingerprint differentiation, explaining 85.6% of total variance, while extraction method modulated the relative abundance of specific aroma-active compounds. Pure Brew selectively enhanced terpene- and ester-derived volatiles, resulting in higher perceived sweetness and aromatic clarity, with reduced astringency. In contrast, Gaiwan and French Press promoted higher phenolic and flavonoid extraction, leading to more structured sensory profiles and increased astringency, particularly in dark tea samples. Partial least squares regression ( $R^2X = 0.835$ ;  $R^2Y = 0.735$ ) identified ester- and furan-derived compounds as key drivers of sweetness perception, while aldehydes and phenolic-related compounds were associated with astringency. Overall, brewing strategy emerges as an effective tool to modulate volatile and phenolic extraction, shaping sensory perception in tea and fruit infusions.

### 1. Introduction

Tea (*Camellia sinensis* L.) is one of the most widely consumed beverages worldwide and represents a chemically complex matrix in which sensory quality is primarily driven by the combined contribution of volatile and non-volatile compounds (Chen et al., 2020; Wang et al., 2022). While polyphenols, amino acids, caffeine and sugars largely determine taste attributes such as bitterness, astringency and umami, aroma perception plays a decisive role in defining overall flavor quality and consumer acceptance (Shao et al., 2021). More than 600 volatile compounds have been identified in tea leaves and infusions (Ho et al., 2015; Zhu et al., 2018). The volatile profile of tea is shaped by multiple factors, including cultivar, geographical origin, agronomic practices and, most importantly, post-harvest processing steps such as withering, rolling, oxidation and drying (Lin et al., 2012a, 2012b; Yang et al., 2013). Different degrees of oxidation lead to marked differences among green, oolong and black teas, not only in terms of chemical composition

but also in sensory identity, with floral, grassy, fruity or roasted notes emerging as a function of both precursor availability and enzymatic or thermal transformations (Wang et al., 2019). However, the final aromatic expression perceived in the cup does not solely depend on the composition of dry leaves. Brewing conditions and extraction methods critically modulate the release, transformation and perception of aroma compounds in the aqueous infusion (Zhang et al., 2020; Sánchez-lópez et al., 2020; Sun et al., 2022). Tea extraction is a dynamic process governed by mass transfer phenomena, solubility, volatility and matrix–water interactions. Parameters such as water temperature, leaf-to-water ratio, contact time and extraction technique influence not only extraction yield but also selectivity toward specific chemical classes (Chen et al., 2019). In recent years, increasing attention has been paid to alternative and non-conventional brewing methods, originally developed for coffee preparation, which may promote different extraction kinetics and volatile release patterns compared to traditional infusion techniques (Yu et al., 2021; Lau et al., 2018). Despite this growing

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interest, systematic studies comparing multiple extraction methods under controlled conditions and linking chemical fingerprints to sensory perception in tea remain limited. Most previous investigations on tea aroma have focused either on comprehensive volatile profiling by gas chromatography–mass spectrometry (GC–MS) or on sensory characterization alone, without fully integrating chemical and sensory datasets (Zhu et al., 2015; Shao et al., 2021). However, recent advances in multivariate data analysis have demonstrated that coupling instrumental aroma analysis with descriptive sensory evaluation provides a more mechanistic understanding of flavor perception: enabling the identification of key aroma-active compounds and chemical drivers of specific sensory attributes (Lin et al., 2012a, 2012b; Jiang et al., 2021; Yang et al., 2022). In this context, approaches combining GC–MS, descriptive sensory analysis and multivariate statistics such as principal component analysis (PCA) and partial least squares regression (PLS) are increasingly recognized as powerful tools in food flavor research. Therefore, the aim of this study was to investigate the impact of different tea extraction methods on the volatile profile and sensory attributes of selected teas and a fruit infusion. Volatile compounds were characterized by HS-SPME–GC–MS, while sensory properties were evaluated through descriptive analysis. An integrated multivariate approach was applied to explore the relationships between chemical composition and sensory perception. This work seeks to contribute to a deeper understanding of how extraction strategies modulate tea flavor, providing useful insights for both scientific research and practical applications in tea preparation and product development.

## 2. Materials & methods

### 2.1. Chemicals and reagents

All reagents and solvents were of analytical grade. HPLC-grade methanol and formic acid ( $\geq 99\%$ ) were obtained from Sigma-Aldrich (St. Louis, MO, USA). Ultrapure water ( $>18\text{ M}\Omega\text{-cm}$ ) was produced using a Milli-Q purification system (Millipore, Bedford, MA, USA). Prior to analysis, all solvents were filtered through  $0.2\ \mu\text{m}$  membrane filters.

### 2.2. Tea samples and experimental design

Two types of tea and one fruit infusion were used in this study: green tea (*Camellia sinensis* var. *sinensis*), dark tea (*Camellia sinensis* var. *assamica*) and fruit infusion (*Hibiscus sabdariffa* L. with mixed berries) were selected for sample preparation (Figure S1 and Figure S2). To achieve a variety of results, teas with different levels of oxidation were chosen: one green and one dark. The green specialty selected was the Spring Harvest Xi Hu Long Jing, from the Zhejiang region, derived from the Chaxin tea plant. While, for the dark tea, the Spring Harvest Yixing Red Tea was chosen, cultivated in Jiangsu region, both teas were supplied from Tea House Exclusive (<https://teahouse-exclusives.com/en/>). While the fruit mixture consisted of a sweet apple flavor fruit infusion, and it was purchased with the green and dark tea from “Eastern Leaves” company (Milan, Italy) (<https://easternleaves.com/?srs>). A specific routine was utilized for each of the three extraction methods, aiming to keep the parameters as constant as possible, without altering the original beverage recipes. All samples were prepared with commercial natural water (Nerea).

### 2.3. Brewing procedures and extraction methods

Brewing parameters were defined according to tea type and kept as constant as possible across extraction methods to minimize variability not related to the extraction technique. Water temperature was set at  $75\text{ }^{\circ}\text{C}$  for green tea and at  $95\text{ }^{\circ}\text{C}$  for dark tea and fruit infusion, except where otherwise specified. Three replications for each method were conducted (Table S1), after brewing, each sample was collected and allowed to cool at room temperature ( $25 \pm 2\text{ }^{\circ}\text{C}$ ). Subsequently, samples were stored

and kept at  $4\text{ }^{\circ}\text{C}$  for further analysis.

#### 2.3.1. Pure Brew extraction

Pure Brew extractions were carried out using a VA388 Black Eagle Maverick system (Victoria Arduino, Simonelli Group, Italy) equipped with a patented double-mesh conical filter basket operating at low pressure ( $<0.15\text{ bar}$ ). Tea leaves (2 g for green and dark tea and for fruit infusion) were placed in the filter basket and extracted to obtain approximately 90 g of beverage. The system was operated using the “Dark Profile” program, with water temperature adjusted according to the sample type.

#### 2.3.2. Gaiwan extraction

Gaiwan extraction was performed using a traditional ceramic gaiwan. The vessel was pre-heated with hot water prior to extraction. Tea leaves (2 g) or fruit infusion powder were placed in the gaiwan and infused with water at the appropriate temperature. After 62 s, the liquor was immediately decanted and collected.

#### 2.3.3. French Press extraction

French Press extraction was carried out using a cylindrical glass French Press equipped with a metal mesh filter (Lacor, Spain). The device was pre-heated before use. Tea leaves (2 g) or fruit infusion powder were infused with hot water ( $75\text{ }^{\circ}\text{C}$  for green tea,  $95\text{ }^{\circ}\text{C}$  for dark tea and for fruit infusion) to obtain approximately 90 g of beverage. After 62 s, the plunger was pressed down to separate the liquid from the solid material.

### 2.4. Sample preparation

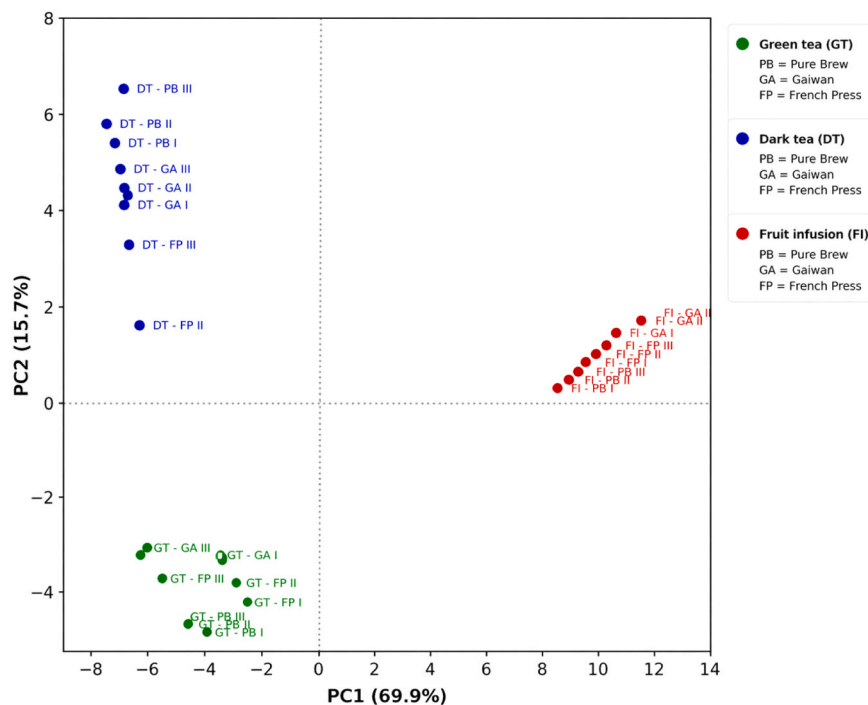
Freshly prepared infusions were allowed to cool to room temperature and centrifuged at 5000 rpm for 5 min. The supernatants were collected and used directly for volatile analysis.

### 2.5. HS-SPME–GC–MS analysis of volatile compounds

A gas chromatography/mass selective detector (GC/MSD with PAL3) was used (Agilent, Santa Clara, CA, USA; Agilent 8890B GC Hardware with Agilent 5977 Series MSD; and MassHunter GC/MSD Data Acquisition (PAL3-Auto Sampler System) (MSD ChemStation software (Agilent, Version G1701DA D.01.00). The column used for separation was DB-WAX ( $0.25\text{ mm} \times 60\text{ m}$ ,  $0.25\ \mu\text{m}$ ) (Agilent 122–7062, Santa Clara, CA, USA). The flow rate (He) was  $1.2\text{ mL/min}$  in splitless mode. The injector temperature was  $260\text{ }^{\circ}\text{C}$ . The column temperature was programmed as follows: from  $35\text{ }^{\circ}\text{C}$  (4 min) to  $120\text{ }^{\circ}\text{C}$  ( $2.5\text{ }^{\circ}\text{C per min}$ ), from  $120\text{ }^{\circ}\text{C}$  to  $250\text{ }^{\circ}\text{C}$  ( $15\text{ }^{\circ}\text{C per min}$ ), then  $250\text{ }^{\circ}\text{C}$  for 3.33 min; the total run time was 50 min. Data were collected in electron impact (EI) mode and in SCAN mode, according to the previously published method (Santanotoglia et al., 2023a). In brief, the sample injection techniques with SPME were implemented through the PAL3 autosampler system. The fiber assembly was from Supelco (Bellefonte, PA, USA) and had a  $50/30\ \mu\text{m}$  coating of divinylbenzene/carboxy/polydimethylsiloxane (DVB/CAR/PDMS). For the analysis, 4 mL of each sample was placed in a shaker, where it was incubated at  $60\text{ }^{\circ}\text{C}$  and shaken at 250 rpm for 20 min. Then, the SPME was automatically injected into the gas-chromatographic system after adsorption. A desorption time of 10 min was sufficient to desorb the analytes from the fiber. Cleaning was performed automatically with the PAL system by inserting the fiber into the conditioning port at  $230\text{ }^{\circ}\text{C}$  for 20 min after each process. Compound putative identification was based on MS spectral matching (NIST), linear retention indices ( $\pm 10$  units) and comparison with literature data.

### 2.6. Sensory analysis

Sensory evaluation was performed using descriptive analysis by a trained panel composed of  $n = 10$  panelists, selected based on their



**Fig. 1.** Principal component analysis (PCA) score plot based on volatile compound profiles of green tea, dark tea and fruit infusion beverages prepared using different extraction methods. Volatile compounds were analyzed by HS-SPME-GC-MS and expressed as relative peak area percentages. Data were log-transformed and autoscaled prior to PCA. The percentage of variance explained by each principal component is reported in parentheses.

experience in sensory evaluation of tea and plant-based beverages. Panelists underwent dedicated training sessions following ISO guidelines (ISO 8586) to familiarize themselves with the evaluation procedure, sensory descriptors and use of intensity scales. Training included consensus-building sessions to ensure a shared understanding of attribute definitions and scale usage. A predefined list of aroma, flavor and mouthfeel descriptors was established during training and used for sample evaluation. Sensory attributes were rated using a structured numerical scale ranging from 0 (not perceived) to 15 (extremely intense). Samples were evaluated under controlled sensory conditions in individual booths, using standardized glassware and neutral lighting. Samples were presented in randomized order and coded with three-digit random numbers to minimize order and carry-over effects. Each sample was evaluated in duplicate in separate sessions. Water was provided for palate cleansing between samples. Sensory data were collected and expressed as mean  $\pm$  standard deviation prior to statistical and multivariate analysis.

### 2.6.1. Ethical statement

The sensory evaluation conducted in this study involved trained adult panelists and the assessment of food products without any clinical, pharmacological or invasive procedures. According to the institutional guidelines of the University of Camerino, studies involving voluntary participation in sensory evaluation of food products, with anonymized data collection and no associated physical or psychological risk, are exempt from formal ethical approval. This exemption applied to the present study and was valid prior to the initiation of the research.

All participants were fully informed about the nature and purpose of the study and provided their written informed consent prior to participation. Sensory analysis was conducted in accordance with ISO 8586 guidelines and the ethical principles outlined in the Declaration of Helsinki.

### 2.7. Determination of bioactive compounds (TPC and TFC)

Total phenolic content (TPC) was determined

spectrophotometrically according to Santanatoglia et al. (2023b), with minor modifications. Tea beverages were analyzed without dilution. An aliquot of 0.5 mL of sample was mixed with 2.5 mL of Folin-Ciocalteu reagent and 7.0 mL of 7.5% (w/w)  $\text{Na}_2\text{CO}_3$ . After incubation for 2 h in the dark at room temperature, absorbance was measured at 765 nm. TPC was quantified using a gallic acid calibration curve and expressed as mg gallic acid equivalents (GAE) per mL of beverage. Total flavonoid content (TFC) was determined following Santanatoglia et al. (2023b), with slight modifications. This method selectively quantifies flavonoids with free hydroxyl groups (e.g., flavones and flavonols); therefore, results should be considered comparative. Sample preparation was performed as described for TPC. Briefly, 0.5 mL of sample was mixed with 0.15 mL of  $\text{NaNO}_2$  (0.5 M), 3.2 mL of methanol (30% v/v) and 0.15 mL of  $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$  (0.3 M). After 5 min, 1.0 mL of NaOH (1 M) was added and absorbance was measured at 506 nm. TFC was quantified using a rutin calibration curve and expressed as mg rutin equivalents (RE) per mL of beverage and per g of tea leaves.

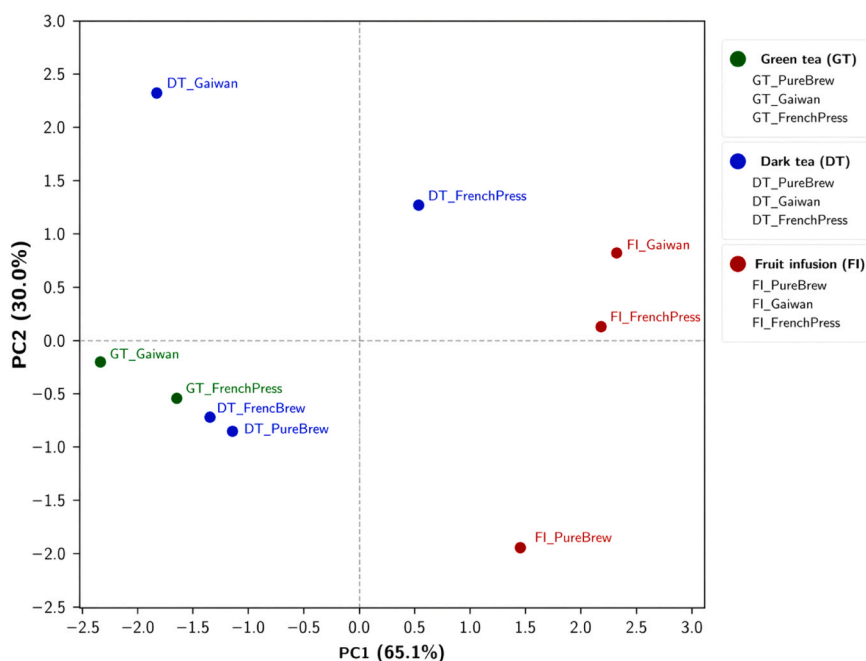
### 2.8. Statistical analysis

All analyses were performed in triplicate, and results were expressed as mean  $\pm$  standard deviation. One-way analysis of variance (ANOVA) followed by Tukey's post hoc test was applied to assess differences among extraction methods within each matrix ( $p < 0.05$ ). Multivariate analyses were conducted to explore relationships among samples and variables. Principal component analysis (PCA) was applied separately to volatile and sensory datasets. Partial least squares (PLS) regression was used to investigate correlations between volatile compounds and sensory attributes. Prior to multivariate analysis, data were log-transformed and autoscaled.

## 3. Results and discussion

### 3.1. Volatile profile of tea and fruit infusion samples

The volatile profiles of tea and fruit infusion beverages were



**Fig. 2.** Principal component analysis (PCA) score plot based on descriptive sensory data of green tea, dark tea and fruit infusion beverages prepared using different extraction methods. Sensory attributes were evaluated by a trained panel using a descriptive analysis approach.

**Table 1a**

Volatile compounds identified in green tea beverages prepared using different extraction methods (Pure Brew, Gaiwan and French Press) by HS-SPME-GC-MS. Compounds are grouped according to chemical class. Retention time (RT), experimental linear retention index (LRI), literature linear retention index (LRI) and main associated aromatic descriptors are reported. Results are expressed as relative peak area percentages (RPA%) and reported as mean  $\pm$  standard deviation ( $n = 3$ ).

RT	LRI	LRI (E)	Compound/Samples	Aromatic Notes	PURE BREW	GAIWAN	FRENCH PRESS
<b>Alcohols</b>							
20.60	1158 + -9	1161	1-Penten-3-ol			0.88 $\pm$ 0.08	
25.66	1250 + -9	1251	1-Pentanol		0.67 $\pm$ 0.16	1.47 $\pm$ 0.56	
32.86	1367 + -7	1381	3-Hexen-1-ol,(E)	Bitter, earthy, fatty	0.51 $\pm$ 0.01	1.18 $\pm$ 0.51	0.98 $\pm$ 0.22
40.33	1547 + -7	1551	Linalool	Citric, floral, lavender	1.58 $\pm$ 0.54	4.04 $\pm$ 1.05	2.45 $\pm$ 1.39
40.65	1557 + -8	1562	1-Octanol	Waxy	1.05 $\pm$ 0.34	1.74 $\pm$ 0.43	1.22 $\pm$ 0.52
45.29	1847 + -10	1848	Geraniol	Floral and citronella-like with a citrus nuance		5.45 $\pm$ 0.56	3.06 $\pm$ 3.72
49.12	2321 + -6	2302	2,4-Di-tert-butylphenol		5.33 $\pm$ 0.62	8.01 $\pm$ 2.40	5.93 $\pm$ 0.68
<b>Aliphatic Aldehydes</b>							
8.71	914 + -8	908	Butanal, 2-methyl-	Cocoa	1.24 $\pm$ 0.32	2.45 $\pm$ 0.04	1.95 $\pm$
8.86	918 + -7	913	Butanal, 3-methyl-	Chocolate peach, fatty	1.39 $\pm$ 0.03	3.29 $\pm$ 0.36	2.28 $\pm$ 0
16.05	1083 + -8	1078	Hexanal	Fruity and clean with a woody nuance	3.92 $\pm$ 1.10	3.3 $\pm$ 0.35	2.40 $\pm$ 1.34
33.24	1391 + -8	1387	Nonanal	Waxy, citrus, with a lemon peel like nuance.	4.41 $\pm$ 2.08		
38.64	1498 + -8	1494	Decanal	Sweet, waxy, and citrus rind.	1.58 $\pm$ 1.20		
<b>Aromatic Aldehydes</b>							
39.32	1520 + -14	1514	Benzaldehyde	Almond, fruity, powdery, nutty.	4.10 $\pm$ 0.84	5.92 $\pm$ 2.86	5.14 $\pm$ 1.62
<b>Ketones</b>							
18.76	1127 + -9	1128	3-Penten-2-one,4-methyl-	Sharp and acetone-like, fruity, phenolic.		1.59 $\pm$ 0.39	
30.21	1339 + -9	1332	5-Hepten-2-one,6-methyl-	Fruity and creamy with and banana nuances	0.63 $\pm$ 0.33	0.91 $\pm$ 0.06	
46.37	1941 + -17	1962	trans-beta-ionone		3.61 $\pm$ 3.58	3.45 $\pm$ 0.69	2.63 $\pm$ 1.78
<b>Esters</b>							
15.69	1074 + -8	1071	Acetic Acid, butyl ester	Etherealsolvent, fruity banana	34.06 $\pm$ 35.11	8.91 $\pm$ 8.05	14.21 $\pm$ 11.95
44.56	1765 + -21	1782	Salicylic acid, methyl ester (betula oil)	Wintergreenmint		2.94 $\pm$ 0	

characterized by HS-SPME-GC-MS, revealing complex aroma fingerprints composed of alcohols, aldehydes, ketones, esters, terpenoids and other aromatic compounds. Consistent with previous literature, the relative abundance and balance among these chemical classes were strongly influenced by botanical origin, degree of oxidation and extraction conditions (Ho et al., 2015; Zhu et al., 2018; Shao et al., 2021). Marked differences were observed among green tea, dark tea and fruit infusion samples, reflecting the combined effects of raw material composition, processing history and brewing strategy.

### 3.1.1. Green tea

Green tea beverages were dominated by alcohols and aliphatic aldehydes, which are typically associated with fresh, floral, green and citrus-like sensory attributes (Yang et al., 2013; Wang et al., 2019) (Table 1a) (Figure S3). Among alcohols, monoterpene alcohols played a central role. Linalool was consistently detected across all extraction methods, with relative peak area percentages (RPA%) ranging from 1.58  $\pm$  0.54 in Pure Brew to 4.04  $\pm$  1.05 in Gaiwan extractions, while intermediate values were observed for French Press (2.45  $\pm$  1.39 RPA %). Geraniol followed a comparable pattern, reaching 5.45  $\pm$  0.56 RPA % in Pure Brew and remaining above 3 RPA% in the other extraction

**Table 1b**

Volatile compounds identified in black tea beverages prepared using different extraction methods (Pure Brew, Gaiwan and French Press) by HS-SPME-GC-MS. Compounds are classified by chemical family. Retention time (RT), experimental linear retention index (LRI), literature linear retention index (LRI) and associated aromatic notes are reported. Results are expressed as relative peak area percentages (RPA%) and reported as mean  $\pm$  standard deviation ( $n = 3$ ).

RT	LRI	LRI (E)	Compound/Samples	Aromatic Notes	PURE BREW	GAIWAN	FRENCH PRESS
<b>Alcohols</b>							
20.60	1158 + -9	1161	1-Penten-3-ol		0.32 $\pm$ 0.36	0.59 $\pm$ 0.21	0.49 $\pm$ 0.12
25.66	1250 + -9	1251	1-Pentanol		1.35 $\pm$ 0.03	1.06 $\pm$ 0.09	0.99 $\pm$ 0.34
29.40	1318 + -7	1316	2-Penten-1-ol, (Z)	Fruity odor reminiscent of cherry upon dilution	0.7 $\pm$ 0.11	0.56 $\pm$ 0.17	0.68 $\pm$ 0.19
31.5	1355 + -7	1356	1-Hexanol	Oily fruity, alcoholic sweet green	0.63 $\pm$ 0.13	0.48 $\pm$ 0.07	0.60 $\pm$ 0.26
32.86	1367 + -7	1381	3-Hexen-1-ol, (E)	Bitter, earthy, fatty	1.83 $\pm$ 0.15	1.47 $\pm$ 0.06	1.41 $\pm$ 0.42
36.34	1450 + -7	1449	1-Octen-3-ol	Earthy and fungal	0.76 $\pm$ 0.03	0.80 $\pm$ 0.17	0.50 $\pm$ 0.15
40.33	1547 + -7	1551	Linalool	Citric, floral, lavender	11.4 $\pm$ 0.64	11.04 $\pm$ 1.62	9.93 $\pm$ 3.15
40.65	1557 + -8	1562	1-Octanol	Waxy	0.91 $\pm$ 0.05	0.75 $\pm$ 0.01	0.62 $\pm$ 0.37
45.29	1847 + -10	1848	Geraniol	Floral and citronella-like with a citrus nuance	11.14 $\pm$ 0.20	10.85 $\pm$ 2.36	9.06 $\pm$ 1.21
<b>Aromatic Alcohols</b>							
45.62	1870 + -13	1879	Benzyl Alcohol	Sweet, floral, fruity with chemical nuances	1.89 $\pm$ 0.06	1.82 $\pm$ 0.04	1.78 $\pm$ 0.23
46.00	1907 + -15	1920	Phenylethyl Alcohol	Fresh and bready with a rosey honey nuance	4.67 $\pm$ 0.21	4.09 $\pm$ 0.52	4.27 $\pm$ 0.43
49.12	2321 + -6	2302	2,4-Di-tert-butylphenol		2 $\pm$ 0.37	1.60 $\pm$ 0.61	13.92 $\pm$ 17.29
<b>Aliphatic Aldehydes</b>							
8.71	914 + -8	908	Butanal, 2-methyl-	Cocoa	3.46 $\pm$ 0.14	2.36 $\pm$ 0.92	3.09 $\pm$ 1.66
8.86	918 + -7	913	Butanal,3-methyl-	Chocolate, peach, fatty	2.53 $\pm$ 0.40	1.52 $\pm$ 0.93	1.99 $\pm$ 1.21
16.05	1083 + -8	1078	Hexanal	Fruity and clean with a woody nuance	2.89 $\pm$ 0.62	2.27 $\pm$ 0.82	1.92 $\pm$ 1.24
21.732	1185 + -9	1180	Heptanal	Fresh, aldehydic, fatty green and herbal cognac like.	0.13 $\pm$ 0.02	0.29 $\pm$ 0.11	
23.50	1216 + -9	1210	2-Hexenal, (E)	Fruity with herbal and spicy herbal nuances	0.42 $\pm$ 0.06	0.56 $\pm$ 0.17	0.29 $\pm$ 0.25
27.55	1289 + -9	1283	Octanal	Aldehydic, waxy, citrus orange with a green peely nuance	0.27 $\pm$ 0.39	0.42 $\pm$ 0.15	
33.24	1391 + -8	1387	Nonanal	Waxy, citrus, with a lemon peel like nuance.	2.36 $\pm$ 0.38		
38.64	1498 + -8	1494	Decanal	Sweet, waxyand citrus rind.	1.09 $\pm$ 1.01	0.93 $\pm$ 0.96	
42.09	1611 + -17	1621	Cyclohexene-1-Carboxaldehyde,2,6,6-trimethyl	Sweettobaccodamasconefruity		0.65 $\pm$ 0.20	0.56 $\pm$ 0.29
43.94	1717 + -19	1735	Citral	Juicy with a sweet tangy green nuance	0.95 $\pm$ 0.16	0.99 $\pm$ 0.06	0.84 $\pm$ 0.65
<b>Aromatic Aldehydes</b>							
39.32	1520 + -14	1514	Benzaldehyde	Almond, fruity, powdery, nutty.	9.54 $\pm$ 0.08	9.76 $\pm$ 2.26	8.03 $\pm$ 2.51
42.35	1641 + -13	1636	Benzeneacetaldehyde	Honey, fermented.	0.57 $\pm$ 0.03	2.02 $\pm$ 0	1.09 $\pm$ 0.13
45.02	1790 + -nd	1822	Benzaldehyde,3,4-dimethyl	Almond, fruity, powdery, nutty.	0.41 $\pm$ 0.07	0.42 $\pm$ 0.09	1.24 $\pm$ 0.75
46.24	1925 + -14	1946	Benzeneacetaldehyde, alpha-ethylidene	musty	0.9 $\pm$ 0.24	0.60 $\pm$ 0.14	0.63 $\pm$ 0.17
<b>Ketones</b>							
21.62	1182 + -8	1179	2-Heptanone	Cheesy	0.64 $\pm$ 0.07	0.49 $\pm$ 0.24	0.53 $\pm$ 0.33
29.07	1317 + -10	1310	Cyclohexanone,2,2,6-trimethyl-	Tobacco	0.25 $\pm$ 0.04	0.23 $\pm$ 0.06	0.14 $\pm$ 0.07
30.21	1339 + -9	1332	5-Hepten-2-one,6-methyl-	Fruity and creamy nuances	1.13 $\pm$ 0.02	1.08 $\pm$ 0.05	1.01 $\pm$ 0.35
46.37	1941 + 17	1962	trans-beta-lonone		1.59 $\pm$ 0.04	1.58 $\pm$ 0.5	1.19 $\pm$ 0.69
<b>Monoterpenes</b>							
20.54	1161 + -7	1160	Beta-Myrcene	Balsamic, herbal, woody, spice, rose, carrot	1.64 $\pm$ 0.96	0.93 $\pm$ 0.39	0.65 $\pm$ 0.35
22.37	1190	1191	D-Limonene	Citrus, orange, lemon, fresh, sweet	0.40 $\pm$ 0.18	0.56 $\pm$ 0.19	0.20 $\pm$ 0.14

(continued on next page)

Table 1b (continued)

RT	LRI	LRI (E)	Compound/Samples	Aromatic Notes	PURE BREW	GAIWAN	FRENCH PRESS
25.48	1250 + -4	1247	Beta-Ocimene	Citrus, tropical	0.38 ± 0.09	0.41 ± 0.06	0.18 ± 0.12
41.76	1610	1602	<b>Pyrroles</b> 1H-Pyrrole-2-carboxaldehyde,1-ethyl			1.48 ± 1.04	1.86 ± 0.93
24.31	1232 + -9	1226	<b>Furans</b> Furan,2-pentyl-	Fruity, green, earthybeany	0.15 ± 0.01	0.41 ± 0.15	0.11 ± 0.02
36.03	non ce	1443	Ethyl 2-(5-methyl-5-vinyltetrahydrofuran-2-yl carbonate		4.19 ± 0.19	5.07 ± 1.49	7.23 ± 0.58
15.69	1074 +8	1071	<b>Esters</b> Acetic Acid, butylester	etherealsolvent, fruity banana	3.96 ± 5.12	6.43 ± 0.68	
44.56	1765 +21	1782	Salicylic acid, methyl ester (betula oil)	Winter, green, mint	7.14 ± 0.23	8.04 ± 0.80	5.38 ± 2.18

methods. These compounds are well established contributors to floral and citrus notes in green tea aroma (Ho et al., 2015; Zhu et al., 2015; Shao et al., 2021). Aliphatic aldehydes further contributed to the aromatic profile of green tea infusions. Hexanal ranged from 2.40 ± 1.34–3.92 ± 1.10 RPA%, while nonanal reached values up to 4.41 ± 2.08 RPA%, imparting green, waxy and citrus-peel nuances. Variations in the relative abundance of these aldehydes across extraction methods indicate differences in extraction selectivity and mass transfer efficiency, consistent with the sensitivity of volatile release to brewing parameters reported in previous studies (Chen et al., 2019; Zhang et al., 2020). Ketones were present at lower relative abundances but were sensorially relevant. Trans- $\beta$ -ionone was detected in the range of 2.63–3.61 RPA% and, despite its low concentration, contributes violet-like and floral nuances due to its extremely low odor threshold (Yang et al., 2013; Jiang et al., 2021).

### 3.1.2. Dark tea

Dark tea samples exhibited a more intense and chemically complex volatile profile compared to green tea, characterized by higher contributions from aromatic alcohols, aromatic aldehydes and ketones. This compositional shift reflects the higher degree of oxidation involved in dark tea processing, which promotes extensive enzymatic and non-enzymatic transformations of aroma precursors (Lin et al., 2012a, 2012b; Wang et al., 2019) (Table 1b and Figure S4). Linalool and geraniol were again among the dominant compounds but were present at higher levels than in green tea. Linalool reached 11.40 ± 0.64 RPA% in Pure Brew and remained above 9.9 RPA% across all extraction methods, while geraniol ranged from 9.06 ± 1.21–11.14 ± 0.20 RPA%, confirming the enhancement of floral terpenoids following oxidative processing (Ho et al., 2015; Zhu et al., 2018). Aromatic alcohols such as phenylethyl alcohol (4.09–4.67 RPA%) and benzyl alcohol (approximately 1.8–1.9 RPA%) were consistently detected and are commonly associated with sweet, floral and honey-like notes characteristic of black and dark teas (Shao et al., 2021; Wang et al., 2022). Among aldehydes, benzaldehyde was particularly prominent, accounting for approximately 8.03–9.76 RPA%, while benzene acetaldehyde reached values up to 2.02 RPA%, contributing almond-like, fruity and honeyed nuances. These compounds are considered markers of advanced oxidation and are linked to the warm, rounded aromatic profile of dark teas (Zhu et al., 2015; Yang et al., 2022). Ketones, including trans- $\beta$ -ionone (1.19–1.59 RPA%), further contributed to sensory differentiation due to their high odor activity values (Jiang et al., 2021). Fruit infusion

Fruit infusion samples displayed a volatile profile clearly differentiated from *Camellia sinensis* beverages. The aroma was dominated by esters, aldehydes and oxygenated compounds associated with fruity and sweet sensory notes, as commonly reported for fruit-based infusions and herbal beverages (El Hadi et al., 2013; Rajendran et al., 2023) (Table 1c and Figure S5). Esters represented the most abundant class, with acetic

acid hexyl ester reaching 12.70 ± 1.86 RPA% in Pure Brew and up to 13.68 ± 0.87 RPA% in French Press extractions, while 3-methylbutyl acetate-related esters exceeded 10 RPA%. Aldehydes such as nonanal (2.68 ± 0.38 RPA%) and hexanal (up to 1.40 ± 0.25 RPA%) further contributed to fresh, sweet and apple-like aroma notes. In contrast to tea samples, terpenoid alcohols played a secondary role, reflecting differences in biochemical origin and precursor pathways between fruit matrices and tea leaves (Zhang et al., 2020). Extraction method influenced the volatile profile also in fruit infusions, indicating that brewing conditions modulate volatile release not only in tea but across different botanical matrices, in agreement with previous findings (Chen et al., 2019; Sánchez-López et al., 2020).

### 3.2. Sensory characterization

Descriptive sensory analysis highlighted clear differences among samples as a function of botanical matrix and extraction method. Green tea, dark tea and fruit infusion exhibited distinct sensory profiles, reflecting their different chemical composition, processing history and degree of oxidation (Ho et al., 2015; Shao et al., 2021; Wang et al., 2022).

#### 3.2.1. Green tea

Green tea samples were characterized by fresh, floral, citrus and vegetal notes, moderate sweetness, low to moderate astringency and limited umami perception (Tables 2 and S2) (Figure S6). Pure Brew extraction produced the most balanced sensory profile, with aroma and flavor intensities of 5.0 ± 1.41 and 8.0 ± 2.66, respectively. Sweetness was relatively high (8.5 ± 2.12), astringency remained low (1.5 ± 0.70) and umami perception was moderate (6.5 ± 2.12), suggesting efficient extraction of aroma-active compounds with limited co-extraction of bitterness- and astringency-related components. French Press extraction yielded a comparable profile, with similar aroma (5.0 ± 1.41) and flavor intensity (6.5 ± 2.12), preserved floral-citrus character and slightly higher astringency (2.5 ± 0.71), indicating a greater contribution of non-volatile components to mouthfeel. In contrast, Gaiwan-extracted green tea showed reduced aromatic intensity, higher astringency (4.0 ± 2.24) and pronounced umami perception (10.0 ± 2.83), consistent with preferential extraction of water-soluble polyphenols and amino acids under traditional infusion conditions (Zhu et al., 2018; Zhang et al., 2020).

#### 3.2.2. Dark tea

Dark tea beverages exhibited higher aroma and flavor intensity than green tea, with dominant roasted, spicy, malty and sweet descriptors (Tables 2 and S2) (Figure S7). Pure Brew extraction resulted in a balanced profile, with aroma and flavor intensities of 6.0 ± 1.40 and 6.0 ± 1.39, moderate sweetness (7.5 ± 0.71), low astringency (2.0

**Table 1c**

Volatile compounds identified in fruit infusion beverages prepared using different extraction methods (Pure Brew, Gaiwan and French Press) by HS-SPME-GC-MS. Compounds are grouped according to chemical class. Retention time (RT), experimental linear retention index (LRI), literature linear retention index (LRI) and main aromatic descriptors are reported. Results are expressed as relative peak area percentages (RPA%) and reported as mean  $\pm$  standard deviation (n = 3).

RT	LRI	LRI (E)	Compound/Samples	Aromatic Notes	PURE BREW	GAIWAN	FRENCHPRESS
20.60	1158 + -9	1161	<b>Alcohols</b> 1-Penten-3-ol	Butter, mild, green	0.64 $\pm$ 0.16	0.29 $\pm$ 0.05	0.43 $\pm$ 0.03
23.31	1209 + -9	1207	1-Butanol,3-methyl				
25.66	1250 + -9	1251	1-Pentanol	Fruity odor reminiscent of cherry upon dilution Oily fruity,alcoholic sweet green	4.02 $\pm$ 0.27	3.26 $\pm$ 0.08	3.76 $\pm$ 0.25
29.40	1318 + -7	1316	2-Penten-1-ol,(Z)				
31.5	1355 + -7	1356	1-Hexanol				
32.86	1367 + -7	1381	3-Hexen-1-ol,(E)	Intensely green, bitter, earthy, fatty	0.50 $\pm$ 0.05	0.44 $\pm$ 0.05	0.46 $\pm$ 0.12
36.34	1450 + -7	1449	1-Octen-3-ol	Earthy and fungal	0.21 $\pm$ 0.02	0.16 $\pm$ 0.07	0.22 $\pm$ 0.04
40.33	1547 + -7	1551	Linalool	Citric, floral, lavender	1.18 $\pm$ 0.22	1.34 $\pm$ 0.25	1.09 $\pm$ 0.19
40.65	1557 + -8	1562	1-Octanol	Waxy	0.35 $\pm$ 0.04	0.08 $\pm$ 0.00	0.12 $\pm$ 0.02
41.61	1637 + -6	1596	dl-Menthol	Peppermint, cooling, woody	0.73 $\pm$ 0.06	0.85 $\pm$ 0.11	0.78 $\pm$ 0.08
41.739	1602 + -9	1601	Terpinen-4-ol		0.21 $\pm$ 0.04	0.24 $\pm$ 0.07	0.20 $\pm$ 0.07
42.51	1633 + -19	1645	Levomenthol	Mentholic	8.95 $\pm$ 0.91	9.95 $\pm$ 0.36	9.02 $\pm$ 1.16
43.45	1697 + -10	1698	alpha-Terpineol	Oil, anise, mint, lemon, citric	1.25 $\pm$ 0.09	1.54 $\pm$ 0.18	1.21 $\pm$ 0.17
43.55	1702 + -16	1704	endo-Borneol	Balsamic notes	0.16 $\pm$ 0.17	0.47 $\pm$ 0.01	0.42 $\pm$ 0.01
45.29	1847 + -10	1848	Geraniol	Floral and citronella-like with a citrus nuance	0.52 $\pm$ 0.02	0.49 $\pm$ 0.07	2.07 $\pm$ 2.04
49.12	2321 + -6	2302	<b>Aromatic Alcohols</b> 2,4-Di-tert-butylphenol		0.60 $\pm$ 0.10	3.51 $\pm$ 1.19	0.66 $\pm$ 0.05
11.17	979 + -9	974	<b>Aliphatic Aldehydes</b> Pentanal		0.05 $\pm$ 0.01	0.05 $\pm$ 0.01	0.07 $\pm$ 0.01
16.05	1083 + -8	1078	Hexanal	Fruity and clean with a woody nuance	1.40 $\pm$ 0.25	1.40 $\pm$ 0.25	0.67 $\pm$ 0.11
21.73	1185 + -9	1180	Heptanal	Fresh aldehydic, fatty green and herbal cognac like.	0.20 $\pm$ 0.03	0.20 $\pm$ 0.03	0.13 $\pm$ 0.02
23.50	1216 + -9	1210	2-Hexenal, (E)	Fruity with herbal and spicy herbal nuances	0.64 $\pm$ 0.19	0.64 $\pm$ 0.19	0.68 $\pm$ 0.16
27.55	1289 + -9	1283	Octanal	Aldehydic, waxy, citrus orange with a green peely nuance	0.18 $\pm$ 0.00	0.18 $\pm$ 0.00	0.13 $\pm$ 0.02
29.41	1323 + -11	1316	2-Heptenal, (E)	Intense green, oily, with fruity overtones	0.18 $\pm$ 0.00	0.18 $\pm$ 0.00	0.29 $\pm$ 0.02
33.24	1391 + -8	1387	Nonanal	Waxy, citrus, with a lemon peel like nuance.	2.68 $\pm$ 0.38	2.68 $\pm$ 0.38	0.20 $\pm$ 0.03
35.09	1429 + -8	1424	2-Octenal, (E)-	Fresh cucumber, banana, waxy	0.32 $\pm$ 0.05	0.32 $\pm$ 0.05	0.22 $\pm$ 0.04
38.64	1498 + -8	1494	Decanal	Sweet, aldehydic, orange, waxy and citrus rind.	0.24 $\pm$ 0.03	0.24 $\pm$ 0.03	0.09 $\pm$ 0.02
39.94	1534 + -10	1537	2-Nonenal, (E)-	Green, cucumber, aldehydic, with a citrus nuance.	0.32 $\pm$ 0.03	0.32 $\pm$ 0.03	0.11 $\pm$ 0.04
39.32	1520 + -14	1514	<b>Aromatic Aldehydes</b> Benzaldehyde	Almond, fruity, powdery, nutty.	0.60 $\pm$ 0.14	0.92 $\pm$ 0.04	0.75 $\pm$ 0.02
42.35	1641 + -13	1636	Benzeneacetaldehyde	Honey, floral rose, sweet, powdery, fermented.			
45.02	1790 + -nd	1822	Benzaldehyde,3,4-dimethyl	Almond, fruity, powdery, nutty.	0.45 $\pm$ 0.29	0.62 $\pm$ 0.11	0.67 $\pm$ 0.46
46.24	1925 + -14	1946	Benzeneacetaldehyde, alpha-ethylidene	musty			
28.69	1294 + -26	1302	<b>Ketones</b> 7-Octen-4-one,2,6-dimethyl-	Citrus	0.18 $\pm$ 0.03	0.19 $\pm$ 0.02	0.14 $\pm$ 0.03
29.078	1317 + -10	1310	Cyclohexanone,2,2,6-trimethyl-	Tobacco			
30.219	1339 + -9	1332	5-Hepten-2-one,6-methyl-	Fruity and creamy with and banana nuances	0.20 $\pm$ 0.05	0.24 $\pm$ 0.02	0.22 $\pm$ 0.04
36.965	1460 + -15	1462	Cyclohexanone 5-methyl-2-(1methylthyl)-,(2R-cis)-		1.40 $\pm$ 0.39	1.66 $\pm$ 0.23	1.20 $\pm$ 0.64

(continued on next page)

Table 1c (continued)

RT	LRI	LRI (E)	Compund/Samples	Aromatic Notes	PURE BREW	GAIWAN	FRENCHPRESS
38.388	nr	1489	L-Menthone	Minty, cooling, sweet, peppermint-like	0.68 ± 0.13	0.96 ± 0.09	0.99 ± 0.18
41.429	1602 + -0	1590	6-Methyl-3,5-heptadiene-2-one	spicy	0.24 ± 0.10	0.27 ± 0.12	0.25 ± 0.09
42.631	1652	1652	Pulegone	Minty	0.26 ± 0.12	0.51 ± 0.07	0.30 ± 0.26
45.431	1841 + -4	1861	6,10-Dimethyl-5,9-undecadien-2-one	fruity-floral, rosy, green magnolia			
45.433	1859 + -9	1861	5,9-Undecandien-2-one,6,10-dimethyl-,(E)		0.39 ± 0.05	0.52 ± 0.07	0.35 ± 0.03
45.491	1840 + -20	1867	Beta-Ionone	floral	0.14 ± 0.06	0.19 ± 0.06	0.19 ± 0.05
46.379	1941 + -17	1962	trans-beta-Ionone		0.52 ± 0.09	0.59 ± 0.27	0.41 ± 0.15
			<b>Monoterpens</b>				
44.051	1741 + -11	1743	D-Carvone	Spicyminty	4.30 ± 0.39	5.71 ± 0.02	4.92 ± 0.18
22.372	1190	1191	D-Limonene	Citrus, orange, lemon, fresh, sweet	0.32 ± 0.04	0.30 ± 0.09	0.25 ± 0.12
23.124	1212 + -8	1203	Eucalyptol	Eucalyptusherbal	0.27 ± 0.03	0.41 ± 0.05	0.25 ± 0.02
25.48	1250 + -4	1247	Beta-Ocimene	Citrus, tropical			
40.818	1569	1568	(1S)-(+)-Neomenthyl acetate	Herbal like	5.96 ± 0.60	5.96 ± 0.35	7.23 ± 0.17
44.24	1752 + -11	1758	Geranyl Acetate	Floral, rosy, waxy, herbal	1.13 ± 0.13	1.59 ± 0.38	1.74 ± 0.20
45.123	1827 + -15	1832	Anethole	Licorice	0.52 ± 0.08	0.65 ± 0.05	0.66 ± 0.15
			<b>Furans</b>				
36.54	1461 + -11	1453	Furfural	Bread, almond, woody, caramelllic	11.63 ± 1.31	15.38 ± 2.68	13.00 ± 1.10
48.161	2138 + -13	2182	2(3 H) -Furanone,5-hexyldihydro-	Caramelllic	3.40 ± 0.12	4.92 ± 0.04	3.77 ± 0.33
			<b>Acids</b>				
35.961	1449 + -13	1441	Acetic Acid	sharppungentsourvinegar	0.72 ± 0.28	0.66 ± 0.18	0.94 ± 0.17
42.875	1662 + -9	1666	Butanoic acid, 2-methyl	Acidic, fruity, dirty and cheesy	0.37 ± 0.00	0.27 ± 0.11	0.27 ± 0.17
45.196	1846 + -12	1839	Hexanoic acid	Cheesy and fruit	1.20 ± 0.15	1.27 ± 0.04	0.75 ± 0.83
47.976	2170 + -17	2158	Nonanoic acid	Waxy, dirty and cheesy	1.12 ± 0.19	1.26 ± 0.17	0.79 ± 0.17
48.836	2276 + -15	2266	n-Decanoic acid	Unpleasantracid	0.94 ± 0.14	1.21 ± 0.17	0.86 ± 0.32
			<b>Esters</b>				
7.971	888 + -9	885	Ethyl Acetate	Pineapple, ethereal, fruity, sweet, weedy, grape, green	0.47 ± 0.01	0.24 ± 0.11	0.35 ± 0.12
11.092	973 + -11	972	n-Propyl acetate	Sweet and fruity	0.22 ± 0.01	0.09 ± 0.04	0.19 ± 0.01
13.922	1036 + -8	1036	Butanoic acid, ethylester	Fruitpineapple cognac	0.22 ± 0.01	0.11 ± 0.01	0.19 ± 0.08
14.777	1052 + -8	1053	Butanoic acid, 2-methyl-,ethyl ester	Apple fruity	1.40 ± 0.05	0.90 ± 0.04	1.43 ± 0.22
15.698	1074 + -8	1071	Acetic Acid, butylester	etherealsolvent, fruity banana	3.93 ± 0.17	2.80 ± 0.18	3.96 ± 0.22
18.391	1123 + -8	1121	1-Butanol,3-methyl-, acetate		12.28 ± 0.11	7.44 ± 1.93	10.27 ± 1.90
26.828	1273 + -7	1271	Acetic acid hexylester	Fruity, Green apple and banana	12.70 ± 1.86	11.27 ± 0.32	13.68 ± 0.87
28.101	1293 + -9	1292	Butanoic acid 3-methyl-,3-methylbutyl ester	Fruity sweet banana and apple, grassy	0.24 ± 0.00	0.23 ± 0.06	0.23 ± 0.07
29.147	1316 + -6	1311	3-Hexen-1-ol, acetate, (Z)-	Sweetfruity banana apple	2.71 ± 0.49	2.71 ± 0.14	2.84 ± 0.05
34.575	1414 + -8	1413	Butanoicacid, hexylester	Sweet fruity apple, waxy, soapy.	1.52 ± 0.03	1.35 ± 0.16	1.77 ± 0.06
43.861	1720 + -22	1729	Aceticacid, phenylmethylester	Sweethoneyfloral, waxy	0.36 ± 0.21	0.53 ± 0.29	0.46 ± 0.08
44.561	1765 + -21	1782	Salicylic acid, methyl ester (betula oil)	Wintergreenmint			

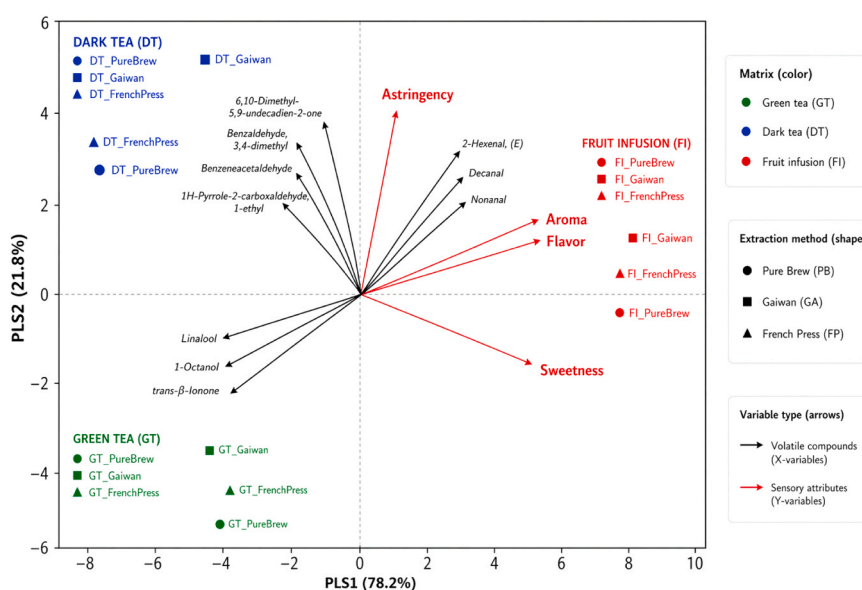
± 2.83) and limited umami perception ( $4.5 \pm 0.71$ ). French Press extraction produced the most intense sensory expression, with aroma and flavor intensities reaching  $10.0 \pm 1.41$ , increased astringency ( $9.0 \pm 2.83$ ) and moderate sweetness ( $8.0 \pm 2.66$ ), indicating enhanced

extraction of polyphenolic fractions contributing to structural intensity. Gaiwan extraction generated the most extreme profile, characterized by high flavor intensity ( $9.0 \pm 2.07$ ), very high astringency ( $10.0 \pm 0.14$ ) and reduced sweetness ( $4.0 \pm 0.21$ ), with moderate umami perception ( $6.5 \pm 0.71$ ). This sensory behavior has been associated with

**Table 2**

Descriptive sensory profile of green tea, black tea and fruit infusion beverages obtained using different extraction methods. Values represent mean perceived intensity levels evaluated by a trained sensory panel, while dominant descriptors indicate the most frequently cited sensory terms for each attribute. Sensory attributes include aroma intensity, flavor intensity, sweetness, astringency and umami perception.

Sample matrix	Extraction method	Aroma intensity	Dominant aroma descriptors	Flavor intensity	Dominant flavor descriptors	Sweetness	Astringency	Umami
Green tea	Pure Brew	Medium	Floral, vegetal	Medium–High	Citrus	Medium–High	Low	Moderate
Green tea	Gaiwan	Medium	Vegetal	Medium	Herbal	Medium	Low	High
Green tea	French Press	Medium	Floral	Medium	Citrus	Medium	Low	Moderate
Dark tea	Pure Brew	Medium–High	Spicy, roasted	Medium	Sweet, malty	Medium	Low	Low-moderate
Dark tea	Gaiwan	Medium	Woody	Medium–High	Bitter	Low	High	Medium
Dark tea	French Press	High	Roasted	High	Sweet	Medium	Medium–High	Low
Fruit infusion	Pure Brew	High	Fruity	High	Sweet, fruity	High	Low	Low
Fruit infusion	Gaiwan	High	Fruity	High	Cooked fruit	Medium-High	Medium	Low
Fruit infusion	French Press	High	Fruity, floral	High	Sweet	High	Medium	Low



**Fig. 3.** Partial least squares (PLS) biplot illustrating the relationships between volatile compounds (X-variables) and sensory attributes (Y-variables) in tea and fruit infusion beverages. Volatile compounds are represented as vectors, while sensory descriptors are shown as response variables. The proximity between variables indicates positive correlations and potential chemical drivers of sensory perception.

preferential extraction of phenolic compounds, which enhances bitterness and astringency while partially masking aroma perception (Chen et al., 2019; Shao et al., 2021).

### 3.2.3. Fruit infusion

Fruit infusion samples were dominated by fruity and sweet descriptors, with negligible umami perception and generally low astringency (Tables 2 and S2) (Figure S8). Pure Brew extraction yielded high aroma and flavor intensity ( $10.0 \pm 0.15$ ), high sweetness ( $12.0 \pm 0.37$ ) and no detectable astringency or umami. French Press extraction produced similarly intense profiles, with aroma and flavor intensities of  $12.0 \pm 2.24$  and  $14.5 \pm 0.71$ , high sweetness ( $11.0 \pm 1.41$ ) and moderately increased astringency ( $6.0 \pm 1.41$ ). Gaiwan extraction resulted in the highest aroma ( $13.0 \pm 2.83$ ) and flavor intensity ( $15.0 \pm 0.0$ ), accompanied by reduced sweetness ( $9.5 \pm 2.36$ ) and increased astringency ( $7.0 \pm 2.22$ ). Across all fruit infusions, umami perception was consistently absent, reflecting the lack of amino acid-rich matrices typical of tea leaves (Zhang et al., 2020; Malongane et al., 2020).

### 3.3. Linking chemistry and sensory perception

Partial least squares (PLS) regression was applied to investigate relationships between volatile composition and sensory attributes across all beverages (Fig. 3) (Table S3). Two latent variables were retained, explaining 58.3% of the X variance and 49.6% of the Y variance for PLS1, with PLS2 accounting for an additional 26.6% of X and 23.9% of Y variance, resulting in cumulative values of  $R^2X = 0.835$  and  $R^2Y = 0.735$ . These results indicate a strong association between chemical composition and sensory perception. PLS1 primarily discriminated samples according to botanical matrix. Fruit infusion samples were associated with sweetness, aroma and flavor intensity and characterized by high loadings of ester- and furan-derived compounds such as acetic acid hexyl ester, 1-butanol, 3-methyl-, acetate, and furfural, which are known contributors to fruity, sweet and caramel-like notes. In contrast, Camellia sinensis beverages were positioned on the opposite side of PLS1, reflecting lower sweetness and a stronger contribution of non-volatile taste-active compounds. Separation along PLS2 further differentiated tea samples according to type and extraction method. Dark tea samples, particularly those prepared using Gaiwan and French Press, were associated with astringency and aligned with aldehydes and

**Table 3a**

Total phenolic content (TPC) of green tea, black tea and fruit infusion samples prepared using different extraction methods. Results are expressed as mg gallic acid equivalents and reported as mean  $\pm$  standard deviation ( $n = 4$ ). Values are expressed on a dry weight basis to allow comparison among different matrices and extraction methods.

Sample matrix	Extraction method	TPC (mg GAE)
Green tea	Pure Brew	6.46 $\pm$ 2.45
Green tea	Gaiwan	219.11 $\pm$ 10.52
Green tea	French Press	321.78 $\pm$ 16.29
Dark tea	Pure Brew	36.16 $\pm$ 8.43
Dark tea	Gaiwan	286.32 $\pm$ 15.51
Dark tea	French Press	277.40 $\pm$ 17.72
Fruit infusion	Pure Brew	10.87 $\pm$ 6.44
Fruit infusion	Gaiwan	47.32 $\pm$ 0.10
Fruit infusion	French Press	130.60 $\pm$ 15.87

**Table 3b**

Total flavonoid content (TFC) of green tea, black tea and fruit infusion samples prepared using different extraction methods. Results are expressed as mg rutin equivalents and reported as mean  $\pm$  standard deviation ( $n = 4$ ). Data are expressed on a dry weight basis for comparative purposes.

Sample matrix	Extraction method	TFC (mg RE)
Green tea	Pure Brew	135.11 $\pm$ 3.13
Green tea	Gaiwan	322.14 $\pm$ 14.91
Green tea	French Press	311.23 $\pm$ 11.96
Dark tea	Pure Brew	143.64 $\pm$ 12.22
Dark tea	Gaiwan	296.10 $\pm$ 11.10
Dark tea	French Press	422.10 $\pm$ 1.95
Fruit infusion	Pure Brew	95.46 $\pm$ 14.57
Fruit infusion	Gaiwan	106.73 $\pm$ 2.34
Fruit infusion	French Press	118.42 $\pm$ 6.25

phenolic-related compounds such as benzeneacetaldehyde, benzaldehyde derivatives and 1H-pyrrole-2-carboxaldehyde. Green tea samples clustered in a region characterized by moderate aroma and flavor intensity, limited astringency and variable umami perception, influenced by compounds such as linalool, trans- $\beta$ -ionone, hexanal and nonanal. Model robustness was evaluated by leave-one-out cross-validation, yielding a  $Q^2$  value of 0.30. Although moderate, this value is considered acceptable for chemical-sensory modeling involving small datasets and biological variability. Permutation testing (1000 permutations) further confirmed model validity, with the original  $Q^2$  exceeding the 99th

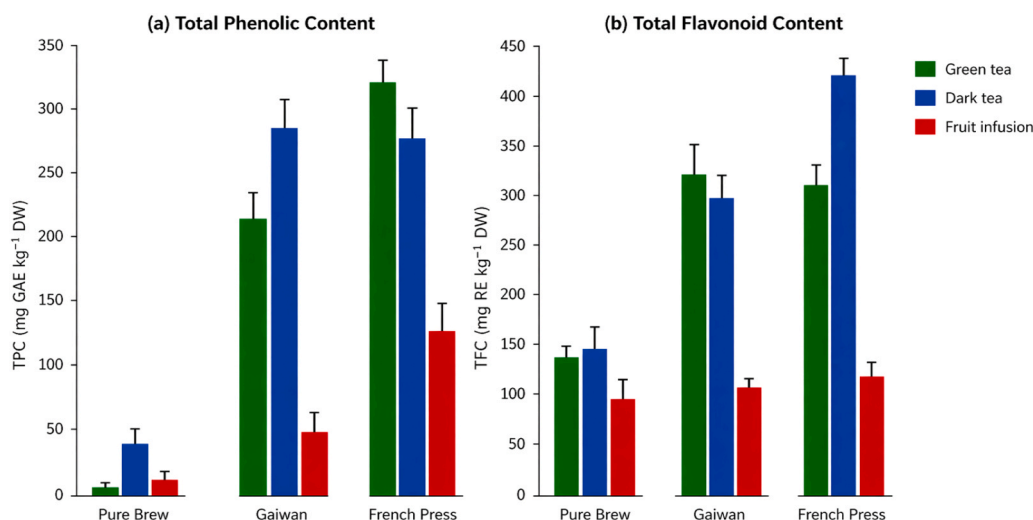
percentile of permuted models.

### 3.3.1. Relationship between phenolic composition and sensory attributes

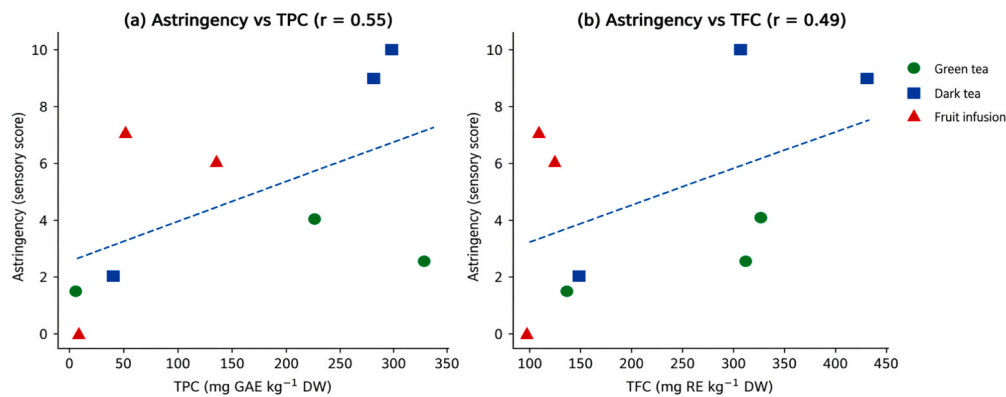
Integration of total phenolic content (TPC), total flavonoid content (TFC) and sensory data showed that extraction method strongly influenced both phenolic recovery and sensory perception (Fig. 4a and b). Higher TPC and TFC values observed for Gaiwan and French Press extractions were associated with increased perceived astringency, particularly in dark tea samples. Pure Brew samples, characterized by lower phenolic content, were consistently associated with smoother mouthfeel and reduced astringency. Positive correlations (Figs. 5a and 5b) were observed between astringency and both TPC ( $r = 0.55$ ,  $p = 0.12$ ) and TFC ( $r = 0.49$ ,  $p = 0.18$ ). Although not statistically significant, these trends are chemically and sensorially consistent. Aroma intensity, flavor intensity and sweetness did not show direct linear relationships with TPC or TFC, indicating that these attributes are primarily driven by volatile composition rather than by bulk phenolic content. Overall, sensory perception in tea and fruit-based beverages emerges from the interplay between volatile aroma compounds and non-volatile phenolic fractions, both of which are strongly modulated by extraction strategy.

## 4. Conclusions

This study provides an integrated chemical sensory assessment of how brewing strategy modulates flavor expression in tea and fruit infusion beverages. By combining HS-SPME-GC-MS volatile profiling, descriptive sensory analysis and multivariate modeling, the results clearly demonstrate that botanical matrix and oxidation degree represent the primary drivers of aroma fingerprint differentiation, while extraction method acts as a secondary but decisive factor in shaping sensory balance and perception. Across all matrices, brewing strategy selectively influenced the relative release of volatile compounds and the extraction of phenolic fractions, thereby modulating the balance between sweetness, aroma intensity and astringency. Pure Brew extraction promoted a higher contribution of ester- and terpene-derived volatiles, resulting in smoother sensory profiles characterized by enhanced sweetness and aromatic clarity, with limited astringency. In contrast, Gaiwan and French Press extractions favored the recovery of phenolic and flavonoid fractions, leading to more structured sensory profiles with increased astringency, particularly evident in dark tea samples. Multivariate analysis confirmed chemical drivers of sensory perception: ester- and furan-derived compounds were strongly associated with sweetness and fruity aroma, while aldehydes and phenolic-related compounds



**Fig. 4.** a) Total phenolic content (TPC) and (b) total flavonoid content (TFC) of green tea, dark tea and fruit infusion beverages prepared using different extraction methods (Pure Brew, Gaiwan and French Press). Data are expressed as mean  $\pm$  standard deviation ( $n = 4$ ).



**Fig. 5.** a) Relationship between perceived astringency and total phenolic content (TPC) and (b) total flavonoid content (TFC) across all samples. Scatter plots show individual samples grouped by botanical matrix, with dashed lines representing linear regression trends. Pearson correlation coefficients ( $r$ ) are reported for each relationship.

contributed to astringency and mouthfeel intensity. Overall, these findings highlight brewing strategy as an effective technological lever to fine-tune flavor expression in tea and botanical infusions, offering practical insights for beverage preparation, product development and sensory optimization.

#### CRediT authorship contribution statement

**Gianni Sagratini:** Project administration, Resources, Supervision. **Luca Boldrini:** Conceptualization, Formal analysis, Investigation, Methodology. **Luca Pittori:** Investigation, Methodology. **Agnese Santanotoglia:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Conceptualization. **Giovanni Caprioli:** Project administration, Supervision, Writing – review & editing.

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#### 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. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.jfca.2026.109214](https://doi.org/10.1016/j.jfca.2026.109214).

#### Data Availability

The authors are unable or have chosen not to specify which data has been used. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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