Beverage Plant Research

ARTICLE

Open Access

https://doi.org/10.48130/bpr-0026-0052

Beverage Plant Research **2026**, 6: e039

Dynamic changes of volatiles and key odorants underlying the tender chestnut aroma of Shangnan Xianming green tea during manufacturing

Zhongqi Tang[1], Dan Chen[1], Rong Zhang[1], Jiamin Nan[1], Jun Tian[2], Bo He[3], Lihui Wang[1], Yugang Qi[1], Chunhui Wang[1], Ziyi Li[1], Yunfei Dong[1], Danning Liu[1], Jun Zhang[3], Youben Yu[1] and Tianshan Zhou[1*]

[1] *College of Horticulture, Northwest A & F University, Yangling, Shaanxi 712100, China*
[2] *Shangnan County Tea Joint Company, Shangnan, Shaanxi 726300, China*
[3] *Key Laboratory of Se-enriched Products Development and Quality Control, Ministry of Agriculture and Rural Affairs, Ankang, Shaanxi 725000, China*
* Correspondence: zhoutianshan@nwsuaf.edu.cn (Zhou T)

Abstract

Shangnan Xianming (SNXM) is a typical high-quality green tea characterized by a pleasant 'tender chestnut-like' aroma. However, the dynamic changes of volatile compounds during its manufacturing process and the key odorants responsible for this specific aroma profile remain poorly understood. Here, gas chromatography-ion mobility spectrometry (GC-IMS) and gas chromatography-mass spectrometry (GC-MS) combined with chemometric analysis were employed to track the changes in volatile components during processing. In total, 59 and 86 volatile compounds were identified via GC-IMS and GC-MS, respectively. The total content of volatile compounds exhibited a variation trend of initial increase, subsequent decrease, and final rebound during processing, with alcohols, aldehydes, and esters serving as the dominant volatile components. Partial least squares discriminant analysis (PLS-DA) demonstrated that spreading, fixation, and drying were the three pivotal stages regulating the transformation of aroma components. Gas chromatography-olfactometry (GC-O) analysis identified 19 aroma-active compounds in the finished tea, with aroma intensity values ranging from 1.17 to 3.67. Furthermore, combined absolute quantification and odor activity value (OAV) analysis confirmed ten key odorants with OAV values greater than 1, including linalool, (*E*)-*β*-ionone, nonanal, hexanal, 1-octen-3-ol, geraniol, heptanal, phenylethyl alcohol, indole, and (*E*)-2-nonenal, among which linalool and (*E*)-*β*-ionone exhibited the highest OAVs at 518.25 and 215.40, respectively. These findings reveal the critical processing stages and key odorants responsible for SNXM aroma formation and provide a theoretical basis for quality evaluation and targeted processing of tender chestnut-like green teas.

Keywords: Shangnan Xianming green tea, Tender chestnut-like aroma, Volatile compound dynamics during processing, GC-MS, GC-O, OAV

Citation: Tang Z, Chen D, Zhang R, Nan J, Tian J, et al. 2026. Dynamic changes of volatiles and key odorants underlying the tender chestnut aroma of Shangnan Xianming green tea during manufacturing. *Beverage Plant Research* 6: e039 https://doi.org/10.48130/bpr-0026-0052

Introduction

Tea, one of the world's three major non-alcoholic beverages, is highly prized by consumers for its unique flavor and health benefits. Based on processing methods and quality characteristics, tea is classified into six categories: green, yellow, dark, oolong, white, and black tea[1,2]. Among these, green tea, typically manufactured from *Camellia sinensis* via fixation, shaping (including rolling), and drying, dominates both production and consumption in China[3,4]. Green tea can be further subdivided into pan-fired green tea, roasted green tea, sun-dried green tea, steamed green tea, broken green tea, and matcha tea[5]. These distinct processing methods yield unique sensory profiles: pan-fired green teas are characterized by a chestnut-like aroma[4]; roasted green teas possess a high, clean floral scent[6]; steamed green teas retain a grassy and fresh character[4,7]; and sun-dried green teas develop a unique "sun-dried" note[8].

Aroma is a critical determinant of tea quality and consumer preference[9]. Currently, hundreds of volatile compounds have been identified in tea, primarily including alcohols, aldehydes, esters, ketones, and terpenes[10]. These compounds originate not only from pre-existing volatile compounds in fresh leaves but are also largely generated during processing via the conversion of precursors such as glycosides, amino acids, fatty acids, and carotenoids[11,12]. Specific processing techniques drive the formation of distinct aroma profiles—such as chestnut-like, fresh, floral, tender, and tippy flavors—through the combination and concentration of these volatile compounds[13–16]. The chemical basis of these profiles varies: floral green teas are defined by linalool, geraniol, nerolidol, and (*E*)-*β*-ionone[17], whereas chestnut-like green teas are characterized by heptanal, benzaldehyde, nonanal, 2-pentylfuran, and (*E*,*E*)-3,5-octadien-2-one[17,18]. Additionally, linalool, geraniol, decanal, nonanal, (*Z*)-3-hexenyl hexanoate, 1-octen-3-ol, and methyl salicylate were identified as the characteristic contributors to the fresh or clean aroma of green tea[19–21], while the tender aroma of green tea showed a significant positive correlation with the contents of compounds such as styrene, hexadecane, and 3-methoxy-1,2-propanediol[22]. It is noteworthy that many premium green teas exhibit complex aroma characteristics, such as a tender chestnut-like aroma.

Based on subtle sensory differences, the chestnut-like aroma can be further subdivided into three sub-types: tender, pure, and cooked chestnut-like aromas[23]. Although they share the same general chestnut-like profile, previous studies utilizing GC-MS coupled with multivariate statistical analysis have revealed that each sub-type possesses a unique set of characteristic markers (e.g., jasmone and geraniol for the tender type; octanal and (*E*)-9-methyl-2-undecenal for the pure type; and (*Z*,*Z*)-3-hexenyl (*Z*)-3-hexenoate, (*Z*)-3-hexenyl pentanoate, and

© The Author(s)

https://doi.org/10.48130/bpr-0026-0052

2-(3-methylbutyl)-3,5-dimethylpyrazine for the cooked type)[24]. Furthermore, odor activity value (OAV) analysis has confirmed variations in the concentrations of key aroma compounds (OAV > 1) among these sub-types[25]. The pure chestnut-like aroma, a species-specific nutty note, typically appears in high-grade green teas processed with precise firing (i.e., drying temperature and time), whereas the cooked chestnut-like aroma forms under high-fire conditions, representing a transition from chestnut-like to high-fired notes[24]. It has been well documented that adjusting drying temperatures (90 to 160 °C) and durations (5 to 45 min) causes a dynamic aroma evolution, transitioning progressively from clean to chestnut-like, cooked chestnut-like (or roasted bean-like), and finally high-fired notes[26,27]. Critically, deeper firing enhances the extent of thermochemical reactions—including the thermal cleavage of fatty acids, esterification of alcohols and acids, cyclization and isomerization of terpenes, and Maillard reactions—thereby driving the transformation from the pure type towards the cooked sub-type[26,27]. In contrast, the tender chestnut-like aroma is typically found in premium green teas made from tender, finely processed fresh leaves, retaining a soft, fresh, and elegant note beyond the basic chestnut-like flavor[24]. To date, however, the key contributors responsible for the characteristic aroma quality of tender chestnut-like green tea have not yet been systematically identified, and the dynamic transformation mechanisms of their precursors during processing remain largely unexplored.

Shangnan Xianming (SNXM) green tea is produced in Shangnan County, located at 33° N, on the northern edge of China's Jiangbei Tea Region. Despite the challenging ecological environment limiting yield, it boasts exceptional quality described as 'green infusion, high aroma, rich taste, and sweet aftertaste', making it a representative premium green tea from southern Shaanxi. The processing of SNXM consists of four steps: spreading, pan-firing, shaping, and drying. Unlike pan-fired green tea, which typically undergoes single-stage drum drying, and baked green tea, which is dried solely by hot-air convection, the drying of SNXM is accomplished through a combined approach integrated into both the shaping and drying stages. Specifically, heat conduction from a trough pan is first applied to partially dehydrate the leaves while simultaneously shaping them into a straight and slightly flattened form; subsequently, hot-air convection is employed to complete the drying process. In general, pan-fired green tea dried by drum heat conduction exhibits a pronounced roasted aroma (e.g., chestnut-like notes), whereas baked green tea dried by hot-air convection tends to present a pure and fresh aroma[28]. Consequently, this hybrid 'pan-firing combined with baking' drying strategy, coupled with its tender fresh leaf materials, contributes to the development of the characteristic 'high and lasting tender chestnut-like aroma' of SNXM. However, the dynamic evolution of volatile compounds during its processing remains unclear; the key influencing stages remain unidentified, and the key odorants responsible for the tender chestnut-like aroma have not been systematically characterized. This lack of fundamental data limits the potential for targeted quality control of SNXM.

Advances in analytical techniques provide robust tools for flavor research[19]. GC-IMS offers high sensitivity, operational simplicity, intuitive visualization, and is solvent-free, showing great potential for rapid volatile screening[29,30]. GC-MS remains the gold standard for the separation, identification, and quantification of volatile compounds[31,32]. Furthermore, GC-O integrates human sensory perception with chemical separation to detect key aroma-active compounds. Recently, the combination of these multi-platform techniques has become a prevailing trend in food flavor research. For instance, Duan et al.[33] characterized aroma dynamics during the baking of Wuyi rock tea using GC-IMS and GC × GC-O-MS; Lin et al.[34] differentiated aroma profiles among green, oolong, and black teas using GC-IMS and GC × GC-O-MS; and Zhu et al.[18] identified key odorants in chestnut-like green tea via GC × GC-TOFMS and GC-O.

Therefore, this study employed GC-IMS, GC-MS, and GC-O techniques alongside chemometric analysis and OAV calculations to achieve the following objectives:

(1) To analyze the dynamic evolution of volatile compounds throughout the entire manufacturing process of SNXM green tea using GC-IMS and GC-MS;

(2) To screen for key compounds responsible for the tender chestnut-like aroma through GC-O sensory sniffing combined with OAV-based quantification;

(3) To identify the critical processing steps that regulate aroma quality based on multivariate statistical analysis, and to elucidate the underlying metabolic mechanisms of aroma precursors.

This work is expected to lay a theoretical foundation for the targeted processing and quality-oriented control of premium green tea.

Materials and methods

Processing of SNXM green tea

Fresh tea leaves of 'Longjing 43' were harvested on March 28, 2025, from the tea plantation of Shangnan Tea Joint Company (33°28′53.58″ N, 110°56 ′10.63″ E, Shangnan County, Shaanxi Province, China). The plucking standard was one bud with one or two newly unfolded leaves. The fresh leaves were processed into SNXM green tea using an industrial production line consisting of four sequential stages: spreading, fixation, shaping, and drying (Fig. 1). Samples were collected immediately after each processing stage and designated as Fresh Leaves (FL), Spreading Leaves (SPL), Fixation Leaves (PL), Shaping Leaves (SHL), and Drying Leaves (DL, representing the finished tea). To fully reflect batch-to-batch variability in industrial-scale production, samples were collected from three independent processing batches. Within each batch, samples from each processing stage were obtained using a five-point sampling method and pooled into a single representative sample. Thus, three biological replicates (n = 3) were obtained for each processing stage. The collected samples were immediately wrapped and sealed with aluminum foil, rapidly frozen in liquid nitrogen, and then vacuum freeze-dried. The pre-freezing was carried out on the shelf at −80 °C, followed by sublimation drying under the conditions of a cold-trap temperature of −56 °C, a vacuum pressure ≤ 20 Pa, and a duration of 72 h. The freeze -dried samples were sealed and stored in a refrigerator at −20 °C for subsequent analysis.

Reagents

Heptanal (≥ 98%), hexanal (≥ 99%), nonanal (≥ 98%), benzeneacetaldehyde (≥ 95%), (*E*)-2-nonenal (≥ 85%), octanal (≥ 99%), hexanol (≥ 99%), linalool (≥ 98%), geraniol (≥ 98%), 1-octen-3-ol (≥ 98%), (*Z*)-jasmone (≥ 99%), (*E*)-*β*-ionone (≥ 98%), methyl salicylate (≥ 98%), butyl acrylate (≥ 99.5%), ethyl hexanoate (≥ 99%), (*Z*)-3-hexenyl hexanoate (≥ 98%), styrene (≥ 99.5%), and indole (≥ 98%) were purchased from Shanghai Yuanye Bio-Technology Co., Ltd. (*Z*)-neral (≥ 95%) was obtained from Shanghai Macklin Biochemical Co., Ltd. *n*-alkanes (C6–C40, ≥ 99%) and *n*-ketones (C4–C9, ≥ 98%) were supplied by Anpel Laboratory Technologies (Shanghai) Inc. and Shanghai Aladdin Biochemical Technology Co., Ltd, respectively.

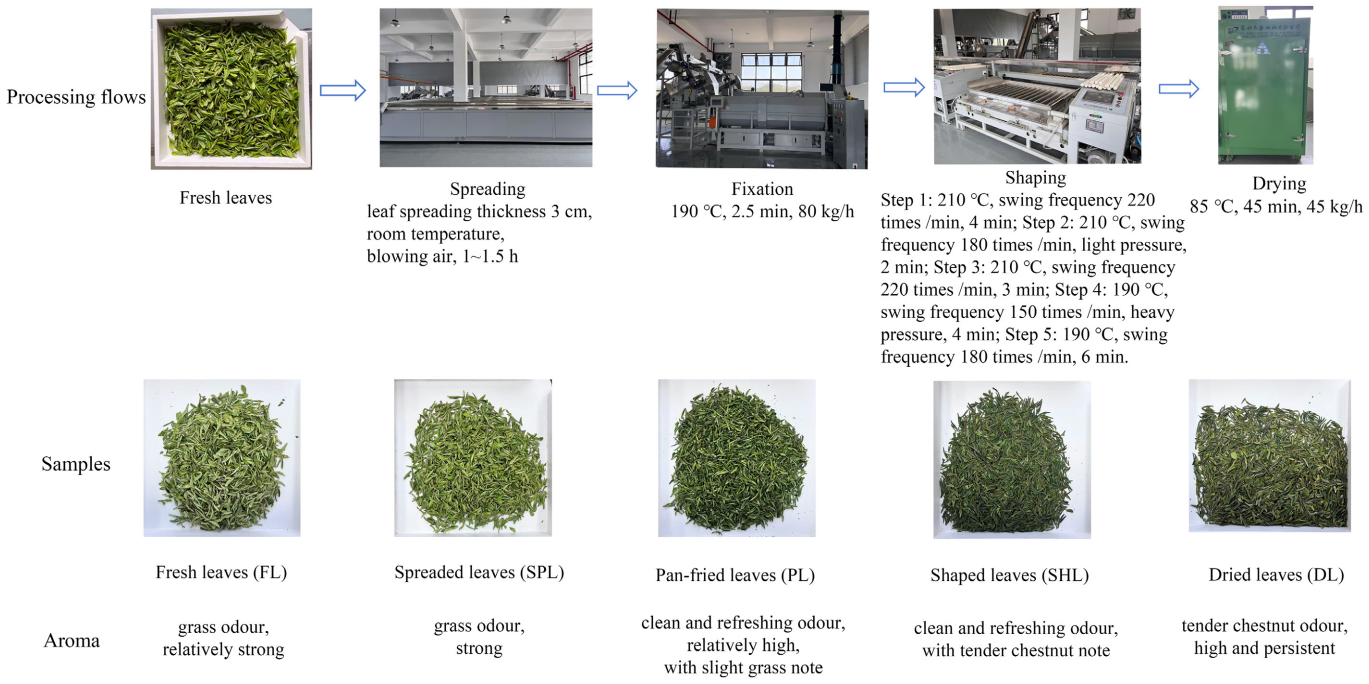

Fig. 1 Processing technology of SNXM and sensory evaluation of aroma in processing samples.

Ethyl decanoate and sodium chloride were purchased from Sigma-Aldrich (St. Louis, MO, USA) and Guangdong Guanghua Sci-Tech Co., Ltd, respectively.

Sensory evaluation and quantitative descriptive analysis of aroma

A trained sensory panel consisting of eight professional tea tasters (four males and four females, aged 23–46 years) evaluated the aroma of SNXM tea samples at different processing stages, according to the Methodology for Sensory Evaluation of Tea (GB/T 23776-2018)[35]. All panelists had at least 1 year of experience in descriptive sensory analysis of tea. The specific procedure was as follows: 3.0 g of tea sample was weighed into a tasting cup, infused with 150 mL of boiling water, and steeped for 4 min. The infusion was then filtered into a tasting bowl, and the infused leaves remaining in the tasting cup were used for aroma evaluation. Panelists assessed the aroma quality and provided descriptive sensory attributes with reference to Tea Vocabulary for Sensory Evaluation (GB/T 14487-2017)[36].

Quantitative descriptive analysis (QDA) was performed by the same trained sensory panel described above. The panelists first evaluated the prepared tea infusions to determine the preliminary aroma attributes. Based on these preliminary assessments, four major aroma attributes—grassy, fresh, tender, and chestnut-like—were identified in samples from the five processing stages. To calibrate the panelists for odor recognition, representative reference standards and tea samples were prepared at a series of concentrations: (*Z*)-3-hexen-1-ol (green), Huangshan Maofeng Grade 1 (fresh), Huangshan Maofeng Supreme Grade (tender), and Zhongcha Longjing (chestnut-like), with detailed preparation parameters provided in Supplementary Table S1. Following training, the tea infusions were randomly coded and presented to the panelists, who evaluated each sample for the intensity of the four aroma attributes. Intensities were rated on a 0–5 scale (0 = not detectable; 1 = extremely weak; 2 = weak; 3 = moderate; 4 = high; 5 = extremely strong). QDA was performed on three biological replicates of each processing stage. Each sample was assessed in triplicate by each panelist on separate days, and the results were expressed as mean values.

GC-IMS analysis

Volatile compounds were analyzed using a FlavourSpec® gas chromatography-ion mobility spectrometer (G.A.S., Dortmund, Germany) equipped with a non-polar capillary column (MXT-5, 15 m × 0.53 mm × 1 μm, Restek, Beijing, China). Analytical conditions were adopted from Yang et al.[28] with minor modifications. Briefly, 2.0 g of sample was placed into a 20 mL headspace vial and incubated at 60 °C with shaking at 500 rpm for 15 min. Subsequently, 500 μL of headspace gas was automatically injected into the inlet using a heated syringe (65 °C). The carrier gas flow rate was initially set at 2 mL/min and held for 2 min, then linearly increased to 100 mL/min within 18 min and maintained for 10 min. The drift tube length was 98.0 mm, and the drift tube temperature was maintained at 45 °C. High-purity nitrogen (≥ 99.999%) was used as the carrier gas, and the drift gas flow rate was set at 75 mL/min. A ^{3}H β-ray source was used as the ionization source, and measurements were performed in positive ion mode.

The retention indices (RI) of target volatile compounds were calculated based on the retention times of normal ketone standards (C4–C9) analyzed under identical conditions. All volatile compounds detected in this study were tentatively identified solely by matching their RI values and ion mobility drift times against the NIST library and the IMS database provided by G.A.S. (Dortmund, Germany); no authentic reference standards were used for compound confirmation in the GC-IMS analysis. Therefore, these tentative identifications should be further verified using authentic reference standards in future studies. Chromatograms were visualized using the Laboratory Analytical Viewer (LAV) software. The 'Gallery Plot' plugin was utilized for visual comparison of volatile differences among samples, and the 'Reporter' plugin was used to construct 2D top-view and 3D fingerprint profiles of the volatile components. All GC-IMS

https://doi.org/10.48130/bpr-0026-0052

measurements were performed on three biological replicates, each with three technical replicates.

Headspace solid-phase microextraction

Volatile compounds were extracted from dry tea and tea infusion using the headspace solid-phase microextraction (HS-SPME) technique. For dry tea, 0.5 g of sample and 1.5 g of sodium chloride were added to a 20 mL headspace vial, followed by the addition of 5.0 mL of distilled water (preheated to 100 °C) and 1 μL of ethyl decanoate (internal standard, 1.724 μg/mL). The vial was immediately sealed with a PTFE-silicone septum cap. A pre-conditioned fiber (50/30 μm DVB/CAR/PDMS, Supelco, Bellefonte, PA, USA) was inserted into the headspace of the vial and exposed for adsorption at 60 °C for 30 min. Following extraction, the fiber was thermally desorbed in the GC-MS inlet at 250 °C for 10 min. For tea infusion, a 3.0 g tea sample was infused with 150 mL of boiling water for 4 min in a tasting cup. Then, 10 mL of tea infusion was transferred to a 20 mL headspace vial. Sodium chloride (1.5 g) and the internal standard solution (1 μL, 1.724 μg/mL) were immediately added, and the headspace vial was sealed with a PTFE-silicone septum cap. The subsequent extraction was identical to that described for the dry tea sample. All HS-SPME extractions were performed on three biological replicates, each with three technical replicates.

GC-MS analysis

Samples were analyzed using a Shimadzu GCMS-TQ-8040-NX gas chromatograph-mass spectrometer (Shimadzu, Kyoto, Japan) equipped with an HP-5MS capillary column (30 m × 0.25 mm × 0.25 μm, Agilent Technologies, Santa Clara, CA, USA). The GC-MS conditions were as follows: High-purity helium (≥ 99.999%) was used as the carrier gas at a constant flow rate of 1.4 mL/min with a split ratio of 1:1. The oven temperature was initially held at 40 °C for 2 min, increased to 160 °C at 4 °C/min and held for 2 min, and finally raised to 270 °C at 10 °C/min and held for 2 min. The mass spectrometer was operated in electron ionization (EI) mode at 70 eV. The detector voltage was set to 0.1 kV, with a scan range of *m/z* 30–600. The ion source and interface temperatures were maintained at 230 and 280 °C, respectively. All GC-MS analyses were performed on three biological replicates, each with three technical replicates.

Qualitative analysis: Compounds were tentatively identified by matching their mass spectra with the NIST library, comparing retention indices (RI) calculated from *n*-alkane standards, and confirming them with authentic standards when available.

Quantitative analysis: (1) Relative quantification. Ethyl decanoate was added to each sample as an internal standard. The relative concentration of each analyte was calculated from the peak area ratio of the target compound to the internal standard (Eq. [1]), and the relative content was further calculated according to Eq. 2. (2) Absolute quantification. Selected key volatile compounds were quantified using the external standard curve method. The formulas for calculating the volatile compound contents were as follows:

$$C_i = (C_{is} \times A_i) \div A_{is} \,, \tag{1}$$

where, C_i is the relative concentration of the target volatile compound (μg/mL), A_i is the peak area of the target compound, C_{is} is the concentration of the internal standard (μg/mL), and A_{is} is the peak area of the internal standard.

$$RC_i = (C_i \times V) \div M \,, \tag{2}$$

where, RC_i is the relative content of the target volatile compound (μg/kg), V is the volume of the solution (mL), and M is the mass of the sample (kg).

GC-O analysis

GC-O analysis was performed according to the method described by Liu et al.[37]. A gas chromatograph-mass spectrometer (GCMS-TQ-8040-NX, Shimadzu, Japan) equipped with an olfactory detection port (ODP4, Gerstel, Germany) was employed to identify aroma-active compounds. The column effluent was split equally (1:1) between the mass spectrometer detector and the sniffing port. The GC-O injector temperature was set at 230 °C, and the transfer line temperature was maintained at 260 °C. All other GC-MS parameters were consistent with those detailed in the GC-MS analysis section.

The olfactory evaluation was conducted by five trained panelists (two males and three females, aged 24–29 years), who had previously undergone training to identify and discriminate different aroma qualities using a series of standard solutions at varying concentrations[37], as listed in Supplementary Table S1. The intensity of each perceived aroma was scored on a 0–5 scale (0 = not detected, 1 = extremely weak, 2 = weak, 3 = moderate, 4 = high, and 5 = extremely strong). GC-O analysis was performed on the finished tea (DL) samples from each of the three biological replicates, with each sample evaluated in duplicate by each of the five panelists.

OAV analysis

OAV was calculated using the method of Guo et al.[38]. Based on the absolute contents of aroma compounds in tea infusion (prepared as described in the "Sensory evaluation" section) and their corresponding odor thresholds in water reported in previous literature, the OAV was calculated using the following equation:

$$OAV_i = C_i \div T_i \,, \tag{3}$$

where, C_i is the absolute concentration of an individual aroma compound in tea infusion (μg/L), and T_i is the odor threshold of the corresponding aroma component in water (μg/L).

Statistical analysis

Partial least squares discriminant analysis (PLS-DA) and permutation tests were performed using SIMCA-P 14.1 (Umetrics, Umeå, Sweden). Basic data calculations were conducted in Excel 2016, and all results were expressed as mean ± standard deviation. One-way analysis of variance (ANOVA) was carried out with IBM SPSS Statistics 22 (IBM Corp., Armonk, NY, USA). Statistical significance was defined at $p < 0.05$, and a highly significant difference was set at $p < 0.01$. Dual y-axis graphs were plotted in Excel 2016, heatmap visualization was performed via the online platform (www.chiplot.online/index.html), and the K-means clustering plot was generated using the online analysis platform (https://cloud.metware.cn).

Results

Sensory evaluation results of aroma in processing samples of SNXM

The processing technology of SNXM green tea primarily consists of four core procedures: spreading, fixation, shaping, and drying (Fig. 1). Specifically, the shaping procedure utilizes trough pan heat conduction for both shaping and staged dehydration, characterizing a pan-firing process, whereas the drying procedure employs hot-air convection to further remove moisture, characterizing a baking process. Consequently, SNXM is classified as a typical 'pan-firing combined with baking' green tea.

To systematically explore the dynamic changes in sensory aroma quality during processing and clarify the regulatory effect of each procedure on aroma formation, sensory evaluation of aroma was performed on samples from fresh leaves and various processing stages (SPL, PL, SHL, and DL), and the results are shown in Fig. 1. The sensory results indicated that fresh leaf samples exhibited an intense grassy odor, which was further enhanced after spreading. High-temperature fixation fundamentally transformed the aroma profile of the in-process samples, with a significant reduction in grassy odor and a gradual emergence of a fresh aroma. The aroma type was further optimized after shaping, and a tender chestnut-like aroma was formed on the basis of a fresh aroma. After final drying, the finished tea presented a high, elegant, and long-lasting tender chestnut-like aroma. In conclusion, each processing procedure exerts differentiated regulatory effects on the directional formation of the characteristic aroma of SNXM green tea.

To further elucidate the evolution of aroma attributes during processing, QDA was employed to evaluate the four major aroma attributes (grassy, fresh, tender, and chestnut-like) in samples from five processing stages (Supplementary Fig. S1). The results showed significant differences in the perceived intensities of all aroma attributes among samples from different processing stages. The grassy note increased slightly after spreading (3.52), decreased significantly to 1.83 after fixation, and continued to decline during shaping (1.21) and drying (0.52), eventually reaching a very low level in the finished tea. The fresh note exhibited an increasing-then-decreasing trend, peaking after fixation (3.95) and then gradually decreasing to 1.46 in the finished tea. In contrast, both tender and chestnut-like notes increased progressively throughout the processing, reaching their highest intensities after drying (3.51 and 4.07, respectively), and together constituted the predominant aroma profile of the finished tea. These quantitative findings are consistent with the sensory evaluation results (Fig. 1).

GC-IMS analysis of volatile compounds in processing samples of SNXM

To rapidly characterize the dynamic changes of aroma substances during the processing of SNXM green tea, GC-IMS was employed to acquire ion mobility spectrometry data of samples from different processing stages. The results are presented in Supplementary Fig. S2. In the three-dimensional spectrum (Supplementary Fig. S2a), the X-axis, Y-axis, and Z-axis represent the ion migration time, retention time, and peak intensity of volatile components, respectively. The two-dimensional topographic plot (Supplementary Fig. S2b) more clearly elucidates the variation trends of volatile compounds across different stages. Each bright spot corresponds to a compound, with white indicating low abundance and red indicating high abundance. The red vertical line at 1.0 on the X-axis represents the normalized Reactant Ion Peak (RIP). The retention times of volatile components in the processing samples ranged from 0 to 600 s, while the drift times were concentrated between 1.0 and 2.0 s. To better visualize the differences among the processing stages, fresh leaf samples (FL) were used as a reference, and comparative difference plots were generated (Supplementary Fig. S2c). In these plots, red dots indicate concentrations higher than the reference, while blue dots indicate concentrations lower than the reference. The spreading samples (SPL) exhibited the highest number of red dots, suggesting that spreading promoted the accumulation of volatile compounds. Although the number of red dots decreased in the fixation (PL), shaping (SHL), and drying (DL) samples, the intensity of some dots increased, indicating that these procedures specifically facilitated the accumulation of certain compounds.

A total of 59 volatile compounds corresponding to 76 signal peaks were identified by GC-IMS, including 13 alcohols, 18 aldehydes, 10 esters, 10 ketones, two hydrocarbons, two acids, and four other compounds (Supplementary Table S2). Notably, some volatile compounds produced multiple signals; for instance, 1-hexanol monomer and dimer showed similar retention times (264.43 and 265.32 s, respectively) but distinct migration times (1.33 and 1.64 a.u., respectively).

To visually reflect the dynamic changes of volatile compounds during processing, a fingerprint plot was constructed using the Gallery Plot module. As shown in Fig. 2, each column represents the content of the same compound in different samples, and each row represents the content of each compound within the same sample. The color intensity reflects the relative content of the compounds. The fingerprint of SNXM can be divided into six regions (A–F). Region A includes heptanal (19#, 20#) and 2-heptanone (59#), which showed no significant changes during processing. Region B includes (*E*)-2-hexenal (36#), 2-hexenal (35#), and propyl butanoate (53#), which were highest in the fresh leaf samples (FL). Region C contains the most compounds, such as heptanol (1#, 2#), 1-hexanol (4#), (*Z*)-3-hexen-1-ol (5#, 6#), 3-methyl-3-buten-1-ol (7#, 8#), linalool (11#), and linalool oxide (12#), reaching peak levels after spreading. Region D includes hexanal (29#, 30#), butyl acetate (47#, 48#), ethanol (13#), 2-methylbutanal (40#), and α-pinene (69#), which peaked after fixation. Region E comprises (*Z*)-2-penten-1-ol (14#), (*E*)-2-heptenal (27#, 28#), acetic acid (70#, 71#), (*E*)-2-octenal (38#), and 1-octen-3-one (58#), showing maximum content after shaping. Finally, region F includes 1-octanal (23#, 24#), (*E*)-2-pentenal (31#, 32#), 3-methyl-2-butenal (43#), 2-ethyl-5-methylpyrazine (76#), and 2-ethylfuran (73#), which reached their highest levels after drying.

GC-MS analysis of volatile compounds during the processing of SNXM

To systematically explore the composition characteristics and dynamic evolution of aroma components in in-process samples of SNXM at different processing stages, GC-MS was employed to conduct qualitative identification and relative quantitative analysis of volatile components in samples at each processing stage.

Identification of volatile compounds during the processing of SNXM

A total of 86 volatile compounds were identified by GC-MS analysis. Their relative contents were calculated based on the ratio of peak areas to that of the internal standard (Supplementary Table S3). Specifically, 74, 75, 69, 70, and 71 volatile substances were detected in fresh leaf samples, spreading samples, fixation samples, shaping samples, and drying samples (namely finished tea), with total contents of 437.48, 566.82, 232.26, 166.39, and 263.39 μg/kg, respectively. All identified compounds were categorized into seven classes: alcohols (24), aldehydes (14), esters (19), ketones (seven), hydrocarbons (16), acids (three), and others (five). The relative content of each class exhibited significant dynamic changes throughout the processing (Fig. 3a), indicating that complex chemical reactions continuously occur throughout the processing of SNXM, which fundamentally drives the dynamic formation of tea aroma quality.

Alcohols were the most abundant aroma components in finished tea, with a content of 122.21 μg/kg accounting for 46.40% of the total volatiles, and their relative proportion fluctuated from 45.57% to 57.74% during processing. The content of alcohols increased obviously from fresh leaves to the spreading stage and decreased

https://doi.org/10.48130/bpr-0026-0052

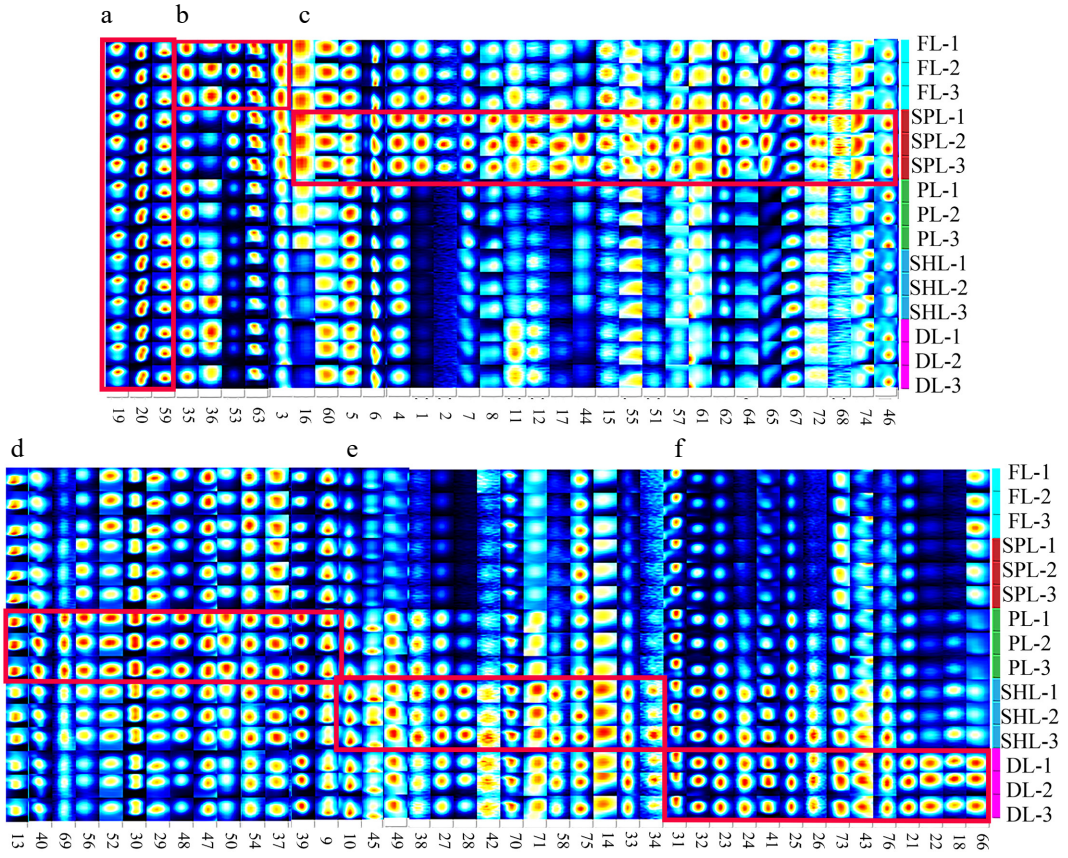

Fig. 2 Dynamic aroma fingerprints of SNXM during processing, constructed by Gallery Plot. Note: FL: fresh leaves; SPL: spreading leaves; PL: fixation leaves; SHL: shaping leaves; DL: dried leaves (representing the finished tea). The numbers of the compounds in the figure correspond to the compound numbers listed in Supplementary Table S2.

sharply after fixation. The spreading sample possessed the highest alcohol content (321.49 μg/kg), while the shaping sample showed the lowest value (79.13 μg/kg). As the second most abundant aroma component in finished tea, aldehydes had a content of 63.28 μg/kg (24.02% of total volatiles), with a proportional range of 13.05%–25.69% during processing. The content of aldehydes decreased continuously from fresh leaves to the shaping stage and increased remarkably after drying. The maximum content was observed in fresh leaves (77.48 μg/kg) and the minimum in shaping samples (42.74 μg/kg).

Esters and hydrocarbons were the third and fourth predominant aroma components in the finished tea, with contents of 31.94 μg/kg (12.13%) and 19.64 μg/kg (7.46%), respectively. Their relative proportions fluctuated in the ranges of 12.13%–20.68% and 5.75%–7.80%. Ketones were the fifth dominant component, with a content of 14.42 μg/kg (5.47%) and a proportional variation of 2.76%–5.47%. The maximum contents of esters, hydrocarbons, and ketones reached 117.25, 32.61, and 15.65 μg/kg, respectively. Overall, alcohols, esters, hydrocarbons, and ketones shared a consistent variation trend: increasing from fresh leaves to spreading, declining after fixation, and rising slightly after drying.

Acids presented the lowest content, ranging from 0.24 to 1.33 μg/kg and accounting for only 0.09%–0.24% of total volatiles, with the maximum value appearing after spreading. The relative content of other volatile compounds ranged from 2.73 to 11.66 μg/kg, occupying 0.80%–4.43% of the total volatiles. Their content decreased gradually from fresh leaves to the shaping stage and increased significantly after drying, which was consistent with the variation trend of aldehydes.

Multivariate statistical analysis of volatile compounds

To visually characterize the differences in volatile components across different processing stages of SNXM, PLS-DA was performed based on the relative quantitative data from GC-MS. As shown in Supplementary Fig. S3a, the PLS-DA model achieved a clear separation of different processing stages. The model exhibited excellent variance explanation and cross-validation prediction capabilities (R^2Y = 0.975, Q^2 = 0.928), and no overfitting was confirmed by 200 permutation tests (R^2 = 0.394, Q^2 = −0.615, Supplementary Fig. S3b). In the score plot, fixation and shaping samples were closest in spatial distance, indicating a high similarity in their volatile composition. In contrast, greater distances were observed between fresh leaves samples and spreading samples, spreading samples and fixation samples, as well as shaping samples and drying samples, suggesting that the volatile profiles were significantly reshaped during these adjacent processing stages. Collectively, these results indicate that spreading, fixation, and drying are the key stages for aroma formation of SNXM.

To identify potential volatile compounds that could distinguish different processing steps, a total of 31 volatile compounds were selected based on variable importance in projection (VIP) > 1.0 from PLS-DA and $p < 0.05$. These included 3 alcohols, 4 aldehydes, 12 esters, 3 ketones, 6 hydrocarbons, and 3 other compounds. A heat map was employed to visually display the content variations of these important volatiles across the processing stages, with red indicating concentrations above the mean and green indicating concentrations below the mean (Supplementary Fig. S3c). The predominant volatile compounds differed among the processing stages. In the fresh leaf samples, the contents of linoleic acid ethyl

https://doi.org/10.48130/bpr-0026-0052

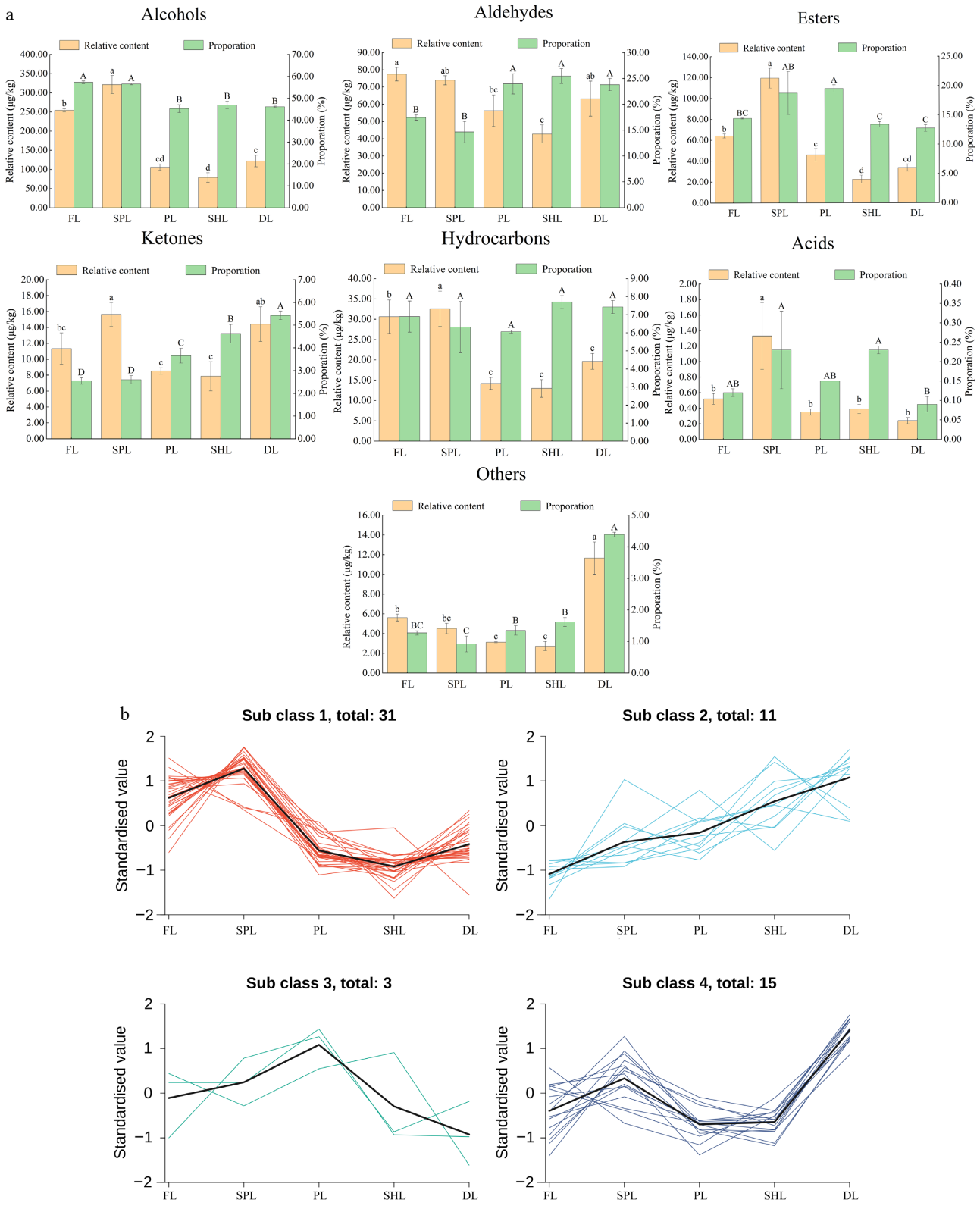

Fig. 3 Dynamic changes and multivariate statistical analysis of volatile compounds in SNXM during processing based on GC-MS. (a) Categories and relative contents of volatile compounds at different processing stages. The y-axis represents the relative content (μg/kg), and the x-axis indicates the processing stages: FL (fresh leaves), SPL (spreading leaves), PL (fixation leaves), SHL (shaping leaves), and DL (dried leaves/finished tea). Values are expressed as mean ± standard deviation (n = 3 biological replicates), with error bars representing standard deviation. Different superscript letters above the same-colored columns in panel a denote statistically significant differences at $p < 0.05$. (b) K-means clustering analysis of 60 common volatile compounds across the five processing stages. Based on their content variation trends, these compounds were grouped into four subclasses (subclass 1:31 compounds; subclass 2:11; subclass 3:3; subclass 4:15), using the mean values derived from the three biological replicates shown in Supplementary Table S3.

https://doi.org/10.48130/bpr-0026-0052

ester, octanoic acid ethyl ester, α-terpinene, styrene, and 3-carene were significantly higher than in the other stages. During the spreading stage, compounds such as (*Z*)-3-hexenyl valerate, (*Z*)-3-hexenyl hexanoate, (*Z*)-3-hexenyl butyrate, tetradecanoic acid ethyl ester, and 2,6-dimethylnaphthalene were significantly enriched. The content of 3-octen-2-one was higher in the fixation stage. Most of the floral and fruity compounds, including (*E*)-nerolidol, α-ionone, indole, methyl jasmonate, and (*E*)-*β*-farnesene, were significantly more abundant in the drying stage than in the other stages.

Dynamic changes of common volatile compounds during processing

A total of 60 volatile compounds were common across the five processing stages of SNXM, including 19 alcohols, 12 aldehydes, 12 esters, four ketones, nine hydrocarbons, one acid, and three other compounds. The dynamic changes of these common volatile compounds during processing were analyzed using *K*-means clustering analysis, and the results showed that their variations in content could be categorized into four patterns (Fig. 3b).

Pattern I: The content of compounds increased substantially from the fresh leaf stage to the spreading stage, dropped sharply after fixation, continued to decrease during the shaping stage, and slightly recovered after drying (Fig. 3b, subclass 1). The content of these compounds peaked at the spreading stage and reached its minimum at the shaping stage, and this group comprised 31 compounds in total. Among them, eight compounds were derived from fatty acid precursors, including (*Z*)-3-hexenol, hexanol, 1-heptanol, (*Z*)-3-nonen-1-ol, heptanal, nonanal, (*E*)-2-nonenal, and decanal[37]. Eleven compounds originated from the hydrolysis of glycosidic aroma precursors, namely linalool, benzyl alcohol, (*Z*)-linalool oxide (furanoid), (*E*)-linalool oxide (furanoid), phenylethyl alcohol, (*E*)-linalool oxide (pyranoid), nerol, geraniol, benzaldehyde, citral, and methyl salicylate[39]. Six compounds were generated by esterification of alcohols and acids, including butyl acrylate, ethyl hexanoate, (*Z*)-3-hexenyl acetate, (*Z*)-3-hexenyl butyrate, (*Z*)-3-hexenyl valerate, and (*Z*)-3-hexenyl hexanoate[40]. Additionally, this group includes the carotenoid degradation product (*E*)-*β*-ionone, the amino acid conversion product 1-methylnaphthalene, and four compounds from other sources: styrene, *β*-myrcene, limonene, and (4*E*,6*Z*)-allo-ocimene. Pattern II: Eleven compounds showed a fluctuating upward trend during processing (Fig. 3b, subclass 2). These compounds generally exhibited relatively low contents, and their levels in the final tea were all higher than those in fresh leaves. Representative substances include 1-octen-3-ol, phytol, (*E*,*E*)-2,4-heptadienal, neral, and *δ*-cadinene. Among these, five compounds were derived from fatty acid precursors, including 1-octen-3-ol, myristyl alcohol, (*E*)-2-heptenal, (*E*,*E*)-2,4-heptadienal, and n-hexadecanoic acid. Only (*Z*)-neral originated from the hydrolysis of glycosidic aroma precursors. In addition, this group included the esterification product hexadecanoic acid, methyl ester, the chlorophyll degradation product phytol, and three compounds from other sources: *α*-cubebene, *δ*-cadinene, and (*E*)-calamenene[39,40]. Pattern III: Only three compounds, namely 1-hexadecanol, hexanal, and (*Z*)-3-hexenyl (*Z*)-3-hexenoate, exhibited a gradual increase in their contents from the fresh leaf stage to the fixation or shaping stage, followed by a decrease after drying (Fig. 3b, subclass 3). Among these, 1-hexadecanol and hexanal were synthesized from fatty acid precursors, while (*Z*)-3-hexenyl (*Z*)-3-hexenoate was generated by the esterification of an alcohol and an acid[39,40]. Pattern IV: This pattern exhibited a similar overall trend to Pattern I, but the 15 compounds in this group reached their highest content in the drying samples (Fig. 3b, subclass 4). Among them, four compounds were derived from fatty acid precursors, including (*E*)-nerolidol, dodecanal, methyl jasmonate, and (*Z*)-jasmone[39]. Two compounds were carotenoid degradation products, namely *α*-ionone and geranylacetone[39]. Two compounds were products of esterification: butyl butyrate and (*E*)-2-hexenyl hexanoate[40]. Two compounds originated from the hydrolysis of glycosidic aroma precursors, namely (*Z*)-linalool oxide (pyranoid) and benzyl nitrile[39]. Additionally, this group included the amino acid conversion products benzeneacetaldehyde and indole, as well as three compounds from other sources: *τ*-muurolol, (*E*)-*β*-farnesene, and *α*-calacorene[39]. Furthermore, 23 volatile compounds were detected only in some processing stages (Supplementary Table S3). Compounds unique to the fresh leaves and spreading stages mainly included (*E*)-2-hexenal, 1-nonanol, octanoic acid ethyl ester, linoleic acid ethyl ester, 3,5-octadien-2-one, and *α*-terpinene, all of which disappeared after fixation. Newly emerging compounds during the fixation and shaping stages included 1-octen-3-one, 3-octen-2-one, and nonanoic acid. Compounds unique to the drying stage included (*Z*)-2-hexenol, (*E*)-4,8-dimethylnona-1,3,7-triene, and 1-ethyl-1H-pyrrole-2-carbaldehyde. In addition, 2,6-dimethylnaphthalene was detected only in the spreading samples, and *γ*-cadinene was detected only in the spreading and shaping samples.

Identification of key aroma components in finished SNXM green tea

Sensory evaluation indicated that the finished SNXM green tea (namely, the dried sample) exhibited a tender chestnut-like aroma. To elucidate the key aroma compounds responsible for this aroma profile, GC-O and OAV analyses were conducted using the finished tea samples.

Identification of aroma-active volatiles based on GC-O

Volatile compounds detected by GC-O are generally considered aroma-active volatiles in tea[41]. Through sniffing analysis of the finished SNXM green tea, a total of 19 compounds with aroma intensity (AI) values ranging from 1.17 to 3.67 were detected (Fig. 4). According to their olfactory characteristics, these compounds could be classified into several categories. Five compounds, namely hexanal, heptanal, (*E*)-2-nonenal, *(E)*-2-heptenal, and 1-octen-3-ol, exhibited green notes. Methyl salicylate was the only component with a fresh note. Eight compounds displayed floral notes, namely linalool, phenylethyl alcohol, geraniol, *(Z)*-neral, indole, *(Z)*-jasmone, (*E*)-*β*-ionone, and benzeneacetaldehyde. Five compounds contributed to the fruity odor, including nonanal, octanal, (*Z*)-3-hexenyl hexanoate, decanal, and *(E)*-decenal. Among them, linalool showed the highest AI (3.67), followed by (*E*)-*β*-ionone (3.33), hexanal (3.17), nonanal (3.17), 1-octen-3-ol (3.17), geraniol (3.17), and (*E*)-2-nonenal (3.00). Moreover, compounds such as phenylethyl alcohol, heptanal, *(E)*-2-heptenal, indole, and octanal also had relatively high AI values (2.50–2.83). Nevertheless, the actual contribution of these aroma-active volatiles to the overall aroma of SNXM green tea needs to be further verified by absolute quantitative analysis and OAV calculations.

Absolute quantification and OAV analysis of key aroma components

The contribution of volatile compounds to the overall aroma quality of SNXM green tea depends not only on their content but also critically on their OAVs[42]. Generally, compounds with an OAV greater than 1 are considered the key contributors to the overall aroma profile of tea[18]. To this end, the aroma-active compounds

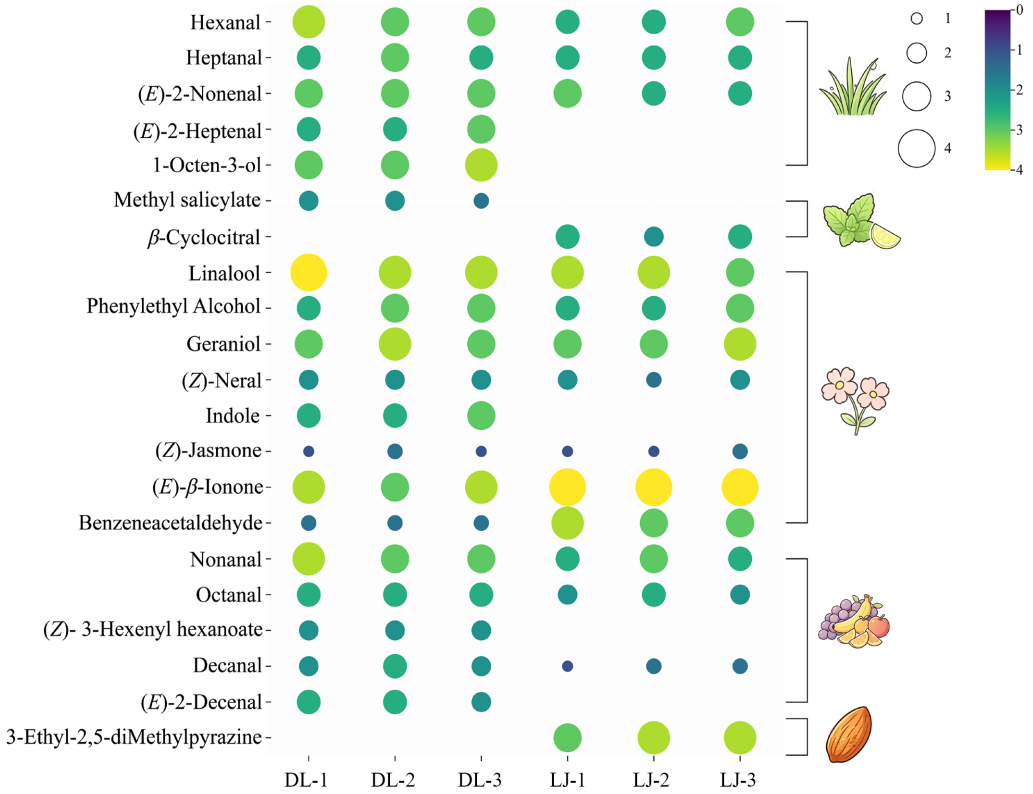

Fig. 4 The aroma-active compounds identified by GC-O and their odor intensity values. Note: DL-1, DL-2, and DL-3 are SNXM samples, while LJ-1, LJ-2, and LJ-3 correspond to Longjing tea samples. The bubble size and color gradient jointly indicate the level of aroma intensity.

identified by GC-O were subjected to absolute quantitative analysis using external standard methods, and their OAVs were calculated (Supplementary Table S4). A total of 10 volatile compounds with OAV > 1 were screened out, including linalool (OAV: 518.25), (*E*)-*β*-ionone (OAV: 215.40), nonanal (OAV: 27.81), hexanal (OAV: 19.62), 1-octen-3-ol (OAV: 11.49), geraniol (OAV: 9.68), heptanal (OAV: 7.89), phenylethyl alcohol (OAV: 2.01), indole (OAV: 1.57), and (*E*)-2-nonenal (OAV: 1.49). Their dynamic changes during processing are shown in Fig. 5.

1-Octen-3-ol, hexanal, heptanal, nonanal, and (*E*)-2-nonenal were derived from the oxidative degradation of unsaturated fatty acids (linolenic and linoleic acids)[39], whereas they exhibited distinct variation trends throughout the processing of SNXM. The content of 1-octen-3-ol gradually increased from the fresh leaf stage to the fixation stage, slightly decreased after shaping, and rose again after drying, with minimal overall fluctuation. The content of hexanal increased after fixation, declined after shaping, and dropped to its lowest value after drying. Heptanal content gradually decreased from the fresh leaf stage to the shaping stage and then significantly increased after drying. Nonanal content peaked after spreading, declined rapidly after fixation, and slightly recovered after drying. The variation trends of (*E*)-2-nonenal, phenylethyl alcohol, (*E*)-*β*-ionone, linalool, and geraniol were similar to those of nonanal during SNXM processing, all reaching their peak values after spreading. In addition, indole exhibited a similar variation trend to that of heptanal during SNXM processing, with the difference that indole peaked after drying. It is thus evident that the accumulation patterns of different key aroma compounds differed remarkably during processing.

Discussion

To comprehensively elucidate the dynamic changes of aroma compounds during the processing of SNXM green tea, this study employed GC-IMS and GC-MS for the detection and analysis of volatile compounds in the samples. A total of 59 and 86 volatile compounds were identified by GC-IMS and GC-MS, respectively (Supplementary Tables S2, S3), yielding 125 compounds after deduplication. Among these, only 16 compounds were commonly detected by both techniques, accounting for 12.7% of the total identified compounds. The 43 compounds exclusively detected by GC-IMS were characterized by high volatility, low boiling points, and small molecular weights (predominantly C2–C8), including short-chain aldehydes (e.g., butanal, pentanal), short-chain alcohols (e.g., ethanol, 2-methyl-1-propanol), short-chain ketones (e.g., 2-butanone, 2-pentanone), and small-molecule esters (e.g., acetic acid ethyl ester, butyl acetate). In contrast, the 66 compounds exclusively detected by GC-MS exhibited low volatility, high boiling points, and large molecular weights (predominantly C6–C20+), encompassing long-chain fatty acid esters (e.g., hexadecanoic acid ethyl ester, linoleic acid ethyl ester), sesquiterpenes (e.g., *γ*-cadinene, *δ*-cadinene, [*E*]-*β*-farnesene), terpene alcohols (e.g., geraniol, [*E*]-nerolidol), and aromatic compounds (e.g., indole, phenylethyl alcohol). These findings indicate that GC-IMS and GC-MS are highly complementary in their detection preferences, and their combined application enables more comprehensive and accurate characterization of the overall volatile profile and dynamic changes during the processing of SNXM green tea.

Aroma is one of the core sensory indicators for evaluating tea quality. Different volatile compounds, when combined at various concentrations, give rise to diverse aroma characteristics. These

https://doi.org/10.48130/bpr-0026-0052

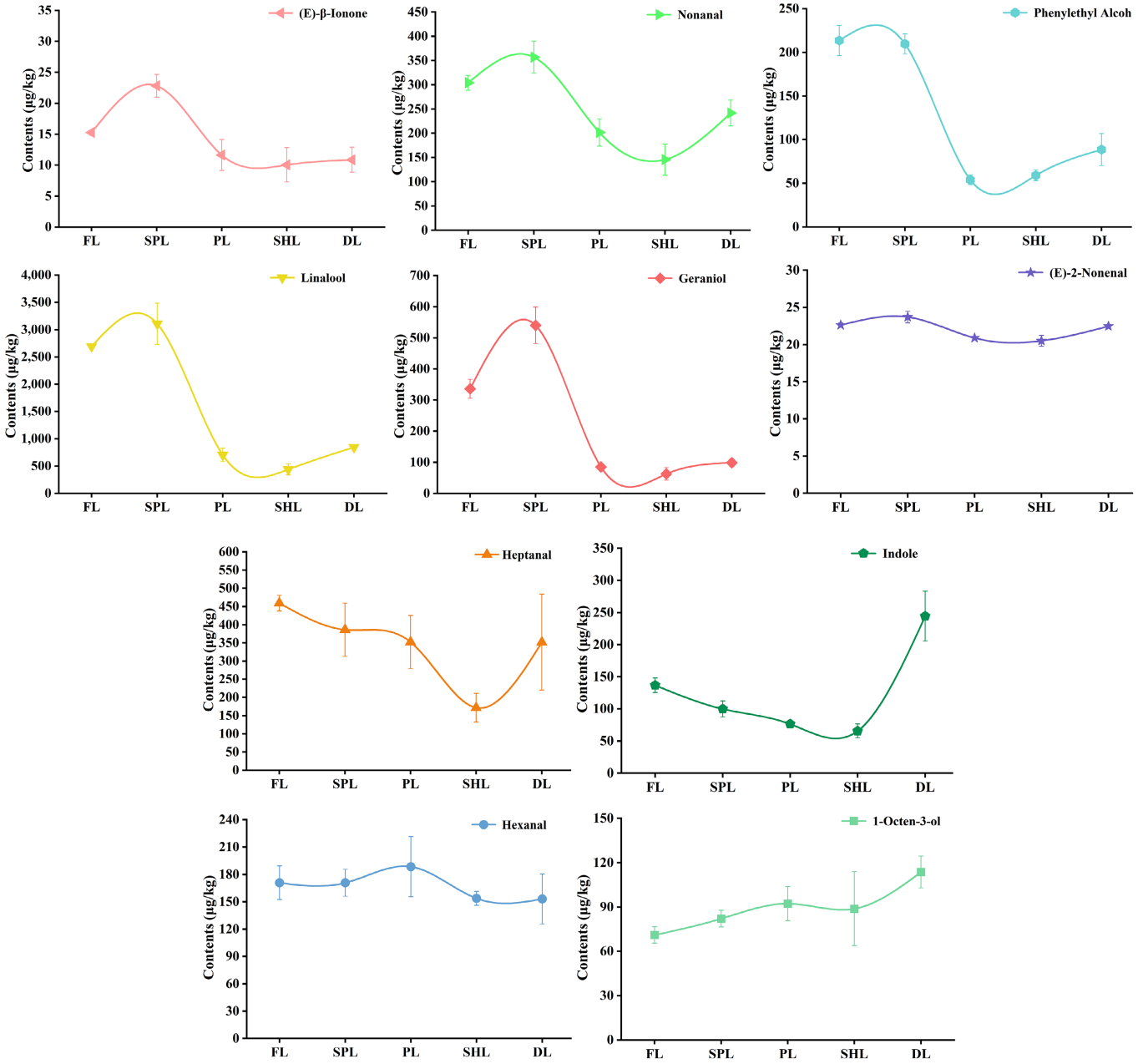

Fig. 5 Dynamic changes in volatile compounds with OAV > 1 during the processing of SNXM green tea. Note: The x-axis represents the processing stages: FL, fresh leaves; SPL, spreading leaves; PL, fixation leaves; SHL, shaping leaves; DL, dried leaves (finished tea). The y-axis represents the compound content (μg/kg). Data are expressed as the mean ± standard deviation from three biological replicates, with error bars representing the standard deviation.

compounds are mainly transformed from endogenous volatile compounds and aroma precursors in fresh tea leaves during processing. SNXM green tea is processed through four main procedures: spreading, fixation, shaping, and drying. Its aroma gradually transitions from grassy to tender chestnut-like throughout processing (Fig. 1). GC-IMS and GC-MS analyses indicated that the composition and content of volatile compounds change significantly as processing proceeded (Figs 2 and 3). PLS-DA analysis further revealed that the volatile compounds undergo the most pronounced changes during the spreading, fixation, and drying stages, identifying these as the key processing steps for aroma formation in SNXM. Previous studies have indicated that the dominant processing procedures differ among green teas with different aroma types. The aroma quality of floral-scented green tea is jointly determined by spreading and fixation[29], while the characteristic aroma of chestnut-like green tea is mainly shaped by fixation and drying[28]. Accordingly, SNXM green tea with a tender chestnut-like aroma possesses a unique aroma formation mechanism.

During the spreading stage, a large number of alcohols, esters, and some terpenoids accumulated significantly. In the GC-IMS fingerprint spectra, most compounds associated with floral and green aromas reached high levels at this stage. It has been documented that water loss leads to cytoplasmic concentration during the spreading of fresh leaves, which enhances the activities of lipoxygenase (LOX), alcohol dehydrogenase (ADH), glycoside hydrolases, and other enzymes. These activated enzymes accelerated fatty acid degradation and hydrolysis of glycosidic aroma precursors[39,43]. Consequently, volatile compounds including (*Z*)-3-hexen-1-ol,

hexanol, linalool, geraniol, and nerol accumulated abundantly (Supplementary Table S3), providing a material basis for subsequent aroma transformation. Meanwhile, the massive accumulation of green-note-related compounds was consistent with the sensory result that green, grassy aromas intensified after spreading.

Fixation serves as a critical turning point for aroma transformation of SNXM. The high temperature during fixation rapidly inactivated enzymes in spreading leaves and terminated enzymatic reactions, making thermal reactions the predominant pathway for aroma conversion[39,44]. A large number of alcohols, esters, and some aldehydes that accumulated during the spreading stage decreased markedly after fixation due to heat-induced volatilization. Meanwhile, compounds such as hexanal, butyl acetate, 2-methyl butanal, and α-pinene reached relatively high levels after fixation (Supplementary Table S3). As a result, the grassy odor of the fixation sample was significantly weakened, and a delicate, fresh aroma began to emerge. Thus, fixation not only reduced the content of compounds associated with grassy odor but also promoted the formation of some new aroma compounds, thereby driving the aroma transformation of SNXM from grassy to fresh.

During the drying stage, high temperatures triggered a series of thermal chemical reactions, including the Maillard reaction, Strecker degradation, and lipid thermal oxidation, generating large quantities of volatile compounds characterized by nutty, roasted, and sweet aromas[45]. Among these, pyrazines and furans have been confirmed as key contributors to the chestnut-like flavor of green tea[28]. The GC-IMS fingerprint analysis in this study revealed that the contents of compounds such as octanal, (*E*)-2-pentenal, 3-methyl-2-butenal, 2-ethyl-5-methylpyrazine, and 2-ethylfuran reached their highest levels after drying (Supplementary Table S2). The substantial generation of these compounds endowed the finished SNXM green tea with a more pronounced chestnut-like aroma. Therefore, the drying stage promoted the further transformation of volatile compounds and played an essential role in the formation of the tender chestnut-like aroma in SNXM.

K-means clustering analysis categorized the content variations of 60 common volatile compounds during SNXM green tea processing into four dynamic patterns, reflecting the predominance of specific biochemical reaction pathways at different processing stages. Tea aroma compounds were primarily derived from lipids, glycosidically bound precursors, carotenoids, and thermal reactions of amino acids and sugars, while processing steps including spreading, fixation, and drying further modulated the conversion and volatilization of these precursors[46,47]. Pattern I (31 compounds) was the largest and most typical representation of the early-stage enzymatic events. The substantial accumulation during spreading was a direct result of the activation of the LOX-HPL pathway and glycoside hydrolysis pathway (such as β-glucosidases and β-primeverosidases)[47,48], which cleaved unsaturated fatty acids (yielding eight compounds) and glycosidic precursors (yielding 11 compounds), respectively. The sharp decline after fixation was a clear manifestation of rapid enzyme inactivation and thermally induced evaporative escape. As the related enzymes were denatured by the extreme heat of fixation, the production of these compounds was abruptly halted, allowing physical volatilization to dominate. The slight recovery during drying was hypothesized to result from the residual non-enzymatic oxidative cleavage of lipids and the thermal degradation of thermally unstable conjugated precursors. Additionally, this pattern included the enzymatically cleaved carotenoid degradation product *(E)*-β-ionone and several ester compounds. Pattern II comprised 11 compounds that exhibited a fluctuating upward trend, with final contents higher than those in fresh leaves. This pattern was characteristic of non-enzymatic thermal generation outpacing evaporative loss. During fixation and drying, high temperatures initiated the thermal oxidative cleavage of lipids (yielding 1-octen-3-ol, [*E,E*]-2,4-heptadienal, etc.) and chlorophyll degradation (yielding phytol)[47,48]. Furthermore, compounds like δ-cadinene (from other sources) may be generated through thermally induced terpene rearrangement. Importantly, because these compounds possessed relatively higher boiling points (e.g., neral, phytol) and were generated continuously in a dry matrix, their rate of thermal formation exceeded the rate of volatile escape, resulting in their final accumulation. This pattern suggested that thermal processing, while causing the loss of some volatile compounds, simultaneously promoted the formation of specific aroma compounds[46]. Pattern III comprised only three compounds—1-hexadecanol, hexanal, and *(Z)*-3-hexenyl *(Z)*-3-hexenoate—which showed an atypical trend of peaking at fixation/shaping and declining after drying. Hexanal and 1-hexadecanol were derived from the oxidative degradation of fatty acids, while *(Z)*-3-hexenyl *(Z)*-3-hexenoate was a fatty acid-derived ester, potentially formed by further esterification of lipid degradation products[48,49]. The initial increase was primarily attributed to the oxidative and thermal degradation of fatty acids. However, the subsequent decline during the prolonged drying stage illustrated the dominance of volatile escape and further thermal transformation over generation. As the matrix dried, the loss of these relatively volatile compounds through evaporation exceeded their generation rate. Meanwhile, they may also act as intermediates, being further converted into other compounds.

Pattern IV (15 compounds) mirrored Pattern I in shape but reached its peak during the drying stage, indicating that the accumulation of these compounds was predominantly governed by the final thermal treatment. During spreading, fixation, and shaping, these compounds likely underwent transformation pathways similar to those of Pattern I: enzymatic reactions during spreading caused a substantial increase in their contents, while the severe thermal volatilization during fixation (190 °C) and shaping (190–210 °C) led to a decline. However, during the prolonged mild-temperature drying (85 °C, 45 min), a dynamic shift occurred. As water activity decreased and the matrix became more dehydrated, the rate of thermal cleavage of specific precursors surpassed the rate of thermal volatilization, resulting in these compounds not only failing to decrease but surging to their peak levels. Specifically, thermal degradation of carotenoids (including α-carotene and lycopene) produced α-ionone and geranylacetone, while thermal cleavage of phenylalanine yielded benzeneacetaldehyde[46,48].

Previous studies have demonstrated that drying not only causes the loss of certain volatiles but also promotes carotenoid degradation and Maillard/Strecker thermal reactions, thereby generating new aroma compounds[46,47]. Processing stage-specific compounds further corroborated the above mechanisms. *(E)*-2-hexenal and linoleic acid ethyl ester, which were unique to the fresh leaf stage and the spreading stage, disappeared after fixation, likely due to complete volatilization at the high fixation temperature (190 °C) accompanied by the inactivation of their synthetic enzymes[46]. 1-Octen-3-one and 3-octen-2-one, which newly emerged during the fixation and shaping stages, reflected the formation of new products from thermally induced lipid oxidation[46]. *(E)*-4,8-Dimethylnona-1,3,7-triene and 1-ethyl-1H-pyrrole-2-carbaldehyde, which were unique to the drying stage, were typical Maillard reaction products[46,48]. In summary, the four *K*-means patterns collectively illustrated a dynamic successional transition in SNXM aroma formation: an early-stage switch from enzymatic generation to

https://doi.org/10.48130/bpr-0026-0052

enzyme inactivation, followed by a late-stage competition between non-enzymatic thermal synthesis and evaporative loss. This transition ultimately dictated the stage-specific accumulation or decline of individual compounds, governed by the nature of their precursors and their specific thermodynamic stability.

Combined GC-O and OAV analyses identified 10 key aroma compounds, namely linalool, (*E*)-*β*-ionone, nonanal, hexanal, 1-octen-3-ol, geraniol, heptanal, phenylethyl alcohol, indole, and (*E*)-2-nonenal. Linalool, a terpene alcohol widely present in plants, has been confirmed as one of the core contributors to tea aroma[49]. Nonanal has been identified as a key component of the chestnut-like aroma of green tea[18]. Heptanal has been previously reported as a key aroma component of Turkish green tea[50]. Derived from oxidative degradation of carotenoids, (*E*)-*β*-ionone has an extremely low odor threshold and thus plays an important role in shaping the flavor of green tea[18]. 1-Octen-3-ol, which possesses mushroom and hay-like aromas, may contribute to the grassy and sweet notes within the chestnut-like aroma[15]. Geraniol has an intense rose fragrance and is regarded as a characteristic aroma component of many green teas[9,15]. Hexanal is the main substance responsible for the fresh flavor of fresh-scented Tieguanyin tea[51]. Indole, which has a typical floral aroma and can be generated from the Amadori rearrangement products of L-tryptophan during pyrolysis, is a key aroma-active compound in pan-fired green tea[39,52]. *(E)*-2-nonenal, a volatile fatty-acid derivative characterized by green and fatty notes, was identified as a key contributor to chestnut-like aroma based on its OAV[18,48]. Phenylethyl alcohol, which possesses a floral aroma and originates from the glycoside hydrolysis pathway, is a characteristic aroma compound of floral-scented green tea[29,39,53]. The synergistic combination of these volatile compounds with diverse olfactory properties formed the long-lasting tender chestnut flavor of SNXM.

The chestnut-like aroma of green tea is generally considered to resemble the flavor profile of cooked Chinese chestnut (*Castanea mollissima*) and is a typical fragrance highly favored by consumers in premium green tea[48]. However, the key contributing compounds responsible for this aroma reported in different studies varied to some extent. Zhang et al. employed the OAV method to identify 12 compounds that significantly contributed to the chestnut-like aroma, and further validated the reliability of these results through aroma recombination experiments[25]. Based on a comparative analysis of OAV and GC-O, Zhu et al. identified eight most significant differential odorants promoting the formation of chestnut-like aroma in green tea[18]. To compare the aroma characteristics between tender chestnut-like and typical chestnut-like green teas (the pure type) under the same analytical method, this study conducted GC-O analysis and OAV calculation on a typical chestnut-like Longjing tea (Fig. 4; Supplementary Table S4). A total of 15 aroma-active compounds were identified (AI: 1.17–4.00), among which 10 compounds with OAV > 1 were screened out as key aroma contributors, namely *(E)*-*β*-ionone (373.24), linalool (305.93), 3-ethyl-2,5-dimethylpyrazine (13.56), geraniol (10.84), hexanal (9.94), nonanal (8.37), heptanal (4.05), phenylethyl alcohol (1.51), benzeneacetaldehyde (1.34), and *(E)*-2-nonenal (1.32).

A total of eight compounds with OAV > 1 were shared between SNXM and Longjing tea, but their content levels differed considerably. The OAVs of linalool, nonanal, hexanal, heptanal, phenylethyl alcohol, and *(E)*-2-nonenal in SNXM were all higher than those in Longjing tea, while the OAVs of *(E)*-*β*-ionone and geraniol were lower (Supplementary Table S4). In addition, SNXM uniquely contained 1-octen-3-ol (11.49) and indole (1.57), imparting fresh green and delicate floral notes, whereas Longjing tea uniquely contained 3-ethyl-2,5-dimethylpyrazine (13.56) and benzeneacetaldehyde (1.34), contributing typical nutty/roasty and sweet aromas. Pyrazines, which possess nutty and roasty notes, are mainly derived from the Maillard reaction between amino acids and reducing sugars during tea processing[39], and exhibit high FD factors in pan-fired green teas[54]. In this study, the detection of 3-ethyl-2,5-dimethylpyrazine with a high OAV (13.56) in Longjing tea indicated that its 'typical chestnut-like aroma' is closely associated with the Maillard reaction induced by high-temperature pan-firing, resulting in a roasted/nutty-dominant aroma profile. In contrast, no roasty/nutty compounds with OAV > 1 were detected in SNXM, which may be attributed to the relatively low leaf temperature during its shaping and drying stages, leading to weaker Maillard reaction intensity. Meanwhile, the lower processing temperature also favored the retention of floral and fruity compounds (linalool, nonanal, phenylethyl alcohol, indole) as well as green-note compounds (hexanal, heptanal, (*E*)-2-nonenal, 1-octen-3-ol). In summary, SNXM shared key aroma compounds with chestnut-like green teas (linalool, *(E)*-*β*-ionone, nonanal, and heptanal)[18], as well as with floral-scented green teas (linalool, *(E)*-*β*-ionone, phenylethyl alcohol, heptanal, geraniol, and hexanal)[29], while also possessing its own unique key aroma compounds (indole and 1-octen-3-ol). This combined aroma profile—characterized by both chestnut-like and floral notes, along with its distinctive components—may account for the tender chestnut-like aroma of SNXM.

It is worth noting that the dynamic changes of the above 10 key aroma components during processing were not completely synchronized. Specifically, (*E*)-2-nonenal, nonanal, (*E*)-β-ionone, linalool, phenylethyl alcohol, and geraniol were clustered into Pattern I; 1-octen-3-ol followed Pattern II; and hexanal followed Pattern III. The mechanisms driving their specific trends have been discussed above. However, heptanal and indole exhibited slight deviations from their predominant patterns (Pattern I and Pattern IV, respectively). Heptanal, clustered in Pattern I, peaked in fresh leaves and then continuously decreased during spreading, fixation, and shaping before slightly rebounding during drying. Indole, clustered in Pattern IV, gradually declined from fresh leaves to shaping but surged dramatically to its highest level during drying. Interestingly, both compounds shared a common characteristic: a decrease from fresh leaves to shaping followed by an increase during drying. These observed trends were fully consistent with the data in Supplementary Table S3. The slight deviations from the *K*-means clustering patterns were likely due to the inherent limitation of clustering analysis, which groups compounds based on overall similarity while potentially overlooking minor variations (Fig. 3b). Mechanistically, the initial decline in both compounds can be attributed to the fact that their generation rates via enzymatic pathways (fatty acid oxidation for heptanal and tryptophan indole-lyase for indole) were surpassed by their volatilization loss during spreading[39,43]. The extremely high temperatures during fixation (190 °C) and shaping (190–210 °C) accelerated this evaporative loss. However, during the prolonged drying stage (85 °C, 45 min), the thermal cleavage of fatty acids and L-tryptophan, respectively, generated these compounds at a rate that exceeded their evaporation, resulting in a rebound in their contents, albeit with different magnitudes[39,46].

In summary, the formation of the tender chestnut-like aroma of SNXM green tea was the result of the synergistic action of three key procedures: spreading, fixation, and drying. Spreading promoted the accumulation of volatile compounds, fixation drove the transformation of aroma types, and drying facilitated the final formation of the tender chestnut-like aroma. Linalool, (*E*)-*β*-ionone, nonanal, hexanal, 1-octen-3-ol, geraniol, heptanal, phenylethyl alcohol,

indole, and (*E*)-2-nonenal acted synergistically to constitute the main chemical basis for the tender chestnut-like aroma of SNXM green tea.

Conclusions

In conclusion, this study experimentally characterized the dynamic evolution of volatile compounds during the manufacturing of SNXM green tea using GC-IMS, GC-MS, and chemometric analysis. Specifically, 59 and 86 volatile compounds were detected by GC-IMS and GC-MS, respectively. The total volatile content exhibited a dynamic trajectory of 'initial increase, subsequent decrease, and final rebound' throughout processing, with alcohols, aldehydes, and esters being the predominant chemical classes. PLS-DA analysis further revealed that spreading, fixation, and drying were the three critical stages associated with the most pronounced separation of volatile profiles, suggesting that these stages play a key role in governing the transformation of aroma compounds. Through GC-O analysis, 19 aroma-active compounds (AI: 1.17–3.67) were identified in the finished tea. Based on absolute quantification and OAV screening (OAV > 1), 10 volatile compounds—linalool, (*E*)-β-ionone, nonanal, hexanal, 1-octen-3-ol, geraniol, heptanal, phenylethyl alcohol, indole, and (*E*)-2-nonenal—were identified as candidate key odorants contributing to the characteristic tender chestnut-like aroma. Notably, although the 10 candidate odorants identified above were selected through OAV-based screening, their actual sensory contributions to the tender chestnut-like aroma require further validation through aroma recombination and omission experiments. Despite these limitations, these findings clarified the critical processing stages influencing aroma composition and identified candidate key odorants, thereby providing a framework for the quality control of SNXM green tea and the targeted processing of tender chestnut-like green teas.

Ethical statements

Not applicable.

Author contributions

The authors confirm their contributions to the paper as follows: study conception and design, review and editing: Zhou T; methodology, formal analysis: Tang Z, Zhou T; data collection: Tang Z, Chen D, Zhang R, Nan J, Tian J, Wang L, Qi Y, Wang C, Li Z, Dong Y, Liu D, Zhou T; resources: Tian J, He B, Zhang J, Zhou T; draft manuscript preparation: Tang Z; funding acquisition: Yu Y, Zhou T. All authors reviewed the results and approved the final version of the manuscript.

Data availability

All data generated or analyzed during this study are included in this published article and its supplementary information files.

Acknowledgments

This research was supported by the Shaanxi Key Research and Development Program (2025NC-YBXM-141).

Conflict of interest

The authors declare that they have no conflict of interest.

Supplementary information accompanies this paper online at: https://doi.org/10.48130/bpr-0026-0052.

Dates

Received 13 June 2026; Revised 27 September 2026; Accepted 28 September 2026; Published online 29 October 2026

References

[1] Jiang L, Zheng K. 2022. A rapid classification method of tea products utilizing X-ray photoelectron spectroscopy: relationship derived from correlation analysis, modeling, and quantum chemical calculation. *Food Research International* 160:111689

[2] Yi T, Zhu L, Peng WL, He XC, Chen HL, et al. 2015. Comparison of ten major constituents in seven types of processed tea using HPLC-DAD-MS followed by principal component and hierarchical cluster analysis. *LWT-Food Science and Technology* 62(1):194–201

[3] Qiu A, Wu S, Chen Y, Yu Z, Zhang D, et al. 2022. Dynamic changes of color, volatile, and non-volatile components during mechanized processing of green tea. *Journal of Food Processing and Preservation* 46(8):e16797

[4] Zhu YM, Dong JJ, Jin J, Liu JH, Zheng XQ, et al. 2021. Roasting process shaping the chemical profile of roasted green tea and the association with aroma features. *Food Chemistry* 353:129428

[5] ISO 20715. International Standard. 2023. Tea—classification of tea types. Geneva: Technical Committee ISO/TC 34, Food products, Subcommittee SC 8, Tea: International Organization for Standardization www.iso.org/standard/85745.html

[6] Yu J, Ho CT, Lin Z, Zhu Y, Feng Z, et al. 2023. Sensomics-assisted characterization of key flowery aroma compounds in *Lu'an guapian* green tea infusion (*Camellia sinensis*). *Journal of Agricultural and Food Chemistry* 71(15):6120–6132

[7] Qin M, Zhou J, Luo Q, Zhu J, Yu Z, et al. 2024. The key aroma components of steamed green tea decoded by sensomics and their changes under different withering degree. *Food Chemistry* 439:138176

[8] Wang Y, Luo H, Yuan L, Wu Q, Yang J, et al. 2021. 不同干燥方式对夏季绿茶香气品质的影响 [Effects of drying methods on volatile components of summer green tea]. *食品工业科技 [Science and Technology of Food Industry]* 42(9):1–9 (in Chinese)

[9] Yin P, Wang JJ, Kong YS, Zhu Y, Zhang JW, et al. 2022. Dynamic changes of volatile compounds during the Xinyang Maojian green tea manufacturing at an industrial scale. *Foods* 11(17):2682

[10] Lasekan O, Lasekan A. 2012. Flavour chemistry of mate and some common herbal teas. *Trends in Food Science & Technology* 27(1):37–46

[11] Chen Q, Zhu Y, Liu Y, Liu Y, Dong C, et al. 2022. Black tea aroma formation during the fermentation period. *Food Chemistry* 374:131640

[12] Feng Z, Li Y, Li M, Wang Y, Zhang L, et al. 2019. Tea aroma formation from six model manufacturing processes. *Food Chemistry* 285:347–354

[13] Flaig M, Qi S, Wei G, Yang X, Schieberle P. 2020. Characterization of the key odorants in a high-grade Chinese green tea beverage (*Camellia sinensis*; Jingshan cha) by means of the sensomics approach and elucidation of odorant changes in tea leaves caused by the tea manufacturing process. *Journal of Agricultural and Food Chemistry* 68(18):5168–5179

[14] Huang J, Shi Z. 2022. 茶叶审评与检验（第五版） *Tea evaluation and inspection*. 5th Edition. Beijing: China Agriculture Press. pp. 37–63 (in Chinese)

[15] Zhang M, Yang Y, Yuan H, Hua J, Deng Y, et al. 2020. Contribution of addition theanine/sucrose on the formation of chestnut-like aroma of green tea. *LWT* 129:109512

[16] Zhu Y, Lv HP, Dai WD, Guo L, Tan JF, et al. 2016. Separation of aroma components in Xihu Longjing tea using simultaneous distillation extraction with comprehensive two-dimensional gas

chromatography-time-of-flight mass spectrometry. *Separation and Purification Technology* 164:146–154

[17] Liu N, Shen S, Huang L, Deng G, Wei Y, et al. 2023. Revelation of volatile contributions in green teas with different aroma types by GC–MS and GC–IMS. *Food Research International* 169:112845

[18] Zhu Y, Lv HP, Shao CY, Kang S, Zhang Y, et al. 2018. Identification of key odorants responsible for chestnut-like aroma quality of green teas. *Food Research International* 108:74–82

[19] Yin P, Kong YS, Liu PP, Jiang CL, Sun MF, et al. 2022. Temporal variation of the non-volatile compounds and key odorants in Xinyang Maojian green teas during the spring and autumn seasons. *Agronomy* 12(5):1085

[20] Wang M, Zhu Y, Zhang Y, Shi J, Lv H, et al. 2019. "清香" 绿茶的挥发性成分及其关键香气成分分析 [Analysis of volatile composition and key aroma compounds of green teas with fresh scent flavor]. *食品科学 [Food Science]* 40(22):219–228 (in Chinese)

[21] Huang H, Ao C, Guo M, Yu J, Mao Y, et al. 2018. 花香与清香绿茶的香气组分及品种相关性分析 [Study on aroma components of scent-flavor and floral-flavor tea and its correlation analysis]. *浙江农业科学 [Journal of Zhejiang Agricultural Sciences]* 59(5):738–741,771 (in Chinese)

[22] Zhou S, Huang C, Li C, Gong S, Guo H, et al. 2021. 不同香气类型龙井茶香气组成及其相关组分比较 [Aroma compositions and comparison of their related components of Longjing tea with different aroma types]. *浙江大学学报 (农业与生命科学版) [Journal of Zhejiang University (Agriculture and Life Sciences)]* 47(2):203–211 (in Chinese)

[23] Yang Y, Zhang M, Yin H, Deng Y, Jiang Y, et al. 2018. Rapid profiling of volatile compounds in green teas using Micro-Chamber/Thermal Extractor combined with thermal desorption coupled to gas chromatography-mass spectrometry followed by multivariate statistical analysis. *LWT* 96:42–50

[24] Yin H, Yang Y, Yao Y, Zhang M, Wang J, et al. 2019. 基于气相色谱-质谱技术与多元统计分析对不同栗香特征绿茶判别分析 [Discrimination of different characteristics of chestnut-like green tea based on gas chromatography-mass spectrometry and multivariate statistical data analysis]. *食品科学 [Food Science]* 40(4):192–198 (in Chinese)

[25] Zhang M, Yin H, Deng Y, Yao Y, Jiang Y, et al. 2020. 基于 HS-SPME/GC×GC-TOFMS/OAV 不同栗香特征绿茶关键香气组分分析 [Analysis of key odorants responsible for different chestnut-like aromas of green teas based on headspace solid-phase microextraction coupled with comprehensive two-dimensional gas chromatography time-of-flight mass spectrometry and odor activity value]. *食品科学 [Food Science]* 41(2):244–252 (in Chinese)

[26] Wang B, Qu F, Wang P, Zhao L, Wang Z, et al. 2022. Characterization analysis of flavor compounds in green teas at different drying temperature. *LWT* 161:113394

[27] Yang Y, Chen J, Jiang Y, Qian MC, Deng Y, et al. 2022. Aroma dynamic characteristics during the drying process of green tea by gas phase electronic nose and gas chromatography-ion mobility spectrometry. *LWT* 154:112691

[28] Yang Y, Qian MC, Deng Y, Yuan H, Jiang Y. 2022. Insight into aroma dynamic changes during the whole manufacturing process of chestnut-like aroma green tea by combining GC-E-Nose, GC-IMS, and GC × GC-TOFMS. *Food Chemistry* 387:132813

[29] Xie J, Wang L, Deng Y, Yuan H, Zhu J, et al. 2023. Characterization of the key odorants in floral aroma green tea based on GC-E-Nose, GC-IMS, GC-MS and aroma recombination and investigation of the dynamic changes and aroma formation during processing. *Food Chemistry* 427:136641

[30] Yao W, Cai Y, Liu D, Chen Y, Li J, et al. 2022. Analysis of flavor formation during production of Dezhou braised chicken using headspace-gas chromatography-ion mobility spec-trometry (HS-GC-IMS). *Food Chemistry* 370:130989

[31] Chen Z, Mei X, Jin Y, Kim EH, Yang Z, et al. 2014. Optimisation of supercritical carbon dioxide extraction of essential oil of flowers of tea (*Camellia sinensis* L.) plants and its antioxidative activity. *Journal of the Science of Food and Agriculture* 94(2):316–321

[32] Xiao Y, Huang Y, Chen Y, Xiao L, Zhang X, et al. 2022. Discrimination and characterization of the volatile profiles of five Fu brick teas from different manufacturing regions by using HS-SPME/GC-MS and HS-GC-IMS. *Current Research in Food Science* 5:1788–1807

[33] Duan Y, Gao X, Shi B, Yu M, Raza J, et al. 2025. Characterize the dynamic changes of volatile compounds during the roasting process of Wuyi rock tea (Shuixian) integrating GC-IMS and GC × GC-O-MS combined with machine learning. *Food Chemistry* 489:144931

[34] Lin Y, Wang Y, Huang Y, Song H, Yang P. 2023. Aroma identification and classification in 18 kinds of teas (*Camellia sinensis*) by sensory evaluation, HS-SPME-GC-IMS/GC × GC-MS, and chemometrics. *Foods* 12(13):2433

[35] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of the People's Republic of China. 2018. *GB/T 23776-2018* 茶叶感官审评方法 *[GB/T 23776 -2018 Methodology for sensory evaluation of tea]*. Beijing: Standards Press of China (in Chinese)

[36] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of the People's Republic of China. 2018. *GB/T 14487-2017* 茶叶感官审评术语 *[GB/T 14487 -2017 Tea vocabulary for sensory evaluation]*. Beijing: Standards Press of China (in Chinese)

[37] Liu P, Zheng P, Feng L, Gong Z, Zheng L, et al. 2022. Dynamic changes in the aroma profile of Qingzhuan tea during its manufacture. *Food Chemistry* 375:131847

[38] Guo X, Ho CT, Wan X, Zhu H, Liu Q, et al. 2021. Changes of volatile compounds and odor profiles in Wuyi rock tea during processing. *Food Chemistry* 341:128230

[39] Ho CT, Zheng X, Li S. 2015. Tea aroma formation. *Food Science and Human Wellness* 4(1):9–27

[40] Wan X. 2003. 茶叶生物化学（第三版） *[Tea biochemistry (3rd Edition)]*. Beijing: China Agriculture Press. pp. 219–245 (in Chinese)

[41] Sasaki T, Ochiai N, Yamazaki Y, Sasamoto K. 2023. Solvent-assisted stir bar sorptive extraction and gas chromatography-mass spectrometry with simultaneous olfactometry for the characterization of aroma compounds in Japanese Yamahai-brewed sake. *Food Chemistry* 405:134640

[42] Wang MQ, Ma WJ, Shi J, Zhu Y, Lin Z, et al. 2020. Characterization of the key aroma compounds in Longjing tea using stir bar sorptive extraction (SBSE) combined with gas chromatography-mass spectrometry (GC-MS), gas chromatography-olfactometry (GC-O), odor activity value (OAV), and aroma recombination. *Food Research International* 130:108908

[43] Qiao D, Mi X, An Y, Xie H, Cao K, et al. 2021. Integrated metabolic phenotypes and gene expression profiles revealed the effect of spreading on aroma volatiles formation in postharvest leaves of green tea. *Food Research International* 149:110680

[44] Baba R, Kumazawa K. 2014. Characterization of the potent odorants contributing to the characteristic aroma of Chinese green tea infusions by aroma extract dilution analysis. *Journal of Agricultural and Food Chemistry* 62(33):8308–8313

[45] Luo J, Ding F, Dai Y, Liu Z, Yang C, et al. 2026. GC-MS analysis reveals the evolution of key aroma compounds during the processing of 'Qiancha 1' white tea. *Journal of Food Measurement and Characterization* 20:7524–7539

[46] Zhang J, Zhao C, Lv J, Qiu G, Tian H. 2025. Description of key aroma components of green tea and the influence of processing. *Journal of Food Composition and Analysis* 141:107367

[47] Lei X, Zhang C, Yan J, Chen Y, Wang W, et al. 2026. Molecular mechanisms and processing regulation of tea aroma. *Horticultural Plant Journal* 12(8):1747–1766

[48] Yin P, Kong YS, Liu PP, Wang JJ, Zhu Y, et al. 2022. A critical review of key odorants in green tea: identification and biochemical formation pathway. *Trends in Food Science & Technology* 129:221−232

[49] Yang T, Zhu Y, Shao CY, Zhang Y, Shi J, et al. 2016. Enantiomeric analysis of linalool in teas using headspace solid-phase microextraction with chiral gas chromatography. *Industrial Crops and Products* 83:17−23

[50] Tontul I, Torun M, Dincer C, Sahin-Nadeem H, Topuz A, et al. 2013. Comparative study on volatile compounds in Turkish green tea powder: impact of tea clone, shading level and shooting period. *Food Research International* 53(2):744−750

[51] Zhang Z, Yang Y, Sun H, Hong P, Huang G, et al. 2016. 3 种清香型铁观音挥发性成分及香味特征 [Volatile components and aroma characteristics of three types of Qingxiang Tieguanyin]. *集美大学学报 [Journal of Jimei University]* 21(3):175−183 (in Chinese)

[52] Yang YQ, Yin HX, Yuan HB, Jiang YW, Dong CW, et al. 2018. Characterization of the volatile components in green tea by IRAE-HS-SPME/GC-MS combined with multivariate analysis. *PLoS One* 13(3):e0193393

[53] Joshi R, Gulati A. 2015. Fractionation and identification of minor and aroma-active constituents in Kangra orthodox black tea. *Food Chemistry* 167:290−298

[54] Kumazawa K, Masuda H. 2002. Identification of potent odorants in different green tea varieties using flavor dilution technique. *Journal of Agricultural and Food Chemistry* 50(20):5660−5663

Copyright: © 2026 by the author(s). Published by Maximum Academic Press, Fayetteville, GA. This article is an open access article distributed under Creative Commons Attribution License (CC BY 4.0), visit https://creativecommons.org/licenses/by/4.0/.