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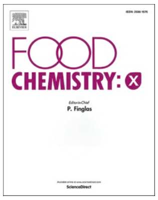

Sensory-directed flavor analysis of Jinggu white tea: Exploring the formation mechanisms of sweet and fruity aromas

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ABSTRACT

White tea is a naturally processed type of tea that has a unique favorable aroma. Typically, the aroma of white tea depends on its origin. Compared with Fujian white tea (FJ) and Yunnan other origin white tea (YO), Jinggu white tea (JG) has a stronger fruity and sweet aroma. In this study, to determine the factors underlying the unique fruity and sweet aroma of JG, we used YO and FJ as control samples and analysed the samples by using a molecular sensory science technique. Olfactory experiments and odor activity analysis revealed 10 key active substances to contribute to the aroma of JG. Aroma addition experiments further showed that linalool and benzeneacetaldehyde were the main contributors to the fruity and sweet aroma of JG, respectively. The results are helpful to understand the aroma of JG and provide a theoretical basis for the quality control of JG.

1. Introduction

White tea is a major type of tea in China. It was first discovered during the Song Dynasty, and it has a long history and an extensive production capacity (Cai et al., 2022; Li et al., 2023). Although the processing method for white tea is fairly simple, involving only withering and drying, the tea has a fresh, sweet, and mellow flavor and a fresh and floral aroma. It is favored by many consumers in China and other countries (Shi et al., 2023). In China, white tea is primarily produced in Fujian Province and Jinggu County in Yunnan Province. In recent years, with the expansion of the white tea market, Lincang City, Baoshan City, Xishuangbanna Dai Autonomous Prefecture, and other areas in Yunnan Province have started to produce white tea. Major differences can be observed in the aroma of white tea of different origins. For example, Jinggu white tea (JG) has a fruity and sweet aroma, Fujian white tea (FJ) has a fresh and floral aroma, and Yunnan other origin white tea (YO) has a sweet and fresh aroma. Jinggu Dabaicha (*Camellia sinensis* var. *assamica* cv. Jinggu Dabaicha) is a large-leaf tea tree found in Jinggu County, Yunnan Province, China. JG is typically manufactured from the young and tender buds and leaves of this tree after sunlight withering (25 °C–30 °C) and low-temperature drying (50 °C–60 °C). JG has a natural appearance. The backs of the leaves are covered by silver hairs, and the aroma of the tea is both clear and persistent, with a rich sweet and fruity component. The tea infusion has a bright honey-yellow colour, and its taste is sweet and delicate. The tea leaves can be brewed for a long time to sip.

Because consumption of white tea has increased, many studies have started to analyze its aroma. White tea is primarily has a fresh, floral, fruity, and sweet aroma, in addition to caramel-like and woody aroma (Feng et al., 2022). These aromas result from interactions between aroma substances at different concentrations (Guo et al., 2022). Multiple studies on the aroma of white tea have indicated the importance of FJ as an experimental raw material and have identified many aroma components that have a strong influence on white tea. Chen et al. (2023) discovered that hexanal was significantly and positively associated with the fresh aroma of white tea. In a study on white tea aging, Qi et al. (2018) reported a herbaceous aroma often emerging during the aging process of white tea that is related to 1,2-dimethoxybenzene and calamenene. Hao et al. (2023) discovered that dihydro-5-pentyl-2(3*H*)-furanone, (*E*)-6,10-dimethyl-5,9-undecadien-2-one, and 2-pentylfuran were the main components responsible for the milky flavor of white tea. Unlike traditional white tea, JG has a fruity and a sweet aroma. However, few studies have been reported on the fruity and sweet aroma of white tea, and little research has been done on the aroma components of

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JG.

Various techniques for extracting aroma compounds are widely used in the study of aroma components in tea, food and other natural products, such as headspace solid phase microextraction (HS-SPME), stir bar sorptive extraction (SBSE), and simultaneous distillation of extraction solvents to aid in the evaporation of flavours (Zhai et al., 2022). Among them, HS-SPME, as a solvent-free and low-cost extraction method, not only meets the requirements of green environmental protection, but also reduces the operating costs and the risk of environmental pollution, and has been widely used in the analysis of aroma compounds in recent years (Zhai et al., 2022). In addition, HS-SPME has high extraction efficiency and excellent reproducibility, especially in the analysis of tea samples (Huang et al., 2022; Zhang et al., 2023; Zheng et al., 2016). It was able to differentiate tea samples with significant differences in aromatic quality and extract the complex and unique aroma components of tea, providing a basis for further analysis of its aroma profile (Wu et al., 2016). Gas chromatography-mass spectrometry (GC–MS) and gas chromatography-olfactometry (GC-O) are common analytical techniques for aroma compounds after extraction. GC–MS, with its high chromatographic separation and detection accuracy, is capable of quantitatively analysing aroma components in complex samples, while GC-O mimics the olfactory perception of the human senses, providing the evaluator with reliable and sensory-relevant chemical information to help him or her understand the extent of the contribution of aromatic substances (Wei et al., 2024; Zhai et al., 2022).

In this study, we used molecular sensory science technology, i.e., sensory evaluation oriented, relying on highly selective, high-throughput, and high-sensitivity analytical detection methods, to qualitatively and quantitatively analyze and characterize the aroma of food products at the molecular level, and to screen and identify the key aroma contributing substances (Deng et al., 2022; Zhai et al., 2022). Specifically, (1) the aroma components of different white tea samples (including JG, FJ and YO) were comprehensively detected and analysed by HS-SPME combined with GC–MS and GC-O techniques. (2) The key aroma actives contributing to the fruity and sweet aroma of JG white tea were screened by odorant activity value (OAV) and aroma addition experiments. In conclusion, using this combination of advanced techniques, we successfully explained the molecular basis of the characteristic flavor produced by JG white tea, provided new insights into the association between sensory flavor and chemical composition, and provided a scientific basis for improving the flavor quality and marketing of white tea.

2. Materials and methods

2.1. Raw material sources and handling

The white tea samples collected in this study were all one bud and two leaves, they were sealed and stored at 4 °C. Subsequently, the samples were divided into three groups on the basis of their origin: Jinggu Dabai tea (JG), Yunnan other origin white tea (YO), and Fujian white tea (FJ). Table S1 presents additional information on the tea samples.

2.2. Chemicals and reagents

For additional details regarding the chemicals and reagents used in this study, please refer to Table S2.

2.3. Quantitative descriptive analysis of aroma of white tea with different origins

Twelve sensory reviewers were recruited for the study in reference to Zhang et al. (2024) trained in 100-fold dilution to identify common odor attributes in the aroma specimens. Five attribute words were preliminarily extracted by the panelists from the aroma descriptions of the white tea samples, and corresponding aroma standards were established with reference to these attribute words. These aroma standards were as follows: fresh (hexanal), herbal (1-octen-3-ol), floral (geraniol), sweet (benzeneacetaldehyde), and fruity (linalool). A modified quantitative descriptive analysis (QDA) was conducted to determine the differences between the aroma attributes of the three samples of white tea (Hou et al., 2020; Wei et al., 2024). We obtained ethical permission from our institution to conduct this human sensory study. Informed consent was collected, and panelists were informed they could withdraw at any time. All tea samples and chemical standards were confirmed safe for consumption.

Three grams of each tea sample were brewed in boiled deionized water for 5 min at a tea to water ratio of 1:50, and the tea infusions were filtered, transferred (20 mL) to a 50 mL brown sniffing flask, and maintained in a 40 °C water bath. The panelists were asked to score the aroma attributes of the tea infusions on a scale of 0 to 10 (indicating weak: 0–2; indicating relatively weak: 2–4; indicating moderate: 4–6; indicating relatively strong: 6–8; indicating strong: 8–10).

2.4. HS-SPME of aroma substances from tea infusions

Prepare the tea infusion according to the method in section 2.3. After the tea infusions were filtered using 400-mesh gauze in a conical flask, they were placed in an ice-water bath to rapidly cool them down to room temperature. Subsequently, 10 mL of each tea infusion was injected into a 20 mL headspace flask, and 5 μL of an internal standard and 3 g of NaCl were added to stimulate its aroma. The headspace flask was equilibrated in a magnetic stirring water bath at a constant temperature of 40 °C for 15 min, and an extraction needle was inserted into the flask and adsorbed over the liquid surface of the tea infusion at approximately 1 cm for 40 min, followed by GC–MS detection. This method was adopted from Huang et al. (2022).

To prepare an internal standard stock solution, 20 mg of ethyl decanoate was weighed in a 10 mL volumetric flask, and then added to anhydrous ethanol for volume fixing, sealed and stored it in a refrigerator at 4 °C, and was subsequently diluted to 10 ppm with deionized water in another 10 mL volumetric flask before the experiment.

2.5. Analysis of aroma components with GC–MS and GC-O

GC–MS was conducted using an Agilent 8890 A Gas Chromatograph and an Agilent 5977B Mass Spectrometer (Agilent, USA) connected to a HP-5MS capillary column (30 m × 0.25 mm × 0.25 μm) to separate and identify aroma substances. This method was adopted from Xiong et al. (2023) with some modifications. For additional details, please refer to Supplementary Table S3.

GC-O was conducted using a gas chromatograph equipped with an olfactory port (ODP4 Gerstel, Germany) by splitting the analytical column effluent at a ratio of 1:1 and directing it to the MS analyte and olfactory port to analyze the aroma of the substance. 8 sensory members participated in the GC-O assessment experiment, with the perception of aroma intensity (AI) expressed on a scale from 0 to 4 (0 = unperceivable odor, 1 = weak but perceivable odor, 2 = basically recognize odor, 3 = highly perceivable odor, and 4 = strongly and clear odor). The sniffing results were analysed to identify each aroma active substance, and odors sniffed by at least 5 panelists within the same time interval (time deviation <0.1 min) and with similar descriptions were selected.

2.6. Quantitative analysis of aroma and odorant activity value calculation

An internal standard method was used to calculate relative content. Ethyl decanoate was used at a known concentration as an internal standard. After the relative content of the target compounds was obtained from the peak area ratio, the relative odorant activity value (rOAV) was calculated using the threshold for each substance. These thresholds were obtained from various databases (Gemert, 2011) and from the Leibniz Institute for Food Systems Biology website (https://www.leibniz-lsb.de). Subsequently, based on AI ≥2 and rOAV ≥1, aroma active compounds that met the conditions were quantitatively analysed by external standardisation (Table S4) to improve the accuracy of subsequent aroma addition experiments. Because aroma active compounds with an OAV ≥1 are often regarded as potential odorants with characteristic aromas (Liao et al., 2020), we focused on analysis of the type and contribution of aroma active substances with an OAV ≥1.

2.7. *Aroma addition experiment*

An aroma addition experiment was conducted to identify the specific substances responsible for the sweet and fruity aroma of JG. The minimum concentrations of additives were determined from the concentrations of the aroma active substances in YO, FJ, and JG infusions. The quality of the aroma actives in YO and FJ infusions was brought into line with that in JG infusions by adding lower amounts to YO and FJ infusions than the equivalents in JG infusions. The YO and FJ tea infusion after the addition of aroma actives are named YO-A and FJ-A. Both the aroma-enhanced group (YO-A and FJ-A) and the control group (JG

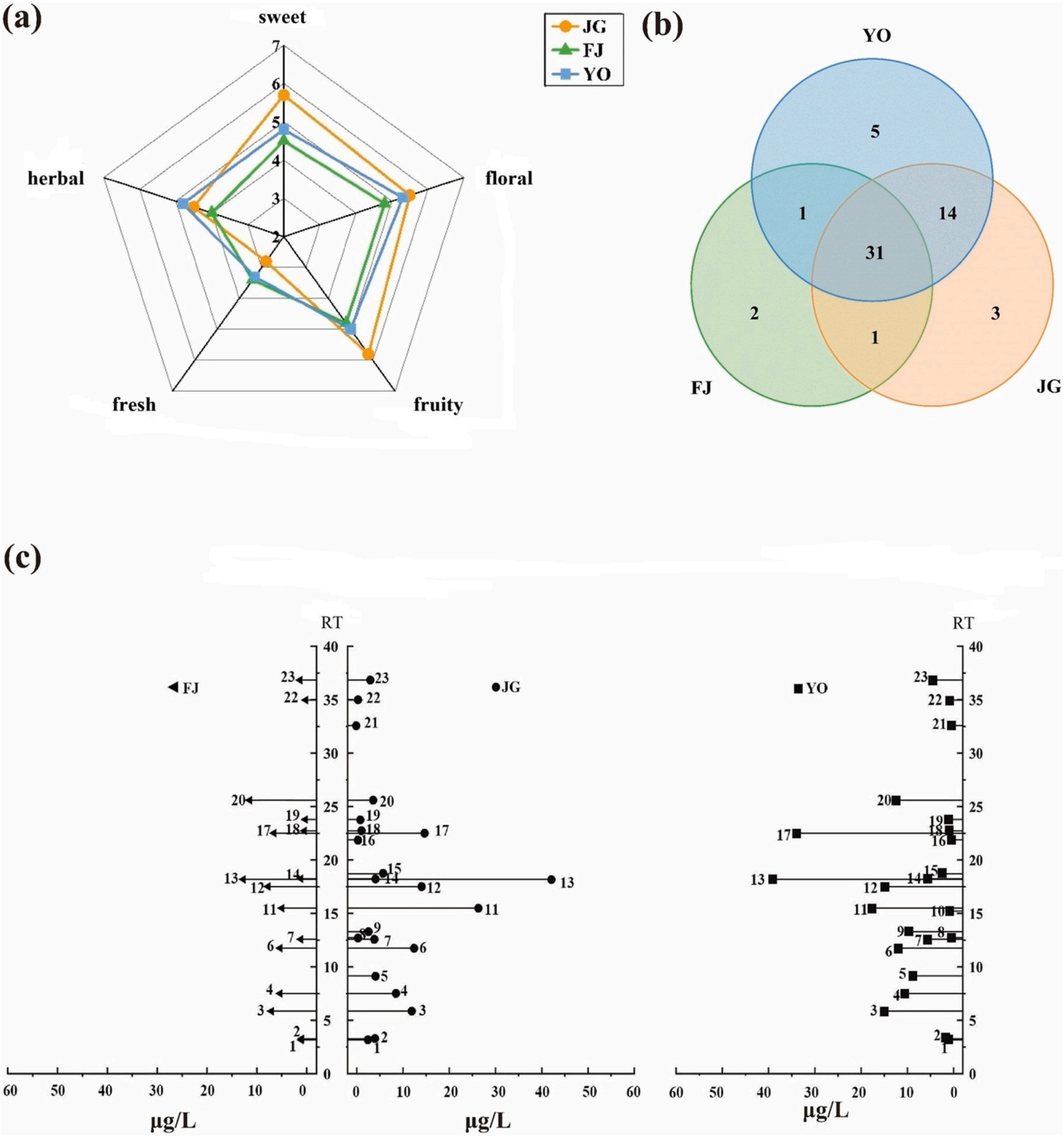

Fig. 1. Analysis of aroma composition of white tea from different origins. (a) Sensory-based olfactory radar charts of aroma profiles of white tea from different origins (JG: orange solid line; YO: blue solid line; FJ: green solid line). (b) Wayne diagram of the aroma compounds of white tea from different origins. (c) Chromatograms obtained for the content of aroma compounds that were sniffed in the JG, YO and FJ infusions of GC-O on a HP-5MS column, with serial numbers of the compounds derived from Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

infusion) were placed in 50 mL covered sniffing flasks and maintained in a 40 °C water bath. All tea infusions were prepared as outlined in Section 2.3. After a QDA was conducted on the samples in the water bath, values of 0–10 were used to indicate the odor intensity of each aroma substance. The same degree of specificity of the 0–10 was used as that indicated in Section 2.3. Key odorants were identified using the method proposed by Yang et al. (2019). Twelve trained panelists assessed the difference in aroma in each tea infusion using a triangular test and determined significance based on the number of correct answers. If 8 panelists answered correctly (α ≤0.05), 9 panelists answered correctly (α ≤0.01), and 10 and more panelists answered correctly. (α ≤0.001).

2.8. *Data processing and statistical analysis*

Partial least squares discriminant analysis was conducted using SIMCA-P software version 14.1 (Umetrics, Umea, Sweden). One-way analysis of variance was conducted using IBM SPSS Statistics version 26.0 (IBM, Armonk, NY, USA), with *p* values of ≤0.05 indicating significant differences and *p* values of ≤0.01 indicating highly significant differences. All images were visualized using Origin 2023b. All tests were conducted three times, with the final results expressed as mean values.

3. Results and discussion

3.1. *Analysis of aroma characteristics and total aroma components of white tea from different origins*

In this study, five odors, namely sweet, floral, fruity, fresh, and herbal, were screened by a sensory panel, and a QDA was conducted to analyze various tea infusions. As presented in Fig. 1(a), FJ had the lowest overall aroma intensity of all the samples, while JG had the strongest overall aroma intensity; it had the most pronounced sweet and fruity aroma, and these odor attributes are referred to as JG aroma. Although YO has a stronger herbal and fresh aroma than JG, its floral intensity is similar to that of JG. In order to better explain the reasons for the differences in the aroma profiles of white teas from different origins, and to explore the molecular mechanisms underlying the intensity of the sweet and fruity aroma of JG white tea, we subsequently analysed the overall aroma components of white tea using HS-SPME and GC–MS.

As shown in Table S5, a total of 56 aroma compounds were identified in JG, YO, and FJ, namely 15 alcohols, 17 aldehydes, 13 ketones, 6 olefins, and 5 other aroma compounds. Among them, alcohols and aldehydes aroma compounds served as the major compound species in the samples. Their total content accounted for 45.24 %, 41.22 %, 46.07 % and 33.54 %, 33.31 %, 30.34 % of the total content in FJ, JG and YO samples, respectively. According to Hong et al. (2023), the majority of alcohols and aldehydes in tea infusions have a pleasant floral and fruity aroma. At the quantitative level, linalool was the most abundant aroma compound in the range of 12.75–42.13 μg/L, with the highest value of 42.13 μg/L for JG. Interestingly, linalool was accurately identified as an important aroma-active compound, with fruity and floral aromas, which are likewise important in famous green teas as well (Zhang et al., 2023). As shown in Fig. 1(b), common aroma substances were identified in all three types of white tea, with only a small quantity of unique aroma substances identified. For example, *cis*-dehydroxylinalool oxide was uniquely identified in JG; heptanal was uniquely identified in FJ; and 2-ethylfuran, 2-hexenal, α-terpinene, and 3-octen-2-one were uniquely identified in YO. This suggests that the reason for differences in aroma profiles between samples may be determined by different concentrations of the same compounds in different samples.

3.2. *Identification of aroma active compounds in white tea from different origins*

In general, not all compounds are perceivable by the human olfactory system. Therefore, in order to determine the major components of white tea aroma, we then systematically investigated the odor properties of the aroma compounds in JG, YO and FJ and the intensity of perception of these odors by the human olfactory system.

GC-O is an effective technique for identifying and screening aroma active compounds in complex and mixed systems (Wu et al., 2022; Zhai et al., 2022), and it provides an efficient method for evaluators to determine the type and intensity of each aroma active substance. As shown in Table 1, a total of 23 aroma active compounds were identified, but the number of aroma active compounds varied among FJ, JG and YO, which were 16, 22 and 23, respectively. All the identified aroma active compounds were mainly alcohols and aldehydes. Most of these odors were from carotenoids, lipids, glycosides and Maillard reaction (Ho et al., 2015). The average aroma content and aroma intensity of these compounds are shown in Fig. 1(c) and Table 1.

Among the compounds identified in JG, benzeneacetaldehyde (AI = 4.0) had the highest aroma intensity, which had honey aroma attributes, followed by linalool (AI = 3.9) with citrus and lily-of-the-valley aroma and trans-*β*-Ionone (AI = 2.8) with violet aroma (Yan et al., 2024). These compounds greatly enriched the fruity, sweet and floral aroma of JG, in addition to other compounds like phenylethyl alcohol (AI = 2.7), geraniol (AI = 2.6), *β*-damascenone (AI = 2.5), nonanal (AI = 2.3), 2-methyl-butanal (AI = 2.0), 3-methyl-butanal (AI = 2.0) and other aroma active compounds with AI ≥2 on the overall aroma profile of JG tea should not be ignored. Among the YO, trans-*β*-Ionone (AI = 2.8) had the highest aroma intensity followed by geraniol (AI = 3.2), linalool (AI = 2.9) and hexanal (AI = 2.9) with a fresh odor. In FJ, on the other hand, hexanal (AI = 3.5), geraniol (AI = 3.2) and linalool (AI = 2.6) were

Table 1
GC-O of aroma active substances in white tea of different origins.

No.	RT [a]	Compounds	AI [c]			Odor [d]
			FJ	JG	YO	
Compounds with fruity aroma						
6	11.76	Benzaldehyde	0.9	1.3	1.3	fruity, almond-like
13	18.19	Linalool	2.6	3.9	2.9	citrus-like, floral
14	18.26	Nonanal	1.3	2.3	1.3	citrus-like
19	23.80	*β*-Cyclocitral	0.9	1.0	1.1	fruity
21	32.58	*β*-Damascenone	nd	2.5	2.0	fruity, cooked-apple-like
Compounds with floral aroma						
12	17.52	(*E*)-linalool oxide (furanoid)	1.6	2.1	2.5	floral
20	25.60	Geraniol	3.2	2.6	3.2	rose-like
22	34.97	α-Ionone	0.6	1.3	1.8	floral
23	36.84	trans-*β*-Ionone	2.3	2.8	3.3	floral
Compounds with fresh aroma						
3	5.85	Hexanal	3.5	1.9	2.9	green, grassy
4	7.51	(*E*)-2-hexenal	0.5	1.5	1.6	green
17	22.52	Methyl salicylate	1.3	1.6	2.5	mint-like
Compounds with herbal aroma						
7	12.58	1-Octen-3-ol	1.4	2.0	2.3	mushroom-like
8	12.73	2,3-Octanedione	nd	0.4	0.6	herbal
18	22.73	Safranal	0.5	1.8	1.9	herbal
Compounds with sweet aroma						
1	3.16	3-methyl-Butanal	1.5	2.0	1.5	sweet
2	3.27	2-methyl-Butanal	1.8	2.0	1.9	sweet
5	9.16	2-Heptanol	nd	1.0	1.0	sweet
11	15.49	Benzeneacetaldehyde	2.3	4.0	2.5	honey-like
15	18.72	Phenylethyl Alcohol	nd	2.7	1.9	honey-like
Compounds with others aroma						
9	13.29	(*E, E*)-2,4-Heptadienal	nd	1.0	1.0	fatty
10	15.23	3-Octen-2-one	nd	nd	1.1	fatty
16	21.90	Naphthalene	nd	0.4	0.6	mothball-like

Note: [a] Retention time (RT), time for the compound to be detected in the HP-5MS capillary column. [b] Mean values of triplicates. White tea of different origins was used, including FJ, YO, and JG. Fujian white tea (FJ), Yunnan white tea (YO), Jinggu Dabai Tea (JG). Nd, not detected. [c] Odor description of each aroma-active compound detected at the olfactory detection port.

mainly perceived by all the panelists as having relatively high aroma intensity. It can be seen that the types of aroma active compounds in white tea are relatively similar, and it is because of the differences in their aroma intensities that different types of white tea exhibit different aroma profiles.

White tea is typically characterized by a floral, sweet, and fresh aroma (Hu et al., 2022; Ni et al., 2020). According to Wu et al. (2022), substances with high concentrations are key contributors to the aroma of tea. Based on the GC-O results, it was found that the highest proportion of aroma active compounds presenting fruity aroma was found in JG, which accounted for 37.29 % of the total content, followed by the aroma active compounds producing the sweet aroma of JG (26.53 %). Meanwhile, the fruity aroma in JG was higher than the total amount of aromatics in the corresponding attributes of FJ and YO by 497.32 % and 34.57 %, and that of sweet compounds was higher than that of FJ and YO by 204.03 % and 10.55 %, respectively. This may be the reason why the fruity and sweet aromas of JG were the most pronounced. Overall, YO primarily had a fruity and fresh aroma, and FJ primarily had a fresh and floral aroma. Although the YO aroma has the highest percentage of fruity notes (29.30 %) and the fresh aroma comes second (26.40 %), the YO aroma still expresses itself as fresh, which is most likely related to the lower aroma threshold of the fresh substance. In contrast, the percentage of clear aroma in FJ ranked first (35.27 %), but the percentages of floral (28.12 %) and fruity (25.30 %) were also higher, which presumably explains its clear, rich, and harmonized overall aroma. In general, the intensity of an aroma is dependent on various content and threshold related factors, with aroma compounds with a high content and low threshold having a strong characteristic aroma. As listed in Table 1, the aromas detected in the three types of white tea were primarily attributable to hexanal, benzeneacetaldehyde, linalool, geraniol, trans-β-Ionone and other substances. These substances are typically responsible for the aroma of white tea and have a significant effect on the aroma (Wu et al., 2022).

3.3. Calculation of OAV of aroma active compounds in white tea of different origins

In order to determine the contribution of aroma active compounds to the overall aroma of tea, we analysed the aroma compounds of JG, YO and FJ based on the results of olfactometry (AI $\geq$2) and external standard quantification, and a total of 10 key aroma active compounds were screened: 3-methyl-butanal, 2-methyl-butanal, hexanal, 1-octen-3-ol, benzeneacetaldehyde, linalool, nonanal, geraniol, β-damascenone, and trans-β-ionone. Their contents were visualized by bar charts (Fig. 2). According to the values in Table 2, it was found that there were differences between the OAV values of white teas from different origins. Among them, the OAV of sweet aroma compounds of JG was 95.33 % higher than that of YO and 231.49 % higher than that of FJ, respectively. Similarly, the OAV of the aroma active compounds responsible for the fruity aroma of JG was 9.77 % higher than that of YO and 298.26 % higher than that of FJ. Overall, the OAV results were consistent with the QDA results shown in Fig. 1(a), confirming the concentrations of the aroma-active compounds identified in JG and YO, and their measured concentrations were reliable. Because high OAVs play a key role in aroma, the different concentrations of sweet, floral, and fruity compounds in JG, YO, and FJ were the main reason underlying the differences observed between their aromas (Table 2). For example, benzeneacetaldehyde, which has a sweet aroma, and linalool, which has a fruity aroma, had significantly higher OAVs in JG than in YO and FJ. Therefore, we hypothesised that benzeneacetaldehyde and linalool were the most important aromatics responsible for the differences in sweet

Table 2
Key aroma active substances responsible for the aroma of white tea.

Aroma-active compounds	OT (μg/L) [a]	OAV [b]			Identification basise [c]
		FJ	JG	YO	
3-methyl-Butanal	0.5	2.18	4.76	2.08	MS, RI, O, Std
2-methyl-Butanal	1	1.02	3.98	1.59	MS, RI, O, Std
Hexanal	2.4	4.22	0.74	1.68	MS, RI, O, Std
1-Octen-3-ol	1.5	0.79	2.71	3.48	MS, RI, O, Std
Benzeneacetaldehyde	5.2	0.96	5.05	3.39	MS, RI, O, Std
Linalool	0.22	57.95	191.50	177.68	MS, RI, O, Std
Nonanal	1.1	1.09	3.63	1.53	MS, RI, O, Std
Geraniol	1.1	11.06	6.07	11.22	MS, RI, O, Std
β-Damascenone	0.006	nd	40.00	35.00	MS, RI, O, Std
trans-β-Ionone	0.021	76.19	160.95	211.90	MS, RI, O, Std

Note: [a] Threshold of aroma-active substances in water. [b] White tea from different origins was used, including Fujian white tea (FJ), Yunnan white tea (YO), Jinggu Dabai Tea (JG). Nd, Mean not detected. [c] Classification of aroma substances based on actual sniffing and documentation. [c] Methods of identification: MS, odorants were identified by mass spectra; RI, retention indices; O, olfactometry; and Std, reference compounds.

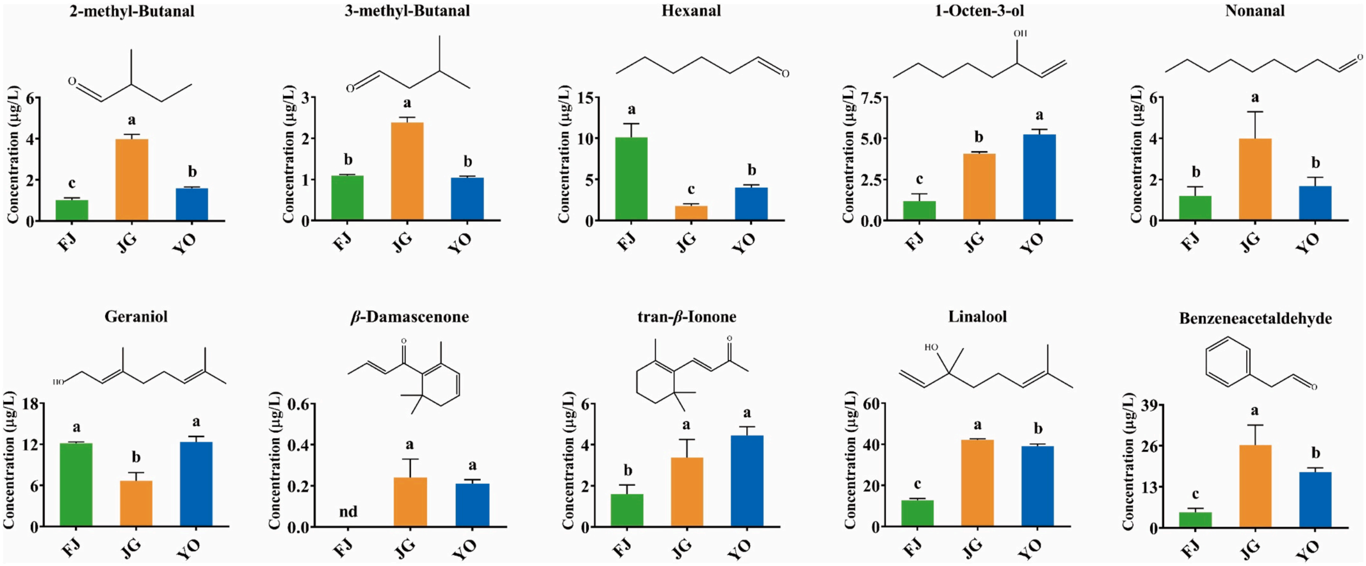

Fig. 2. Concentrations of key aroma active compounds in white teas of different origins (Different letters indicate significant differences at the 0.05 level; nd indicates not detected in the samples).

and fruity aromas of JG, YO and FJ, and for the strong sweet and fruity aromas of JG.

3.4. Aroma addition experiment of key aroma active substances of JG

Aroma addition experiments can be used to verify the characterization of aroma-active compounds (Zhai & Granvogl, 2019). Further screening of aroma active compounds that contribute most to the sweet and fruity aroma of JG. In this study, we used JG as a control, and added FJ and YO infusions separately according to the difference in substance concentrations in Table 2 so that they eventually reached the OAV concentration in JG infusions. Fig. 3 presents the effect of our aroma addition experiment. The results indicated that the addition of sweet, floral, fruity, and herbal aroma-active substances to the FJ infusion at equidistant values from JG caused the overall aroma of FJ to be similar to that of JG, which considerably increased its fruity and sweet aroma and reduced its fresh aroma. Similarly, the addition of aroma-active substances to the YO infusion at equidistant values from JG caused the overall aroma of YO to be similar to that of JG, which effectively reduced the fresh aroma of YO but did not significantly affect its herbal aroma.

A total of 12 trained panelists participated in an aroma addition triangle experiment. During the experiment, they reported perceiving strong linalool and benzeneacetaldehyde aromas (Table 3). All panelists reported perceiving the addition of linalool because of its strong fruity aroma and intermediate floral aroma. Lin et al. (2024) and Feng et al. (2022) have reported that the addition of a high concentration of linalool increased both the fruity and the floral aroma of white tea; this finding is consistent with the results of our aroma addition experiment. After benzeneacetaldehyde was added, 11 and 10 panelists reported perceiving an enhanced aroma in FJ-A and YO-A, respectively, and an increase in the sweet aroma of white tea. They also reported that nonanal, β-damascenone, and trans-β-Ionone had a major effect on the aroma of white tea, primarily enhancing its fruity, sweet and floral aroma. Taken together, these findings indicate that linalool and benzeneacetaldehyde are the key odor factors responsible for the fruity and sweet aroma, respectively, of JG.

3.5. Mechanism underlying fruity and sweet aroma of JG

Linalool is the main active component responsible for the fruity aroma of JG; it is produced through hydrolysis of glycosidic substances. During the processing of white tea, withering is the longest and most crucial process. During withering, linalool glycosides are hydrolyzed by glucoside hydrolase to form free linalool, which has a distinctive fruity aroma (Dai et al., 2017; Wang et al., 2000). Sunlight withering is often adopted in the manufacture of JG, with such withering occurring at temperatures ranging between 20 °C and 30 °C. Sunlight withering increases the concentration of linalool in white tea (Wu et al., 2022). It is also used to enhance the fruity and floral aroma of black tea during the withering process (Wu et al., 2023). Zeng et al. (2021) reported a significant positive correlation between the concentration of linalool and the area of tea leaves, with larger leaves containing higher concentrations of linalool. In this study, JG and YO were obtained from large-leafed trees. However, the leaves of JG were larger than those of FJ, indicating that JG had a larger concentration of linalool. In addition, JG underwent sunlight withering, whereas FJ and YO were predominantly withered in withering tanks, which may explain the higher conversion rate of linalool in JG. These two factors likely increased the concentration of linalool in JG, thereby enhancing its fruity flavor.

Benzeneacetaldehyde, the second most abundant component in JG, is the main compound responsible for the sweet aroma of JG. It is produced by the degradation of phenylalanine at Strecker's degradation (Ho et al., 2015). This process typically requires temperatures, particularly during tea leaf drying (Ho et al., 2015). Strecker's degradation reactions also require high humidity (Dong et al., 2023). At suitable temperatures or humidity, white tea leaves undergo extensive withering, and incomplete drying of the leaves results in a minor degree of fermentation, which gives white tea a sweet and sour aroma or a winey aroma. In this study, these aromas were clearly perceived in JG, which

Table 3
Results of key aroma compounds tested in aroma addition experiments.

Key aroma-active compounds [a]	Number of correct judgments [b]		Description of odor difference
	FJ-A	YO-A	
Linalool	12***	12***	Increase fruity and floral
trans-β-Ionone	11***	–	Increase floral
Benzeneacetaldehyde	11***	10***	Increase sweet
Nonanal	8*	8*	Increase fruity
β-Damascenone	8*	3	Increase fruity and sweet
3-methyl-Butanal	7	7	
2-methyl-Butanal	6	5	
1-Octen-3-ol	4	–	

Note: [a] Key aroma active compounds with OAVs ≥1 in FJ-A and YO-A. [b] Number of correct judgments from 12 panelists in the triangle test. "*" = significant (α <0.05); "**" = highly significant (α <0.01); "***" = extremely highly significant (α <0.001). "-" The concentration of the compound is higher than the concentration of the compound in the corresponding JG. FJ-A, Fujian White Tea Aroma Addition Sample. YO-A, Sample of White Tea Aroma Addition from Other Origins in Yunnan Province.

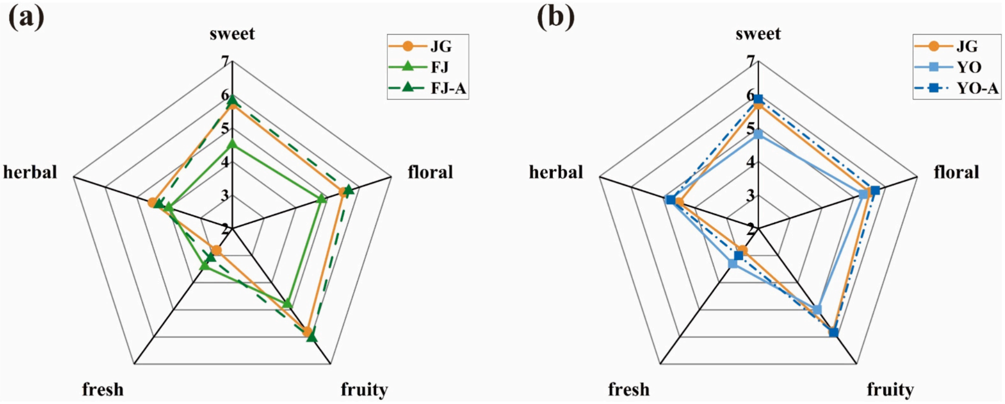

Fig. 3. Aroma addition experiment QDA radar chart. (a) Jinggu white tea (JG: orange solid line), Fujian tea (FJ: green solid line) and Fujian tea aroma-added samples (FJ-A: dark green dashed line) (b) Jinggu white tea (JG: orange solid line), white tea from other Yunnan origins (YO: blue solid line) and white tea aroma-added samples from other Yunnan origins (YO-A: dark blue dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

could be attributed to the fact that the sunlight treatment and low-temperature drying induced a slight degree of fermentation of the tea leaves, leading to enhanced Strecker degradation reaction in JG, which promoted the production of degradation products (e.g., benzeneacetaldehyde), thereby enhancing the sweet aroma attribute of JG.

In summary, the raw materials of JG play a key role in its aroma. Processing JG through either sunlight withering or low-temperature drying promotes glucoside hydrolysis and Strecker's degradation. These processes increase the concentrations of linalool and benzeneacetaldehyde, which are responsible for the favorable fruity and sweet aroma of JG.

4. Conclusion

In this study, GC–MS and GC-O were used in combination with sensory analysis to identify key odorants in JG, including 3-methyl-butanal, 2-methyl-butanal, hexanal, 1-octen-3-ol, benzeneacetaldehyde, linalool, nonanal, geraniol, *β*-damascenone, and trans-*β*-ionone. An aroma addition experiment was conducted to identify the key components responsible for the fruity and sweet aroma of JG, namely linalool and benzeneacetaldehyde. Mechanistic analysis of the formation of these key odorants indicated that sunlight withering during white tea processing presumably promoted hydrolysis of glycosides and enhanced Strecker's degradation of free amino acids. Overall, this study provided valuable insights into the aromatic profile of JG through chemical experiments and sensory analyses. We screened and validated the main aroma active compounds that form the aroma of JG, which provides a theoretical basis for a deeper understanding of the aroma quality of JG and helps to quality control the characteristic aroma of JG.

CRediT authorship contribution statement

Junlan Huang: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Jixin Zhang:** Writing – original draft, Software, Methodology, Formal analysis. **Zhenbin Chen:** Resources, Methodology, Investigation, Data curation. **Zhichao Xiong:** Investigation, Data curation. **Wanzhen Feng:** Investigation, Data curation. **Yuming Wei:** Visualization, Supervision, Investigation. **Tiehan Li:** Visualization, Supervision, Investigation. **Jingming Ning:** Resources, Project administration, Funding acquisition.

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.fochx.2024.102026.

Data availability

Data will be made available on request.

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