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Why Does Braising Enhance the Aroma Profile of Xinjiang Braised–Roasted Chicken? Insights into Precursor Conversion and Aroma Formation Pathways

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ABSTRACT

Braising could significantly enhance the aroma profile of Xinjiang traditional roasted chicken, but the underlying mechanisms remain unclear. This study investigated the mechanisms underlying the enhanced aroma profile of Xinjiang braised-roasted chicken (BRC) using sensory evaluation, GC–MS, fatty acid profiling, free amino acid analysis, and reducing sugar determination. A total of 70 aroma compounds were identified, with BRC exhibiting the highest concentration and diversity. Compared with single treatments (marination, braising, or roasting), the combined braise-then-roast process enriched terpenoids, furans, pyrazines, and phenolic compounds, while reducing off-odor compounds. Correlation analysis revealed that lipid oxidation, Maillard reactions, and spice-derived volatiles synergistically shaped the aroma profile. The findings demonstrate that braising promotes precursor accumulation and spice infusion, while roasting activates thermal reactions, jointly enhancing aroma intensity and complexity. These results provide mechanistic insights into the unique flavor of Xinjiang BRC and may support quality optimization in meat processing industries.

1. Introduction

Braised–roasted chicken (BRC) is highly popular among consumers for its complex and distinctive aroma and taste in the south of the Xinjiang Uyghur Autonomous Region, China (hereinafter referred to as “Xinjiang”). Unlike the single-step roasted or braised chicken that commonly found in other regions, BRC adopts a “braising–then–roasting” sequence that reflects the regional cooking characteristics of Xinjiang. In the braising stage, chicken is simmered in a spice-rich broth containing cumin, chili, cinnamon, and star anise, which promotes the penetration of spice constituents and the enrichment and transformation of flavor precursors (such as reducing sugars, free amino acids, and fatty acids) (Xu et al., 2020; Yao et al., 2020). The subsequent roasting stage further triggers lipid oxidation, Maillard, and related coupled reactions under high temperatures, resulting in strong aromas (Dashdorj et al., 2015; Shi et al., 2019). Because this combined process exhibits significant Xinjiang regional characteristics and has not been systematically studied, elucidating the contribution of braising to the overall flavor formation of BRC is of both culinary and scientific importance.

The flavor of cooked chicken arises from the interplay between non-volatile precursors—such as free amino acids, fatty acids, and reducing sugars—and volatile compounds including aldehydes, ketones, alcohols, esters, and heterocyclics (Yang et al., 2022; Zhang et al., 2019). During thermal processing, Maillard reactions, Strecker degradation, and lipid oxidation occur simultaneously, generating aroma-active compounds that contribute to meaty and roasted characteristics (Wang et al., 2022). Lipid-derived products are particularly important in shaping the overall aroma of meat (Luo et al., 2022). In addition, spice-derived constituents may migrate into the muscle matrix and interact with proteins or lipids, further modifying volatile composition (Wang et al., 2023). Although numerous studies have examined volatile compounds in roasted or braised chicken, the stage-wise evolution of precursors and volatiles in Xinjiang BRC has not been systematically characterized, and the

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relationships between precursor composition and key odorants remain unclear. Addressing these gaps is essential for understanding the flavor uniqueness and complexity of BRC.

Therefore, this study aims to elucidate how different processing stages—particularly the braising and roasting steps—affect flavor precursor transformation and aroma formation in Xinjiang BRC. Specifically, the objectives are to: (1) characterize the aroma substances of marinated chicken(MC), braised chicken(BC), roasted chicken(RC), and BRC by GC–MS, respectively, and screen out the dominant flavor compounds in BRC; (2) explore the relationship between aroma precursors reducing sugars, amino acids, and fatty acids and the dominant aroma compounds in BRC; and (3) reveal the formation mechanism of key aroma compounds in BRC, providing a theoretical basis for optimizing the flavor quality of BRC.

2. Materials and Methods

2.1. Materials and chemicals

Thirty-six randomly selected yellow-feathered chickens (73–78 days old) were obtained from Kezhou Tycoon Food Co., Ltd., Urumqi, China, with a carcass weight of 1.5 ± 0.2 kg. After washing with cold water, the chicken carcasses were frozen to −35 °C, vacuum-packed, and then transported to the laboratory through typical cold chain logistics (−25 °C). 2-Methyl-3-heptanone (99%) standards were purchased from Sigma-Aldrich (Sigma Aldrich, St. Louis, MO, U.S.A.). N-alkanes (C_7-C_{40}) was purchased from Beijing Biochem Biotechnology Co., Ltd. Other chemicals were purchased from Sinopharm Chemical Reagent Beijing Co. Ltd. (Beijing, China).

2.2. Sample preparation

The sample preparation method was obtained through orthogonal optimization experiments, and the specific preparation method is as follows: Chickens were first immersed in a spice extract (prepared from the same spice formulation used for braising) for 30 min and then marinated at 4 °C for 12 h to obtain MC. The marinated chickens were subsequently braised at 90 °C for 25 min in the same spice mixture to obtain BC. The braised chicken was then baked in an oven at 115 °C for 30 min to obtain BRC. RC was obtained by direct roasting without braising. After natural cooling to room temperature, the skin, breast, and leg muscles were chopped using an FSJ-A03D1 meat grinder. As BRC is consumed as a whole-chicken product, the skin, breast, and leg portions were mixed in their original proportions to simulate the actual flavor composition of the final product. This approach also minimized variability caused by regional differences in fat and protein distribution among chicken parts. All samples were rapidly frozen in liquid nitrogen, sealed in polyamide/polyethylene bags, and stored at −80 °C. A detailed workflow is shown in Fig. 1.

2.3. Quantitative descriptive analysis (QDA)

The sensory evaluation team consisted of 12 members, including 6 males and 6 females. They were all from the Chinese food processing and equipment innovation team of institute of food science and technology, Beijing, China. The sensory assessors received training before the formal experiment to improve their ability to perceive, distinguish, and describe flavors. Specifically, the panelists underwent daily training for one week (once a day, 1 h per session) to ensure accurate recognition and discrimination of the aroma attributes in the samples, including familiarization with descriptor definitions and calibration of the intensity scale using reference standards, to develop discrimination skills as described in (ISO 8586, 2012) (Sensory analysis—General guidelines for the selection, training and monitoring of selected assessors and expert sensory assessors) and Yao et al. (2024).Based on relevant food standards and discussions within the sensory analysis team, six flavor descriptors were determined: meaty, caramel, roasted, oily, spice-aroma, and poultry-like. The food references were prepared as follows: meaty (roasted chicken breast, roasted at 180 °C for 10 min, size 1 × 1 × 0.5 cm, intensity 3.0), caramel (caramel popcorn, weight: 2 g, intensity 3.0), roasted (roasted peanut pieces, weight: 2 g, intensity 2.5), oily (chicken fat, weight: 2 g, intensity 2.5), spice-aroma (spice bag, weight: 2 g, intensity 2.5), poultry-like (raw/animal-like note, considered an off-flavor, weight: 2 g, intensity 2.5). The sensory analysis laboratory was maintained at a constant temperature of 25 °C, all panellists rated the intensity of the odor descriptors on a scale of 0–3 with 0.5 points per level. Each team member participated voluntarily and was informed of the experimental sample preparation and evaluation methods. All samples were confirmed to be non-toxic and safe for humans. The team members fully understood the requirements and risks of the study and gave their consent. All details about the sensory assessors were kept confidential.

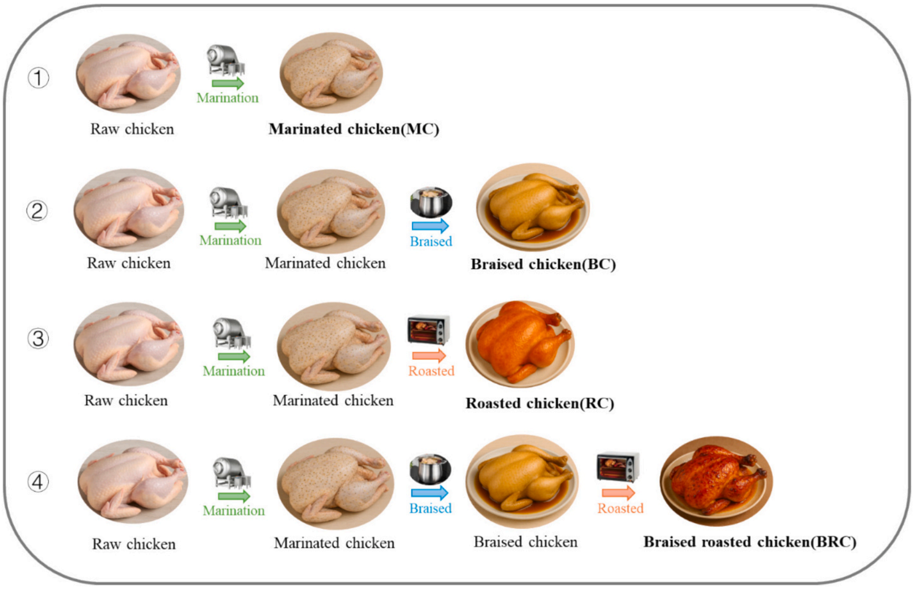

Fig. 1. Workflow of chicken processing under different cooking methods.

2.4. GC–MS analysis

Volatile flavor compounds were detected by headspace solid phase microextraction (SPME, Supelco, Bellefonte, PA) combined with gas chromatography-mass spectrometry (8860–5977 GC–MS system, Agilent, Agilent Technologies, Santa Clara, CA) according to the method of Chen et al. (2024) with slight modifications. In brief, 2.0 g of sample was accurately weighed in a 20 mL headspace vial, 1 μL of 13.6 mg/L 2-methyl-3-heptanone was added as an internal standard, and the vial was quickly sealed with a polytetrafluoroethylene (PTFE) cap. After preheating at 60 °C for 20 min, a baked extraction fiber (50/30 μm, 2 cm, DVB/CAR/PDMS) was used for adsorption at 60 °C for 40 min, followed by desorption at 250 °C for 5 min at the injection port. The ratio of sample to mass spectrometer and sniffer was 1:1. The temperature program was as follows: an initial temperature of 40 °C, held for 3 min, then ramped to 210 °C at a rate of 5 °C/min and held for 1 min. The temperature was then ramped to 230 °C at 8 °C/min and held for 3 min. DB-WAX column (30 m × 0.25 mm × 0.25 μm, Agilent Technologies, Santa Clara, USA) was used to separate the volatile compounds. Helium (99.999% purity) was used as carrier gas with a flow rate of 1 mL/min. MS fragmentation was detected in electron impact (EI) mode (electron energy 70 eV), with a mass scan range of m/z 30–400. The transfer line temperature was 280 °C, and the ion source temperature was 250 °C.

2.5. Qualitative and quantitative analysis of volatile flavor compounds

Retention index (RI) was calculated based on the linear retention time of alkanes (C_7-C_{40}). Compared with the National Institute of Standards and Technology (NIST) database, the MS identification of the compounds was performed. Further, a qualitative analysis was performed by odor description (O) and verified by the standard compounds (STD).The retention index (RI value) of each compound to be tested was calculated. The retention index calculation formula is as follows:

$$RI = \frac{t_x - t_n}{t_{n+1} - t_n} \times 100 + n \times 100\# \tag{1}$$

In formula (1), t_x is the retention time of the sample (min), t_n is the retention time of normal alkane C_n (min), and t_{n+1} is the retention time of normal alkane C_{n+1} (min).

The concentration of each volatile compound is calculated based on the ratio between the peak area of each volatile compound and the peak area of 2-methyl-3-heptanone.

$$C_i = \frac{A_i \times C_s}{A_s}\# \tag{2}$$

In formula (2), C_i represents the concentration of each volatile compound(ng/g), A_i represents the peak area of each volatile compound, C_s represents the concentration of 2-methyl-3-heptanone (ng/g), A_s represents the peak area of 2-methyl-3-heptanone.

2.6. Odor activity values (OAVs) analysis

The OAV was calculated by dividing the concentration of the compound by its threshold value in water according to Formula 3. When OAV > 1, the compound was identified as the key aroma-active compound.

$$OAV = \frac{C}{T}\# \tag{3}$$

C is the concentration of the compound based on the standard addition method or the internal standard method, and T is the odor threshold of the compound in water(Sohail et al., 2022; Van Gemert, 1977).

2.7. Fatty acid analysis

The fatty acid content was determined by the internal standard method according to the National Food Safety Standard Determination of Fatty Acids in Food (GB 5009.168–2016). First, 5 g of chicken sample was weighed into a 250 mL flat-bottom flask, and 2 mL of 11-carbonic acid triglyceride internal standard solution (5.00 mg/mL) and 100 mg of pyrogallic acid were added. Then, 2 mL of 95% ethanol and 4 mL of deionized water were added, mixed and then acid hydrolysed. 10 mL of hydrochloric acid solution was added, and heated in a 70–80 °C water bath for 40 min, shaking every 10 min. After hydrolysis, the hydrolysate was transferred to a separatory funnel, and 50 mL of ether-petroleum ether mixture (1,1, *v*/v) was added. The mixture was shaken and extracted 3 times, the organic phases were combined, and the solvent was removed by rotary evaporation to obtain a fat extract.

The obtained lipid extract was refluxed with 8 mL of 2% NaOH/methanol solution in an 80 °C water bath until the oil droplets disappeared. Then, 7 mL of 15% BF3/methanol solution was added and the reaction continued in an 80 °C water bath for 2 min. After the reaction was completed, it was cooled to room temperature, 10 mL of n-heptane was added, and the mixture was shaken for 2 min. Then, a saturated NaCl solution was added, and the layers were allowed to stand. The upper n-heptane extract was taken for gas chromatography analysis.

Fatty acid analysis was performed using an Agilent 7890B gas chromatograph equipped with a hydrogen flame ionization detector (FID) and a capillary column (100 m × 0.25 mm × 0.2 μm, Supelco CD-2560). The carrier gas was high-purity nitrogen with a flow rate of 5 mL/min, a split ratio of 100:1, and an injection volume of 1 μL. The injection port and detector temperatures were 270 °C and 280 °C, respectively. The column temperature program was as follows: initial temperature 100 °C, maintained for 13 min; heated to 180 °C at 10 °C/min, maintained for 6 min; heated to 200 °C at 1 °C/min, maintained for 20 min; and finally heated to 230 °C at 4 °C/min, maintained for 10 min.

2.8. Free amino acids (FAAs) analysis

Refer to the method of Geng et al. (2018) with slight modifications. Take 5 g of the crushed sample, add 20 mL of ultrapure water, homogenize in an ice bath at 18000 r/min for 3 times (10 s each time, 10 s interval), add 20 mL of 5% (*v*/v) trichloroacetic acid aqueous solution, mix well, and place at 4 °C for 12 h; filter with qualitative filter paper after taking out, adjust the pH of the filtrate to 6.0 with 4 mol/L KOH, and then make up to 50 mL with ultrapure water, take 1 mL and filter with 0.45 μm filter membrane for use. Take 10 μL of the obtained filtrate, treat it according to the pre-column derivatization method, and use RP-HPLC to determine the content of free amino acids in the sample.

Pre-column derivatization: dilute the amino acid mixed standard solution to 10, 25, 50, 75, 100, and 200 μmol/L respectively. Pass through a 0.45 μm filter membrane, accurately pipette 10 μL of the diluted standard sample into the bottom of the derivatization tube, add 70 μL AccQ·Fluor Buffer into the derivatization tube, then pipette 20 μL of the freshly prepared AccQ·Fluor derivatization agent, add it to the derivatization tube, keep vortex mixing for 10 s, leave it at room temperature for 1 min, place it in a 55 °C oven and heat it for 10 min. When the powder is completely dissolved, take it out and inject it.

Chromatographic conditions: Nova-Pak TM C18 amino acid analysis column, column temperature: 37 °C, UV detection wavelength: 248 nm, injection volume: 10 μL, flow rate: 1.0 mL/min. Mobile phase A: AccQ·Tag Eluent A, diluted with ultrapure water at 1:10 (*V*/V); mobile phase B: acetonitrile (chromatographic grade); mobile phase C: ultrapure water.

2.9. Total reducing sugar analysis

The method for determining total reducing sugars was based on Zhao et al. (2019) and was appropriately improved. One gram of meat sample was homogenized with 5 mL of 80% ethanol at 50 °C and centrifuged at 4500 rpm for 10 min. The supernatant was filtered with filter paper and dried with nitrogen gas with a purity of ≥99.999%. The residual sugar was then dissolved in 2 mL of distilled water, and 1 mL of the solution was mixed with 2 mL of dinitrosalicylic acid (DNS) reagent (formula: 8 g of sodium hydroxide, 0.5 g of DNS, and 150 g of potassium sodium tartrate dissolved in 500 mL of distilled water) and heated in a 90 °C water bath for 5 min. After cooling, the absorbance was measured using a microplate reader at a wavelength of 550 nm, and the reducing sugar content in the sample was calculated based on the glucose standard curve.

2.10. *Statistical analysis*

All experiments were repeated three times for replicability and to limit human error. Data were analysed using ANOVA followed by Duncan's test using SPSS (version 26.0, IBM Corporation) for Windows, and differences among means were significant at $P < 0.05$. Origin 2018 software was used for statistical analysis and plotting of experimental results and figures. Heatmaps, Venn diagrams, and correlation plots were generated using the online platform Chiplot (https://www.chiplot.online). All data are expressed as mean ± standard deviation (SD, $n = 3$).

3. Results and Discussion

3.1. *Sensory evaluation*

As can be observed from Fig. 2, the sensory panel gave higher scores to the poultry-like in MC. Raw meat only has a bloody smell and no aroma, which is consistent with the results reported by previous researchers (Jayasena et al., 2013). After marination, the raw meat exhibited a noticeable herbal aroma and spice-aroma, attributed to the added spices. Following braising, the intensity of the ‘poultry-like’ note in BC decreased significantly, while the spice-aroma became more pronounced. This is due to the spices in the marinade imparting to the chicken. Qiang et al. (2025) found that terpenes in cloves migrate into beef, thereby increasing the aroma of beef. Similarly, Li et al. (2016) found that camphene, β-pterene and β-citral in ginger were detected in fish soup, indicating that these terpenes in ginger can migrate into fish soup. After being roasted, RC and BRC had a higher caramel and roasted score, which was due to the Maillard reaction during the roasting process. Similarly, among the four groups of samples, BRC had the highest meaty score. After undergoing braising followed by roasting, the chicken develops a markedly more intense aroma.

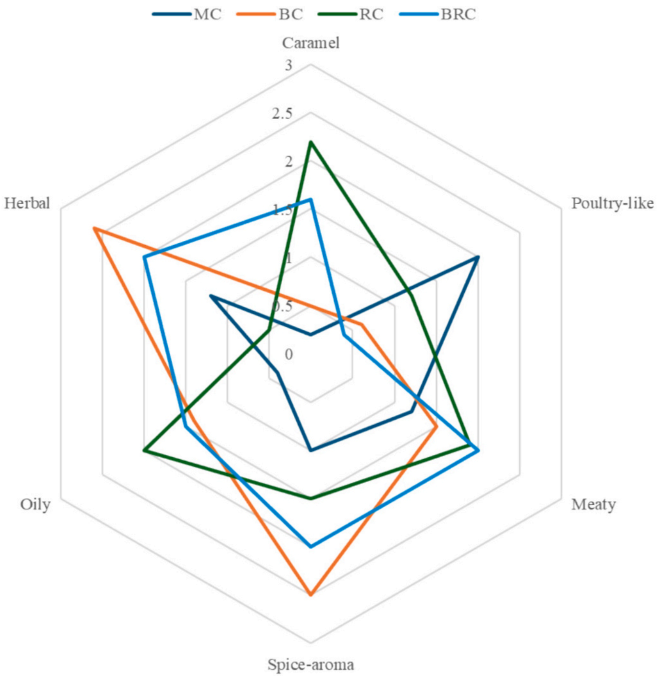

Fig. 2. Sensory evaluation of chicken under different treatment conditions. MC, marinated chicken; BC, braised chicken; RC, roasted chicken; BRC, braised-roasted chicken.

3.2. *GC–MS analysis of aroma compounds*

Heat maps and stacked bar charts were used to observe the dynamic changes in the content and types of aroma compounds in chicken at different processing stages (Fig. 3). In addition, a Venn diagram was employed to provide a more intuitive visualization of the differences among the four samples (Fig. 4). A total of 71 aroma compounds were detected using GC–MS (See Tables 1–2). Among them, 19, 44, 46, and 54 flavor compounds were measured in the four samples of MC, BC, RC and BRC, respectively. As can be observed from Fig. 3B, the fewest flavor compounds types were detected in the chicken that was only marinated, only 5 types. The number of chicken compound types after braising increased to 8. The chicken that was roasted after braising combined the pyrazine compounds unique to the roasting process with the esters and aromatic hydrocarbon compounds contained in the braising process, which was richer than the chicken roasted alone. The above results highlight the important contribution of braising in the formation of aroma. The concentration of aroma compounds in BRC was also significantly higher than that in BC, RC, and MC groups, which indicated that the combined process of braising and roasting had a significant synergistic effect in regulating the formation of chicken aroma, and the enhancement of this aroma was mainly attributed to the mechanism of multiple interactions.

Aldehydes are an important aroma compounds in chicken, especially closely related to lipid oxidation. The data showed that the aldehyde content in the BC and RC groups was significantly higher than that in the MC and BRC groups. For example, hexanal, octanal, and nonanal reached 26.04, 71.67, and 108.82 ng/g in BC, respectively, which was much higher than 1.59, 1.11, and 2.04 ng/g in the MC group. In contrast, these three compounds in the BRC group decreased to 5.63, 8.34, and 20.22 ng/g, respectively, showing a significant inhibitory trend. In addition, more types of long-chain aldehydes such as decanal, (*E*)-2-octenal, and (*E*)-2-nonenal were detected in the BC group, while they were almost not detected in the BRC, indicating that although some fat oxidation products were released during the marinating process, the subsequent high-temperature heat treatment would cause these aldehydes to be transformed, degraded, or masked by aroma compounds (Qin et al., 2020). Therefore, the BRC group effectively reduced the risk of unpleasant odors such as oily and poultry-like while maintaining meaty odor. Wan et al. (2023) found that the use of star anise in braised duck legs inhibited the release of fatty aldehydes in the meat, reducing the bloody and greasy odors in braised duck legs. This finding is consistent with our results. The effect may be due to the polyphenols in plant spices. Polyphenols can react with fatty acid radicals or hydroxyl radicals, preventing the spread of lipid peroxidation in the meat (Al-Dalali, Li and Xu, 2022).

The content of alcohols in the RC and BC groups was relatively high, especially 1-hexanol and 1-octen-3-ol, which were as high as 225.15 and 79.4 ng/g in BC, respectively. Although these compounds have a certain grassy or mushroom smell, they are prone to cause fishy discomfort at high concentrations (Pu et al., 2022). It is worth noting that the concentrations of most alcohols in the BRC group decreased significantly, such as 1-octen-3-ol dropped to 10.12 ng/g, and 1-hexanol was not even detected. It is speculated that BRC treatment not only promotes the oxidation of alcohols to aldehydes or further participates in the Maillard reaction through thermal reactions (Nie et al., 2024), but also may reduce potential poultry-like odor risks and optimize aroma profiles through reaction pathway regulation (Zhang et al., 2021).

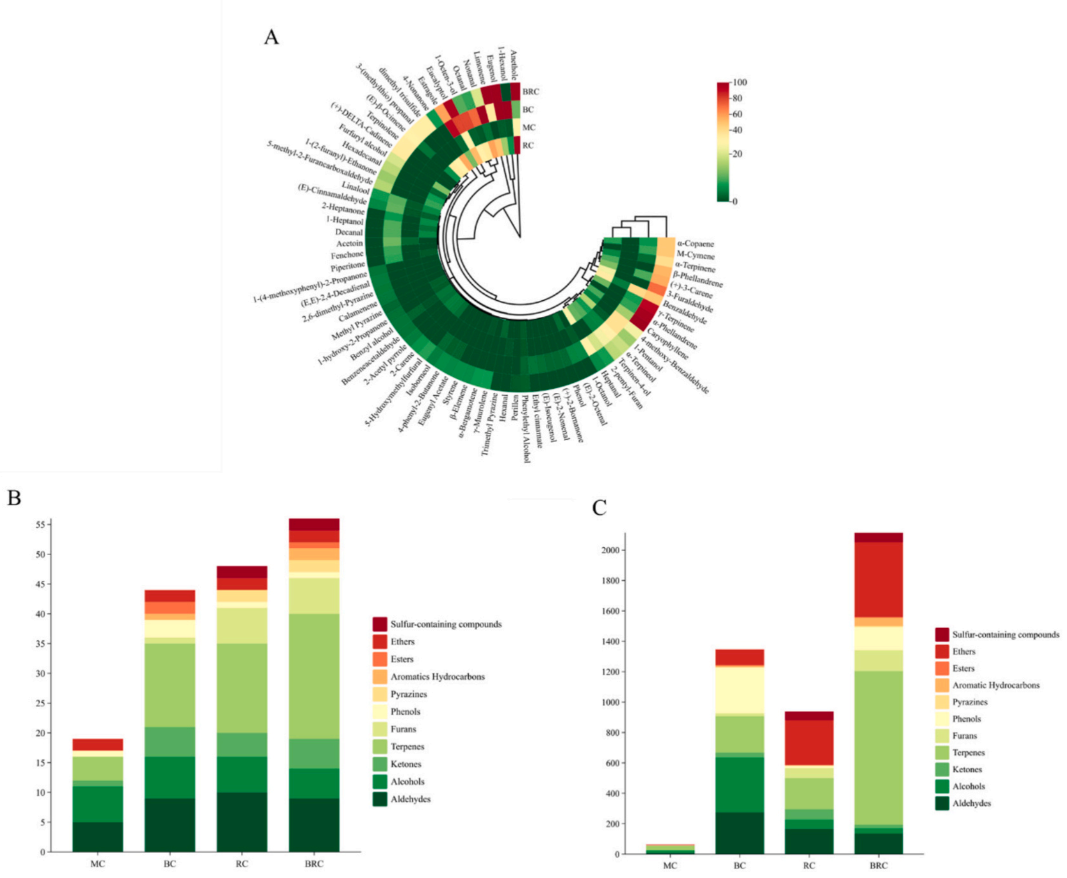

Fig. 3. Comparative analysis of volatile flavor compounds profiles in chicken under different treatments. (A) Radial clustering heatmap of volatile flavor compounds. (B) Number of volatile flavor compounds detected in each group. (C) Total concentration of volatile flavor compounds classified by chemical type. MC, marinated chicken; BC, braised chicken; RC, roasted chicken; BRC, braised-roasted chicken.

Ketones are common intermediates in thermal reactions, and their aroma characteristics vary due to structural differences. The content of 4-nonanone in the RC group was as high as 56.65 ng/g, while it dropped to 7.09 ng/g in the BRC group. Similarly, 2-heptanone and 2-bornanone also appeared in the BC and RC groups, but were no longer enriched in the BRC. This may be due to the fact that some of the precursors were consumed in advance by brine preparation, or that ketones in the BRC reaction system were converted into other more stable or pleasant volatile compounds (Sun et al., 2023).

The total amount of terpenoids in the BRC group was as high as 1502.54 ng/g, which was 3–40 times that of the RC, BC, and MC groups. Especially represented by limonene, anethole, α-phellandrene, caryophyllene, etc., these compounds are usually derived from spicy plants in the marinade, indicating that the braising process achieves the effective migration and fixation of a large number of spice aromas, and the subsequent roasting further releases or stimulates these compounds, making them highly enriched in BRC. Qiang et al. (2025) investigated the migration of odor-active compounds from clove during cooking. After stewing, several clove-derived odorants were detected in stewed beef, and their OAVs exceeded 1, indicating that the aroma of stewed beef (SBC) was notably influenced by clove. In addition, it has been reported that aldehydes dominate the aroma profile of stewed pork in the absence of star anise; however, upon the addition of star anise, (E)-anethole, 1,8-cineole, and linalool were found to migrate into the stewed pork matrix (Qin et al., 2020). Limonene and eucalyptol, are responsible for citrusy, floral, and herbaceous notes. In our study, the concentration of limonene increased significantly during the braising and roasting processes, contributing to the bright, fresh aromas in the BRC group. The higher concentration of terpenoids in the BRC group led to a fresher, more complex aroma. This increase in terpenoid concentration helped mask oxidation-related off-odors, contributing to an overall more pleasant sensory profile. In addition, terpenes exhibit strong affinity with lipid and protein molecules because of their small molecular size and hydrophobicity, allowing them to interact with fat via van der Waals forces and with proteins through hydrophobic interactions (Bi et al., 2025; Liu et al., 2025). These properties enable terpenes to be effectively adsorbed and retained within the meat matrix during the braising process. Upon subsequent roasting, the elevated temperature promotes their volatilization and release, resulting in a rich spice aroma and contributing to the unique and complex flavor characteristics of BRC.

The BRC group showed significant enrichment of furans and pyrazines, such as furfural, furfuryl alcohol, 5-methyl-2-furancarboxaldehyde, and 2,6-dimethylpyrazine. These compounds are typical products of the Maillard reaction and thermal cracking of sugars, giving the food a strong caramel and roasted characteristic (Liu et al., 2022). It is worth noting that MC and BC contain almost no pyrazines. Although RC contains pyrazines, the amount and concentration are lower than those of BRC. This indicated that the precursors such as reducing sugars and free amino acids accumulated during the braising process provide more sufficient substrates for the Maillard reaction in the subsequent roasting, thereby enhancing the generation of pyrazine and furan flavors and improving the pleasant feeling of roasting aroma (Wang et al., 2024). The terpenoids and pyrazines exhibited synergistic effects, where the fresh, citrusy notes from the terpenoids complemented and enhanced the roasted, nutty notes from the pyrazines. This interaction created a more harmonious and well-rounded aroma (Yao et al., 2024).

Phenolic compounds such as eugenol and ester compounds such as eugenyl acetate in BRC increased significantly. These compounds are

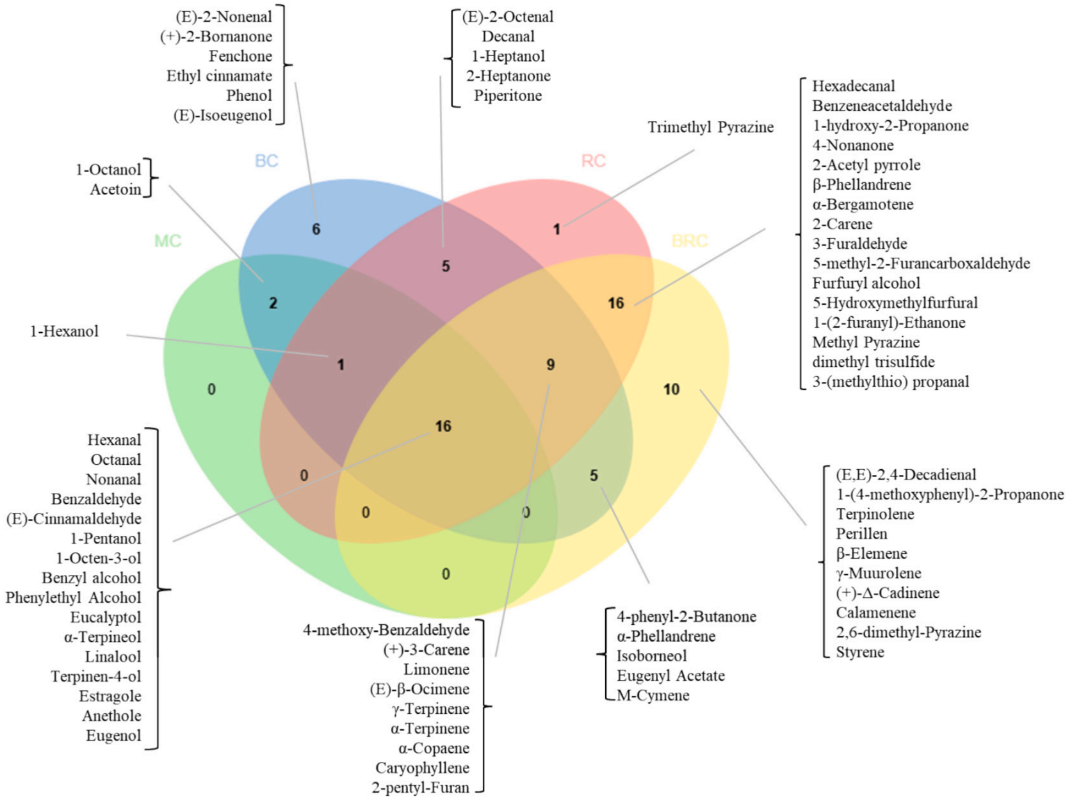

Fig. 4. Venn diagram of volatile compounds in chicken samples under different processing methods.

mostly derived from spice essential oils, have certain antioxidant and give complex aromas such as spice and sweet aromas. Their increase indicated that they could be stably retained under heating conditions after braising, and cooperate with other flavor compounds to form a more stable and lasting aroma structure (Qiang et al., 2025).

Sulfur-containing compounds were not detected in MC and BC samples but appeared during the roasting stage (RC), where dimethyl trisulfide and 3-(methylthio) propanal were first identified. This indicates that high-temperature treatment promoted the thermal degradation and Strecker reactions of sulfur-containing amino acids, leading to the formation of typical volatile sulfur compounds (Hou et al., 2017; Zhao et al., 2019). In the braised–roasted sample (BRC), these compounds further accumulated, suggesting that the braising process provided more precursors and enhanced subsequent thermal reactions. Overall, sulfur-containing compounds were mainly generated at high temperatures, and the braising process facilitated their formation and enrichment by influencing precursor availability and reaction conditions.

3.3. *Aroma contributions revealed by OAV values*

OAV was calculated to evaluate the contribution of aroma compounds to the overall aroma characteristics of chicken during processing. Compounds with OAV ≥ 1 are considered to dominate the overall aroma and are defined as key aroma compounds (Chen et al., 2023).

In the MC sample, compounds such as eucalyptol, hexanal, and 1-octen-3-ol already exhibited some aroma activity (see Table 3), contributing eucalyptus-like, grassy, and mushroom-like notes; however, the overall aroma structure was still simple, lacking depth and complexity.

The overall aroma activity in BC increased significantly. Higher levels of eucalyptol, octanal, nonanal, (*E*, *E*)-2,4-decadienal, and eugenol indicated that braising promoted the diffusion of terpenes from spices and the accumulation of lipid oxidation products, thereby enhancing herbal, fruity, and fatty characteristics. Since no sulfur-containing key compounds were detected at this stage, the meaty note was still limited, and the aroma profile was dominated by spice and aliphatic aldehydes, with an overly strong herbal tone.

During roasting, high temperatures intensified lipid oxidation and Maillard-related reactions, leading to a noticeable increase in typical roasted and meaty compounds. Lipid oxidation products such as hexanal and 1-octen-3-ol increased markedly, while pyrazines began to appear, contributing nutty and roasted aromas. Meanwhile, the emergence of sulfur-containing compounds enhanced roasted-meat and onion-like notes. Compared with BC, spice-derived components in RC were further released, while phenolic compounds decreased sharply, shifting the overall aroma profile from herbaceous to one dominated by roasted and sulfurous notes, with a simpler and less layered structure.

The braising process significantly influenced the generation and balance of key aroma compounds in roasted chicken. Compared with RC, the OAVs of lipid oxidation-related aldehydes and alcohols—including hexanal, octanal, nonanal, (*E*, *E*)-2,4-decadienal, 1-octen-3-ol, and 3-(methylthio) propanal—were markedly lower in BRC. This indicates that the incorporation of antioxidant constituents from spices during braising may have inhibited lipid oxidation, thereby reducing poultry-like associated with fatty and over-roasted notes (Sampaio et al., 2012). This trend is consistent with sensory evaluation results. Compared with RC, the relative contribution of 2,6-dimethylpyrazine in BRC decreased, mainly because the introduction of spices and the higher-moisture environment during braising inhibited Maillard reactions (Bassam et al., 2022). In addition, the strong terpenic notes derived from spices likely masked the nutty and roasted aroma of pyrazines, resulting in a softer and more balanced overall aroma in BRC. In contrast, the OAVs of spice-derived terpenes and phenolic compounds—such as estragole, anethole, eugenol, linalool, caryophyllene, 3-carene, limonene, and β-phellandrene—were significantly higher in BRC than in RC. This suggests that braising facilitated the diffusion and retention of spice volatiles within the meat matrix, enabling their

Table 1
Identification results of chicken volatile compounds with different treatment by GC-O-MS.

No.	CAS number	Compounds	RI[a]	Odor description[b]	Identificate method[c]
1	66–25-1	hexanal	1083	green, grassy	MS[d]/RI[a]/O[b]/STD[e]
2	124-13-0	octanal	1287	citrus-like, green	MS/RI/O/STD
3	124–19-6	nonanal	1380	citrus-like, soapy	MS/RI/O/STD
4	25,152–84-5	(*E*, *E*)-2,4-decadienal	1785	fatty, deep-fried	MS/RI/O/STD
5	112–31–2	decanal	1471	soapy, citrus-like	MS/RI/O/STD
6	2548-87-0	(*E*)-2-octenal	1416	fatty, nutty	MS/RI/O/STD
7	18,829–56-6	(*E*)-2-nonenal	1532	fatty, green	MS/RI/O/STD
8	629–80-1	hexadecanal	2120		MS/RI/STD
9	100–52-7	benzaldehyde	1529	bitter almond-like, marzipan-like	MS/RI/O/STD
10	123–11-5	4-methoxy benzaldehyde	1980		MS/RI/STD
11	122–78-1	benzeneacetaldehyde	1617	floral, honey-like	MS/RI/O/STD
12	14,371–10-9	(*E*)-cinnamaldehyde	2015		MS/RI/STD
		Alcohols (8)			
13	111–87-5	1-octanol	1546	soapy, citrus-like	MS/RI/O/STD
14	111–27-3	1-hexanol	1359	grassy, marzipan-like	MS/RI/O/STD
15	71–41-0	1-pentanol	1241	fruity, ethereal	MS/RI/O/STD
16	3391-86-4	1-octen-3-ol	1430	mushroom-like	MS/RI/O/STD
17	100–51-6	benzyl alcohol	1864	bitter almond-like, fruity	MS/RI/O/STD
18	60–12-8	phenylethyl alcohol	1912	floral, honey-like	MS/RI/O/STD
19	111–70-6	1-heptanol	1440	fruity, soapy	MS/RI/O/STD
20	124–76-5	isoborneol	1670	earthy, moldy	MS/RI/STD
		Ketones (9)			
21	110–43-0	2-heptanone	1180	fruity, soapy	MS/RI/O/STD
22	464–49-3	2-Bornanone	1527	camphor-like	MS/RI/O/STD
23	116–09-6	1-hydroxy-2-propanone	1290		MS/RI/STD
24	2550-26-7	4-phenyl-2-butanone	1851	floral	MS/RI/O/STD
25	4485-09-0	4-nonanone	1356	soapy, fruity	MS/RI/O/STD
26	513–86-0	acetoin	1259	butter-like, carrot-like	MS/RI/O/STD
27	1072-83-9	2-acetylpyrrole	1952		MS/RI/STD
28	122–84-9	1-(4-methoxyphenyl)-2-propanone	2185		MS/RI/STD
29	1195-79-5	fenchone	1391		MS/RI/STD
		Terpenes (24)			
30	470–82-6	eucalyptol	1209	eucalyptus-like	MS/RI/O/STD
31	498–15-7	3-carene	1146	terpene-like	MS/RI/O/STD
32	99–83-2	α-phellandrene	1157		MS/RI/STD
33	5989-27-5	limonene	1242	citrus-like	MS/RI/O/STD
34	555–10-2	β-phellandrene	1195	terpene-like	MS/RI/O/STD
35	3779-61-1	(*E*)-β-ocimene	1232	terpene-like	MS/RI/O/STD
36	99–85-4	γ-terpinene	1238	petrol-like	MS/RI/O/STD
37	99–86-5	α-terpinene	1225	terpene-like	MS/RI/O/STD
38	1,000,360–33-0	α-copaene	1475		MS/RI
39	78–70-6	linalool	1540	citrus-like, floral	MS/RI/O/STD
40	562–74-3	terpinen-4-ol	1594		MS/RI/STD
41	87–44-5	caryophyllene	1585	moldy	MS/RI/O/STD
42	98–55-5	α-terpineol	1680	floral, citrus-like	MS/RI/O/STD
43	554–61-0	2-carene	1142		MS/RI
44	586–62-9	terpinolene	1274		MS/RI/STD
45	539–52-6	perillen	1409		MS/RI/STD
46	17,699–05-7	α-bergamotene	1566		MS/RI
47	515–13-9	β-elemene	1573		MS/RI/STD
48	89–81-6	piperitone	1715		MS/RI/O/STD
49	30,021–74-0	γ-muurolene	1671		MS/RI
50	483–76-1	cadinene	1675		MS/RI
51	483–77-2	calamenene	1827		MS/RI/STD
		Furans (6)			
52	3777-69-3	2-pentylfuran	1224	vegetable-like	MS/RI/O/STD
53	98–01-1	furfural	1455	marzipan-like, oats-like	MS/RI/O/STD
54	67–47-0	5-hydroxymethylfurfural	2526		MS/RI/STD
55	98–00-0	furfuryl alcohol	1635	cooked ham-like, sweaty	MS/RI/O/STD
56	620–02-0	5-methyl-2-furancarboxaldehyde	1555	sweet, bitter almond-like	MS/RI/O/STD
57	1192-62-7	1-(2-furanyl)-ethanone	1479	smoky	MS/RI/O/STD
		Phenols (3)			
58	97–53-0	eugenol	2141	clove-like	MS/RI/O/STD
59	108–95-2	phenol	1987	ink-like, phenolic	MS/RI/O/STD
60	5932-68-3	(*E*)-isoeugenol	2355	smoky, clove-like	MS/RI
		Pyrazines (3)			
61	109–08-0	methyl pyrazine	1263	burned, roasty	MS/RI/O/STD
62	108–50-9	2,6-dimethyl-pyrazine	1345	earthy, nutty	MS/RI/O/STD
63	14,667–55-1	trimethyl pyrazine	1395	earthy	MS/RI/O/STD
		Esters (2)			
64	103–36-6	ethyl cinnamate	2127	fruity, soapy	MS/RI/O/STD
65	93–28-7	eugenyl acetate	2277		MS/RI/STD
		Aromatic Hydrocarbons (2)			
66	100–42-5	styrene	1247		MS/RI/STD

(*continued on next page*)

Table 1 (*continued*)

No.	CAS number	Compounds	RI[a]	Odor description[b]	Identificate method[c]
67	535–77-3	M-cymene	1267		MS/RI/STD
		Ethers(2)			
68	140–67-0	estragole	1655	aniseed-like, licorice-like	MS/RI/O/STD
69	104–46-1	anethole	1815	aniseed-like	MS/RI/O/STD
		Sulfur-containing compounds(2)			
70	3658-80-8	dimethyl trisulfide	1362	sulfuric, cabbage-like	MS/RI/O/STD
71	3268-49-3	3-(methylthio) propanal	1480	cooked potato-like	MS/RI/O/STD

[a] RI, retention index obtained by GC-O-MS (DB-Wax, 60 m × 0.25 mm × 0.25 μm).

[b] The odor profile of each odor-active compound as detected at the sniffer port.

[c] The various identification methods include mass spectrometry (MS), retention index (RI), odor description (O), and standard compounds (S).

Table 2

Identification results of chicken odor-active compounds with different treatment by GC-O-MS.

No.	Compounds	selected ions (*m/z*)	MC	BC	RC	BRC
			Concentration(ng/g)			
1	hexanal	44,56,41	77.39 ± 5.29^{c}	739.91 ± 24.03^{b}	1866.89 ± 21.28^{a}	774.16 ± 20.41^{b}
2	octanal	43,44,41	1.11 ± 0.89^{d}	71.67 ± 35.76^{a}	33.69 ± 5.07^{b}	8.34 ± 1.61^{c}
3	nonanal	57,41,43	2.04 ± 0.02^{d}	108.82 ± 12.84^{a}	58.08 ± 5.07^{b}	20.22 ± 1.90^{c}
4	(*E*, *E*)-2,4-decadienal	81,41,29	N.D.	12.04 ± 1.84 ^{a}	5.39 ± 0.84^{b}	4.11 ± 0.25^{c}
5	decanal	43,41,57	N.D.	9.7 ± 1.22^{a}	5.04 ± 0.74^{b}	N.D.
6	(*E*)-2-octenal	41,55,29	N.D.	5.01 ± 0.87^{a}	2.84 ± 0.67^{b}	N.D.
7	(*E*)-2-nonenal	43,55,70	N.D.	2.27 ± 0.61	N.D.	N.D.
8	benzaldehyde	77,106,105	1.52 ± 0.96^{d}	40.70 ± 9.15^{ab}	31.29 ± 5.68^{bc}	48.09 ± 9.05^{a}
9	benzeneacetaldehyde	91,92,120	N.D.	N.D.	3.14 ± 1.33^{a}	3.45 ± 0.52^{a}
10	1-octanol	56,55,41	4.65 ± 0.54^{ab}	5.14 ± 3.84^{a}	N.D.	N.D.
11	1-hexanol	56,43,41	3.33 ± 0.44^{c}	225.15 ± 186.63^{a}	6.01 ± 1.09^{b}	N.D.
12	1-pentanol	42,55,41	2.41 ± 0.61^{c}	37.54 ± 29.15^{a}	16.85 ± 1.43^{b}	15.02 ± 3.88^{b}
13	1-octen-3-ol	57,43,72	4.29 ± 1.21^{d}	79.4 ± 29.87^{a}	28.78 ± 5.19^{b}	10.12 ± 0.50^{c}
14	benzyl alcohol	79,108,107	1.01 ± 0.24^{c}	2.21 ± 0.90^{b}	3.56 ± 1.11^{a}	3.56 ± 0.94^{a}
15	phenylethyl alcohol	91,92,65	1.06 ± 0.27^{d}	2.17 ± 0.35^{a}	1.44 ± 0.65b^{c}	1.75 ± 0.57^{b}
16	1-heptanol	70,56,43	N.D.	9.71 ± 0.31^{a}	3.2 ± 0.48^{b}	N.D.
17	isoborneol	95,41,93	N.D.	N.D.	N.D.	4.33 ± 0.12
18	2-heptanone	43,58,27	N.D.	7.04 ± 3.95^{a}	5.60 ± 1.36^{ab}	N.D.
19	4-phenyl-2-butanone	43,105,148	N.D.	1.79 ± 0.40^{b}	N.D.	5.66 ± 0.19^{a}
20	4-nonanone	43,71,58	N.D.	N.D.	56.65 ± 4.29^{a}	7.09 ± 2.08^{b}
21	acetoin	45,43,88	1.26 ± 1.71^{b}	11.61 ± 1.97^{a}	N.D.	N.D.
22	eucalyptol	43,81,108	0.91 ± 13.26^{d}	79.79 ± 8.66^{ab}	51.94 ± 7.45^{c}	96.09 ± 15.83^{a}
23	3-carene	93,91,92	N.D.	9.65 ± 1.35^{c}	12.79 ± 2.42^{b}	55.82 ± 4.75^{a}
24	limonene	68,93,67	N.D.	32.69 ± 2.27^{c}	49.77 ± 3.44^{b}	248.04 ± 28.66^{a}
25	β-phellandrene	93,77,91	N.D.	N.D.	10.64 ± 1.20^{b}	53.63 ± 9.05^{a}
26	(*E*)-β-ocimene	93,41,79	N.D.	3.57 ± 0.05^{c}	6.24 ± 0.63^{b}	27.92 ± 3.70^{a}
27	γ-terpinene	93,91,136	N.D.	7.57 ± 0.55^{c}	11.86 ± 1.61^{b}	92.10 ± 11.15^{a}
28	α-terpinene	121,93,136	N.D.	2.87 ± 0.52^{c}	5.08 ± 1.11^{b}	39.40 ± 2.98^{a}
29	linalool	71,93,55	1.52 ± 0.17^{d}	10.21 ± 1.62^{a}	5.22 ± 1.46^{bc}	7.37 ± 2.10^{b}
30	caryophyllene	93,133,91	N.D.	15.39 ± 2.54^{b}	9.52 ± 1.55^{c}	108.69 ± 10.65^{a}
31	α-terpineol	59,93,121	25.03 ± 1.96^{ab}	28.27 ± 2.61^{a}	7.37 ± 1.91^{d}	18.55 ± 0.58^{c}
32	piperitone	82,110,39	N.D.	8.25 ± 3.14^{a}	1.25 ± 0.30^{b}	N.D.
33	2-pentylfuran	81,82,138	N.D.	19.58 ± 10.26^{a}	11.10 ± 0.20^{b}	7.58 ± 0.41^{c}
34	furfural	96,95,39	N.D.	N.D.	22.71 ± 4.64^{b}	70.62 ± 2.27^{a}
35	furfuryl alcohol	98,41,53	N.D.	N.D.	12.97 ± 2.53^{b}	19.82 ± 3.07^{a}
36	5-methyl-2-furancarboxaldehyde	110,109,53	N.D.	N.D.	8.56 ± 1.66^{b}	16.81 ± 5.96^{a}
37	1-(2-furanyl)-ethanone	95,110,39	N.D.	N.D.	7.62 ± 1.38^{b}	14.83 ± 0.46^{a}
38	eugenol	164,103,77	1.60 ± 0.42^{d}	296.99 ± 40.00^{a}	14.98 ± 1.33^{c}	151.87 ± 13.96^{b}
39	phenol	94,66,65	N.D.	2.61 ± 1.00	N.D.	N.D.
40	(*E*)-isoeugenol	164,149,103	N.D.	2.8 ± 0.99	N.D.	N.D.
41	methyl pyrazine	94,67,40	N.D.	N.D.	1.82 ± 0.25^{b}	2.58 ± 0.1^{a}
42	2,6-dimethyl-pyrazine	108,42,40	N.D.	N.D.	8483.57 ± 129.32^{a}	1654.29 ± 21.31^{b}
43	trimethyl pyrazine	42,122,39	N.D.	N.D.	6.61 ± 0.24^{a}	3.10 ± 0.04^{b}
44	ethyl cinnamate	131,103,176	N.D.	3.43 ± 0.45	N.D.	N.D.
46	estragole	148,147,77	5.01 ± 1.05^{d}	92.34 ± 6.56^{a}	12.21 ± 3.31^{c}	57.86 ± 4.45^{b}
47	anethole	148,147,117	0.96 ± 0.05^{d}	11.43 ± 0.78^{c}	284.21 ± 48^{b}	434.95 ± 54.24^{a}
48	dimethyl trisulfide	126,45,79	N.D.	N.D.	25.97 ± 0.43	30.74 ± 0.44
49	3-(methylthio) propanal	48,104,47	N.D.	N.D.	31.72 ± 2.15	31 ± 0.69

efficient release during roasting and contributing to richer herbal and floral notes (Zhong et al., 2024). Similarly, Zhao et al. (2023) reported that major ginger-derived compounds (e.g., citronellal, eucalyptol, and terpineol) can migrate into beef during stewing, thereby conferring a distinctive olfactory perception to the meat. Meanwhile, the increased contribution of dimethyl trisulfide further enhanced the roasted and meaty characteristics of BRC.

Overall, the braising process not only improved aroma purity by suppressing lipid oxidation but also enhanced the overall aroma complexity and layering through the effective penetration and release of spice-derived volatiles, demonstrating a dual mechanism of “oxidation inhibition and aroma enhancement.

Table 3
OAVs of key aroma-active compounds in chicken under different treatment.

No.	Compounds	Threshold(μg/kg)	OAV				Perception
			MC	BC	RC	BRC	
1	3-carene	0.044	N.D.	<1	<1	1	Piney
2	limonene	0.034	N.D.	1	1	7	Citrus
3	β-phellandrene	0.036	N.D.	N.D.	<1	1	Minty
4	eucalyptol	0.0011	23	73	290	87	Eucalyptus
5	hexanal	0.005	15	147	373	154	Green
6	2-pentylfuran	0.0058	N.D.	3	2	1	Beany
7	(*E*)-β-ocimene	0.034	N.D.	<1	<1	1	Floral
8	acetoin	0.014	<1	1	N.D.	N.D.	Buttery
9	octanal	0.000587	2	122	57	14	Citrusy
10	4-nonanone	0.041	N.D.	N.D.	1	<1	Creamy
11	1-hexanol	0.0056	<1	40	1	N.D.	Green
12	(*E*, *E*)-2,4-decadienal	0.000077	N.D.	156	70	53	Fried-fatty
13	2,6-dimethyl-pyrazine	0.718	N.D.	N.D.	12	2	Nutty
14	nonanal	0.0011	3	99	53	18	Waxy
15	(*E*)-2-octenal	0.003	N.D.	2	1	N.D.	Fatty
16	1-octen-3-ol	0.0015	46	93	288	256	Mushroom
17	1-heptanol	0.0054	N.D.	2	1	N.D.	Fruity
18	decanal	0.003	N.D.	3	2	N.D.	Orange peel
19	(*E*)-2-nonenal	0.00019	N.D.	12	N.D.	N.D.	Stale-cucumber
20	linalool	0.0024	1	4	2	3	Floral
21	caryophyllene	0.064	N.D.	<1	<1	2	Peppery
22	estragole	0.016	<1	6	1	4	Anise
23	anethole	0.111	<1	<1	3	4	Licorice
24	4-methoxy-benzaldehyde	0.047	N.D.	1	N.D.	N.D.	Anise
25	eugenol	0.0025	1	119	6	61	Clove
26	dimethyl trisulfide	0.0001	N.D.	N.D.	260	307	Onion-like
27	3-(methylthio) propanal	0.00045	N.D.	N.D.	71	69	Potato

3.4. *PLS-DA analysis*

The PLS-DA score plot (Fig. 5) shows clear separation among the four groups along the first two principal components, with the BRC group distinctly separated from the others, indicating that the "braise-then-roast" process plays a unique role in shaping volatile flavor compounds. Furthermore, the VIP analysis indicates that spice-derived compounds—such as eugenol, anethole, limonene, and estragole—contribute most to sample discrimination, which is closely related to the infusion of spice constituents during braising. Meanwhile, lipid-oxidation products including nonanal, 1-hexanol, and 1-octen-3-ol make significant contributions in the BRC group, suggesting that the combined process promotes lipid degradation and the formation of thermal reaction products. These results collectively demonstrate that the distinctive aroma of BRC arises from the synergistic effects of aromatic compounds derived from spice sources and lipid-derived oxidation products, yielding both the characteristic floral notes of spices and the nutty and roasted attributes typical of heat-treated meats.

3.5. *Fatty acid analysis*

The generation of flavor compounds is inseparable from the accumulation of substrates. Lipid oxidation is one of the core reaction pathways for the generation of meat aroma (Wu et al., 2022). It can be observed from Table 4 that different treatment methods significantly affect the release and accumulation of fatty acids in chicken. Overall, the total amount of fatty acids in the BRC group was the highest, significantly higher than that in the BC, RC, and MC groups, indicating that the composite heat treatment significantly enhanced lipid release. During the marinating process, because the cell structure was not destroyed by high temperature, myofibrils and adipose tissue were relatively intact, and lipid release was extremely limited (Shakoor et al., 2025). During

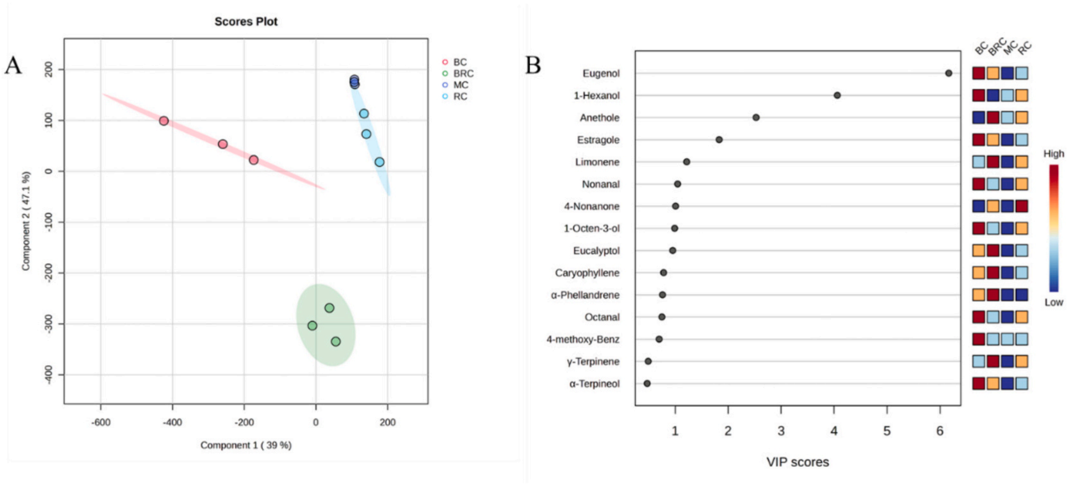

Fig. 5. PLS-DA analysis of volatile compounds in chicken under different processing conditions. Scores plot showing clear separation among MC, BC, RC, and BRC. (B) VIP scores highlighting the top discriminant compounds. MC, marinated chicken; BC, braised chicken; RC, roasted chicken; BRC, braised-roasted chicken.

Table 4
Fatty acid content of chicken under different treatment conditions.

no.	Fatty acid	MC	BC	RC	BRC
1	C10:0	N.D.	0.3 ± 0.01^{b}	N.D.	0.66 ± 0.01^{a}
2	C12:0	N.D.	1.32 ± 0.01^{c}	1.94 ± 0.01^{b}	2.79 ± 0.06^{a}
3	C14:0	4.61 ± 0.04^{d}	35.66 ± 0.01^{c}	54.15 ± 0.43^{b}	75.84 ± 0.03^{a}
4	C14:1	N.D.	2.59 ± 0.04^{c}	7.84 ± 0.01^{b}	8.18 ± 0.08^{a}
5	C15:0	2.23 ± 0.01^{c}	1.8 ± 0.02^{d}	3.11 ± 0.02^{b}	5.13 ± 0.1^{a}
6	C16:0	137.19 ± 0.34^{d}	1497.78 ± 1.31^{c}	2066.42 ± 12.65^{b}	2878.1 ± 10.39^{a}
7	C16:1	13.03 ± 0.1^{d}	120.63 ± 0.4^{c}	300.41 ± 1.8^{b}	326.35 ± 1.49^{a}
8	C17:0	N.D.	7.17 ± 0.03^{c}	9.94 ± 0.01^{b}	17.45 ± 0.09^{a}
9	C18:0	71.68 ± 1.17^{d}	744.65 ± 0.09^{c}	840.51 ± 0.08^{b}	1304.53 ± 1.58^{a}
10	C18:1n9t	0.73 ± 0.01^{d}	12.71 ± 0.04^{c}	15.18 ± 0.2^{b}	23.4 ± 0.08^{a}
11	C18:1n9c	109.86 ± 1.78^{d}	1192.16 ± 1.99^{c}	2388.92 ± 7.78^{b}	2987.26 ± 3.69^{a}
12	C18:2n6c	159.31 ± 1.18^{d}	1204.38 ± 3.24^{c}	1500.02 ± 4.5^{b}	2302.09 ± 5.51^{a}
13	C20:0	1.35 ± 0.01^{c}	7.31 ± 0.03^{a}	6.52 ± 0.04^{b}	6.58 ± 1.79^{ab}
14	C18:3n6	1.3 ± 0.01^{d}	4.75 ± 0.01^{c}	8.09 ± 0.04^{b}	10.16 ± 0.02^{a}
15	C20:1	N.D.	15.12 ± 0.03^{c}	34.83 ± 0.14^{b}	38.36 ± 0.06^{a}
16	C18:3n3	1.84 ± 0.01^{d}	19.81 ± 0.02^{c}	32.67 ± 0.14^{b}	48.65 ± 0.1^{a}
17	C20:2	2.26 ± 0.02^{d}	14.35 ± 0.04^{c}	17.03 ± 0.05^{b}	22.61 ± 0.64^{a}
18	C22:0	1.04 ± 0.01^{d}	6.54 ± 0.02^{b}	5.94 ± 0.06^{c}	7.17 ± 0.06^{a}
19	C20:3n6	3.32 ± 0.03^{d}	14.94 ± 0.02^{c}	23.22 ± 0.05^{b}	29.94 ± 0.08^{a}
20	C20:4n6	24.64 ± 0.1^{d}	76.91 ± 0.45^{b}	67.87 ± 0.24^{c}	107.44 ± 2.62^{a}
21	C23:0	1.06 ± 0.01^{d}	2.35 ± 0.01^{b}	2.04 ± 0.01^{c}	3.06 ± 0.02^{a}
22	C24:0	N.D.	N.D.	3.52 ± 0.01	N.D.
23	C20:5n3	N.D.	N.D.	1.33 ± 0.01	N.D.
24	C22:6n3	N.D.	2.02 ± 0.01^{c}	2.29 ± 0.01^{b}	4.86 ± 0.01^{a}
	Total	535.45 ± 4.68^{d}	4985.26 ± 7.34^{c}	7393.8 ± 26.1^{b}	$10{,}210.6 \pm 28.74^{a}$

the marinating and roasting process, the protein and fat structure was destroyed, and the muscle contraction and cell wall rupture caused the endogenous lipids to be released rapidly (Jiang et al., 2024).

Different fatty acids can generate different types of flavor compounds through thermal degradation, lipid oxidation, β-decarboxylation, and other pathways (Ren et al., 2024). Palmitic acid (C16:0), stearic acid (C18:0) and oleic acid (C18:1n9c) are the main fatty acids, and their contents in RC and BRC groups increased significantly ($P < 0.05$), indicating that high temperature promotes the release of lipids from tissues. Unsaturated fatty acids, especially linoleic acid (C18:2n6c), oleic acid (C18:1n9c), linolenic acid (C18:3n3), etc., are typical flavor precursors (Gu et al., 2019). The contents of the above fatty acids in the BRC group were significantly higher than those in other groups, and only DHA (C22:6n3) was detected in BRC, indicating that long-chain polyunsaturated fatty acids are more easily released or stably present under composite treatment conditions. Oxidation of linoleic acid (C18:2n6c) can generate typical volatiles with grassy and nutty aromas, such as hexanal and 2-pentylfuran (Duan et al., 2024), while linolenic acid (C18:3n3) and DHA may form flavor compounds with mushroom and meaty aromas, such as 1-octen-3-ol and (*E*, *E*)-2,4-decadienal(Jin et al., 2023), enhancing the aroma complexity and sensory richness of BRC samples.

3.6. *FAAs analysis*

Different treatment methods have significant effects on the composition and content of free amino acids in chicken. The content of FAAs in MC is generally higher than that in the other three groups, especially the flavor FAAs such as threonine, serine, and glutamic acid are at a higher level. The FAAs in the BC group are slightly lower, but the difference is not large, indicating that the single braising process does not significantly promote the degradation of FAAs. In contrast, the FAAs content in the RC group and the BRC group decreased significantly ($P < 0.05$). They may be consumed during thermal processing and used to participate in flavor formation pathways such as Maillard reaction or Strecker degradation (Bassam et al., 2022). However, the FAAs content in BRC is the lowest, indicating a stronger degree of FAAs degradation and conversion. The biggest difference between BRC and RC is that it has undergone a braising process in advance, which promotes partial thermal and enzymatic hydrolysis of proteins, allowing FAAs to be released more thoroughly. In subsequent roasting, these FAAs are easily further degraded, decarboxylated, or deaminated. The significant reduction of FAAs in BRC reflects its stronger reactivity than in RC, laying the foundation for subsequent flavor enhancement. The levels of phenylalanine-related flavor compounds such as benzeneacetaldehyde, benzaldehyde, and phenylethyl alcohol in BRC were higher than those in RC and BC groups, indicating that phenylalanine was fully degraded and transformed at high temperatures. Glutamic acid may be converted into nitrogen-containing heterocyclic compounds such as 2-acetylpyrrole, which were also detected at a high level in BRC, indicating an intensified Maillard reaction and resulting in enhanced roasted and sweet aroma characteristics (Zou et al., 2018). These findings suggest that FAAs play a key role in enhancing the aroma of roasted chicken by participating in non-enzymatic browning reactions. Relatively speaking, the content of neutral sweet FAAs such as Thr remains at a high level after heat treatment, which may help soften the overall flavor and reduce the perception of bitterness (Liu et al., 2020). Overall, heat treatment not only changes the FAAs composition, but also promotes the production of flavor compounds through the participation of FAAs.

3.7. *Total reducing sugar analysis*

Reducing sugar is one of the most important flavor precursors of meat. The Strecker reaction and Maillard reaction between sugar and amino acid are important reactions for producing meat aroma, and many of the reaction products derived from them are also compounds with meat aroma (Bassam et al., 2022). Different processing methods have a significant effect on the reducing sugar content in chicken (Table 5). Among them, the MC group had the highest reducing sugar content, followed by the BC group, the RC group, and the BRC group. The content of reducing sugar in BC was significantly reduced. This is because the reducing sugar in the chicken meat gradually dissolved into the soup (Lou et al., 2018). On the other hand, reducing sugar may be involved in the formation of certain flavor compounds (Zhang et al., 2025). As the processing heat intensity increases, the content of reducing sugar, one of the key substrates of the Maillard reaction, shows a decreasing trend, indicating that sugar substances continue to undergo thermal reactions and are consumed during processing. Especially in the BRC group, because the samples underwent continuous brine and baking, reducing sugars were converted to the maximum extent in the reaction, thereby forming more aroma compounds. This result is consistent with the detection of high abundance of typical thermal reaction products such as pyrazines, furans and fatty aldehydes in the BRC group in GC–MS, suggesting that reducing sugars significantly promote the production of flavor compounds by participating in the Maillard reaction and carbonylamine reaction during the “first brine and then roast” process (Zhong et al., 2024). In addition, the reduction of reducing sugars may also be related to partial carboxylation reactions and sugar degradation, further promoting the release of compounds such as pyrazines, aldehydes and ketones, giving the BRC sample a richer and more complex caramel and roasted flavor.

Table 5
Changes of free amino acids and reducing sugar under different treatment conditions.

	MC	BC	RC	BRC
FAAs(mg/100 g)				
Aspartic acid (Asp)	10.79 ± 0.24^{a}	9.95 ± 0.41^{bc}	9.35 ± 0.19^{c}	8.42 ± 0.29^{d}
Serine (Ser)	16.87 ± 0.06^{a}	16.57 ± 0.39^{ab}	16.16 ± 0.25^{cd}	15.25 ± 0.14^{d}
Glutamic acid (Glu)	13.51 ± 0.13^{ab}	13.26 ± 0.13^{b}	12.57 ± 0.41^{c}	12.12 ± 0.15^{d}
Glycine (Gly)	9 ± 0.11^{a}	8.81 ± 0.09^{ab}	8.52 ± 0.07^{b}	8.61 ± 0.18^{b}
Histidine (His)	13.51 ± 0.41^{a}	13.45 ± 0.32^{a}	11.53 ± 0.41^{c}	11.17 ± 0.37^{c}
Arginine (Arg)	14.84 ± 0.45^{ab}	14.49 ± 0.2^{b}	13.22 ± 0.51^{c}	12.06 ± 0.22^{d}
Threonine (Thr)	34.53 ± 0.7^{a}	33.07 ± 0.21^{b}	33.54 ± 0.82^{ab}	33.86 ± 0.73^{ab}
Alanine (Ala)	14.25 ± 0.03^{a}	13.06 ± 0.3^{b}	13.99 ± 0.35^{a}	13.1 ± 0.35^{ab}
Proline (Pro)	10.86 ± 0.38^{a}	10.8 ± 0.35^{a}	9.88 ± 0.38^{b}	9.65 ± 0.17^{b}
Cystine (Cys)	5.5 ± 0.1^{a}	4.1 ± 0.18^{b}	2.49 ± 0.26^{c}	1.8 ± 0.16^{d}
Tyrptophan (Tyr)	7.85 ± 0.3^{a}	7.29 ± 0.15^{b}	4.07 ± 0.22^{c}	2.9 ± 0.22^{d}
Valine (Val)	5.87 ± 0.19^{a}	4.87 ± 0.14^{c}	4.07 ± 0.22^{d}	2.9 ± 0.22^{e}
Methionine (Met)	14.11 ± 0.37^{a}	12.46 ± 0.47^{b}	10.94 ± 0.45^{c}	10.69 ± 0.15^{c}
Lysine (Lys)	4.14 ± 0.23^{a}	4 ± 0.11^{a}	2.99 ± 0.13^{b}	2.84 ± 0.24^{b}
Isoleucine (Ile)	3.01 ± 0.2^{a}	1.89 ± 0.49^{b}	1.77 ± 0.11^{b}	1.68 ± 0.16^{b}
Leucine (Leu)	11.18 ± 0.42^{ab}	10.31 ± 0.34^{b}	10.57 ± 0.33^{b}	9.57 ± 0.33^{c}
Phenylalanine (Phe)	6.71 ± 0.45^{a}	6.64 ± 0.4^{a}	6 ± 0.09^{a}	5.29 ± 0.11^{b}
Reducing sugar(μg/g)	26.39 ± 0.69^{a}	23.4 ± 0.85^{b}	17.63 ± 1.03^{c}	12.32 ± 0.52^{d}

MC, marinated chicken. BC, Braised chicken. RC, roasted chicken. BRC, Braised-roasted chicken.

3.8. Correlation analysis of the aroma formation mechanism of BRC

The correlation heatmap (Fig. 6) highlights the close relationships among lipids, amino acids, reducing sugars, and key aroma compounds, providing data-driven support for the mechanism underlying aroma enhancement in BRC. Long-chain unsaturated fatty acids (e.g., C18:2n6, C18:3n3) showed strong positive correlations with aldehydes such as nonanal and octanal, confirming lipid oxidation as a central pathway for roasted and fatty notes (Domínguez et al., 2019). Amino acids, particularly sulfur-containing species (Met, Cys), correlated with pyrazines and sulfur-containing volatiles, underscoring the importance of Maillard and Strecker reactions in generating nutty and roasted aromas (Zou et al., 2018). Notably, reducing sugar displayed positive correlations with multiple amino acids (Ala, Gly, Lys, Met) as well as pyrazines and methanethiol derivatives, suggesting that braising increases sugar availability and thereby enhances Maillard reactions during roasting. In addition, spice-derived volatiles such as eugenol and anethole were associated with aromatic amino acids, indicating potential interactions between spice infusion and amino acid degradation that contribute to floral attributes. Collectively, braising enhances the aroma profile of roasted chicken by enriching lipid precursors, modulating amino acid–sugar interactions, and incorporating spice volatiles, which together drive the formation of a more intense and complex aroma.

3.9. Potential pathways of key aroma compounds

Based on the changes in flavor precursors, correlation analysis, and literature reports, this study further explored the potential formation mechanisms of the key aroma compounds in BRC (Fig. 7) (Sohail et al., 2022). The proposed mechanism integrates experimental results with existing knowledge and illustrates three major pathways involved in the formation of key aroma compounds in BRC: lipid oxidation, diffusion of spice-derived volatile molecules, and the Maillard reaction.

In the lipid oxidation pathway, oleic acid (C18:1) undergoes thermal cleavage of its 9/10-hydroperoxides, yielding octanal, nonanal, and decanal. Linoleic acid (C18:2) can form 9- and 13-hydroperoxides (9-HPOD and 13-HPOD); among them, 9-HPOD generates (*E*, *E*)-2,4-decadienal through β-scission and isomerization under heating, while 13-HPOD mainly decomposes to hexanal and can also produce 2-pentylfuran through cyclization reactions. Previous studies have reported that free fatty acids, especially n-6 and n-9 polyunsaturated fatty acids, can produce octanal, nonanal, and (*E*, *E*)-2,4-decadienal through oxidation or subsequent cleavage (Cha et al., 1992). In addition, 10-hydroperoxy linoleic acid can decompose to 1-octen-3-one, which is then reduced to 1-octen-3-ol. Similar alcohols have also been identified in secondary hydroperoxides of fatty acids (Girard & Durance, 2000).

In the spice-derived pathway, volatile compounds such as eucalyptol, limonene, linalool, and eugenol are introduced into the meat matrix through thermal extraction and diffusion during braising, and these volatiles are further released or transformed during roasting, imparting distinctive floral notes to BRC.

In the Maillard reaction pathway, interactions between amino acids and reducing sugars generate nitrogen- and sulfur-containing aroma compounds, including pyrazines, methanethiol, and their derivatives, which are key contributors to roasted and nutty aromas (Bassam et al., 2022). Liang et al. (2016) reported that the formation and accumulation of sulfur-containing compounds, such as dimethyl trisulfide (DMTS), are closely associated with Maillard reactions involving free amino acids and reducing sugars. During roasting, the higher surface temperature and lower water activity provide favorable conditions for sugar–amine condensation, Amadori/Heyns rearrangement, and the formation of reactive carbonyl and dicarbonyl intermediates (Mottram, 1998; Sun et al., 2022). Specifically, reducing sugars initially react with amino acids (e.g., Ala and Gly) to form Schiff bases, which subsequently undergo Amadori/Heyns rearrangement to yield early Maillard products. Further fragmentation and rearrangement of these intermediates generate carbonyl compounds and α-amino carbonyl species. Condensation and cyclization reactions involving these carbonyl fragments and nitrogen-containing species (amino acids, ammonia, or amine-derived fragments) can produce alkylpyrazines with characteristic roasted and nutty notes, such as 2,6-dimethylpyrazine (Whitfield, 1992; Mottram, 1998; Van Lancker et al., 2010; Zou et al., 2018). In the present study, 2,6-dimethylpyrazine was predominantly detected and significantly increased during the roasting stage, consistent with the observed changes in relevant precursors and correlation trends; therefore, it was considered a marker compound associated with enhanced Maillard activity. Meanwhile, sulfur-containing amino acids serve as important sulfur sources for roasted meaty sulfur volatiles. Reactive α-dicarbonyl compounds can react with methionine via Strecker degradation to form Strecker aldehydes such as methional, which can further generate sulfur intermediates such as methanethiol. In the presence of oxygen, methanethiol may undergo oxidative coupling to form dimethyl disulfide (DMDS), followed by further oxidation to yield DMTS, thereby reinforcing meaty and roasty sulfur nuances (Mottram, 1998; Jayasena et al., 2013). Consistent with this chemistry, our GC–MS results showed that methional and DMDS/DMTS were mainly formed and increased during the roasting-related stage, supporting the notion that high temperature, low water activity, and oxygen exposure favor Strecker reactions and subsequent oxidative coupling.In summary, the combination of braising and roasting enhances the overall aroma of BRC

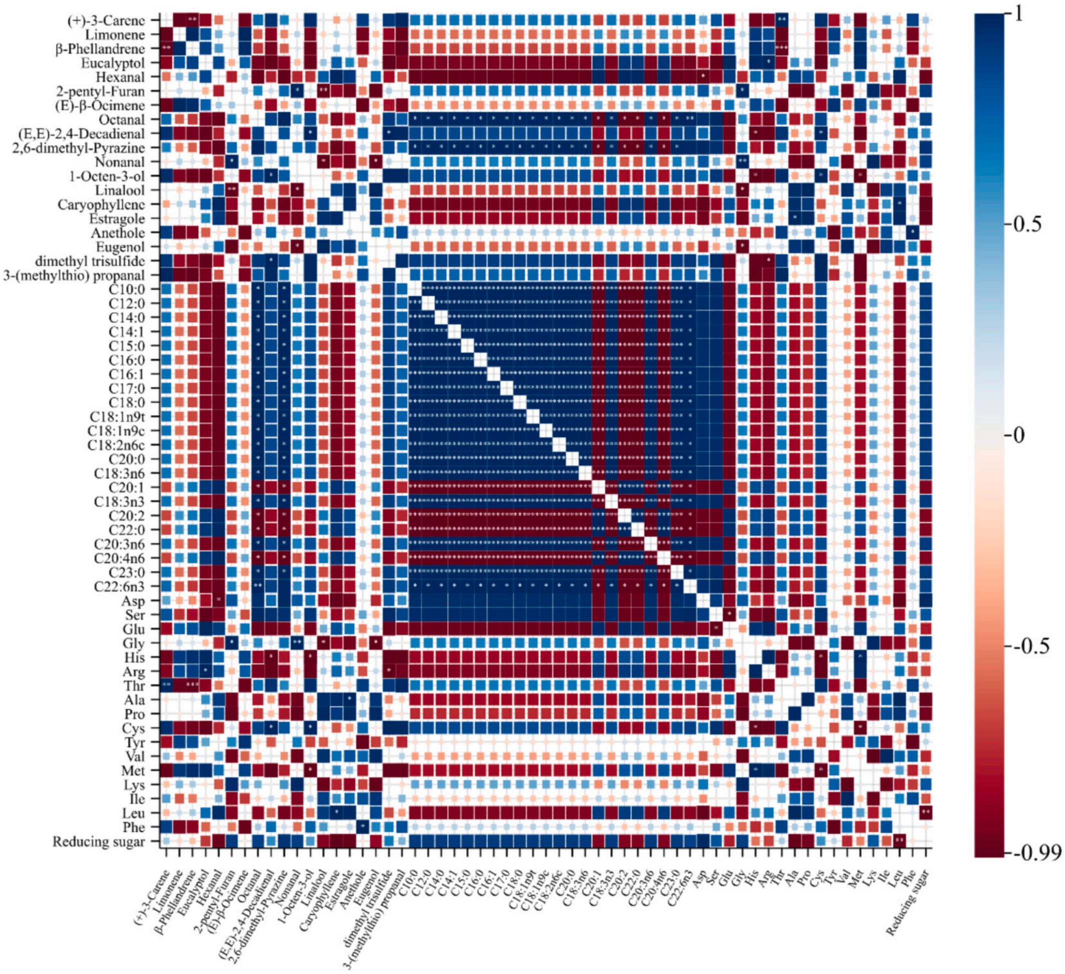

Fig. 6. Correlation heatmap between key precursors and aroma compounds in chicken samples.

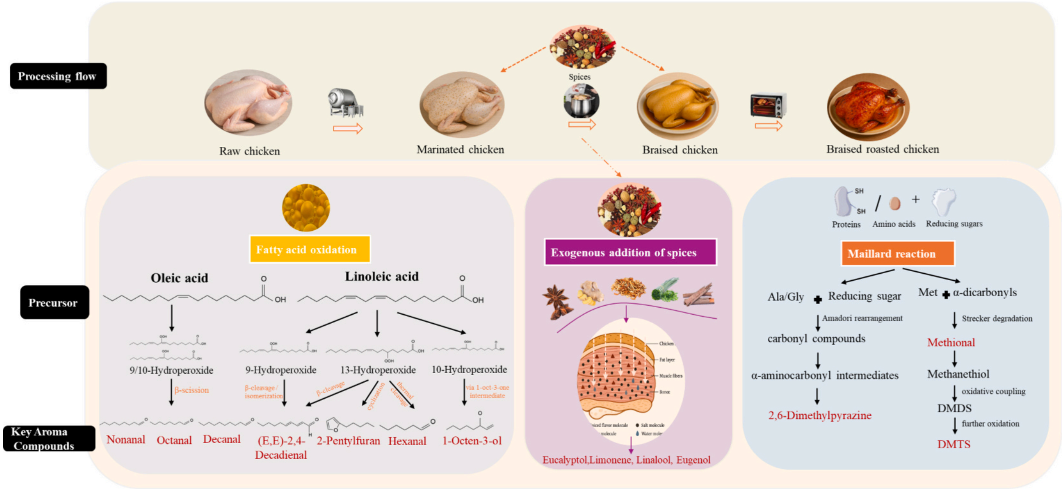

Fig. 7. Formation mechanism of key flavor compounds in braised-roasted chicken.

through a dual mechanism: the incorporation of exogenous spice volatiles and the modulation of endogenous flavor precursors, which together synergistically promote lipid oxidation and the Maillard reaction, thereby producing a more intense and complex aroma profile.

4. Conclusion

This study elucidated the aroma formation mechanism of Xinjiang BRC. The combination of braising and roasting enhanced the complexity and balance of chicken aroma through synergistic effects of precursor regulation and spice infusion. During braising, the accumulation of amino acid- and lipid-derived precursors was promoted, excessive lipid oxidation was inhibited, and spice-derived terpenes and phenolics were incorporated into the meat matrix. Subsequent roasting further activated lipid oxidation, Maillard, and Strecker reactions, generating key aroma compounds such as pyrazines, furans, and sulfur-containing volatiles. Overall, braising was identified as the key step determining the intensity, harmony, and uniqueness of BRC aroma. This study provides important theoretical support for understanding and optimizing the characteristic flavor of thermally processed poultry products and offers a scientific foundation for targeted odor formation and editing. In future work, stable isotope dilution assays (SIDA) combined with calibration curves, as well as carbon module labeling (CAMOLA) approaches could be applied to verify the carbon origin and formation pathways of key aroma compounds. Further studies under controlled reaction conditions are also required to support each proposed step and to establish a chemically reasonable reaction mechanism.

CRediT authorship contribution statement

Ke Bi: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Yue Liu:** Data curation, Conceptualization. **Dong Han:** Data curation. **Xinwei Li:** Data curation. **Yinfeng Lei:** Data curation. **Hong Pan:** Data curation. **Ping Yang:** Writing – review & editing, Validation, Supervision. **Chunhui Zhang:** Supervision, Resources, Project administration, Funding acquisition. **Marie-laure Fauconnier:** Writing – review & editing, Supervision.

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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MC, marinated chicken. BC, Braised chicken. RC, roasted chicken. BRC, Braised-roasted chicken.

N.D., not detected.

MC, marinated chicken. BC, Braised chicken. RC, roasted chicken. BRC, Braised-roasted chicken.

Data availability

Data will be made available on request.

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