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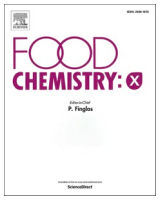

Analysis of the flavor profile of chicken white soup with varying fat addition using GC–MS, GC-IMS and *E*-nose combined with *E*-tongue

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ABSTRACT

The research utilized a combination of gas chromatography–mass spectrometry (GC–MS), gas chromatography-ion mobility spectrometry (GC-IMS), and *E*-nose to examine the impact of fat addition on the aroma profile of chicken white soup. The concentration of volatile flavor compounds in the white soup significantly increased with rising fat addition. A total of 105 volatile compounds were detected in the soup through GC–MS, and 72 by GC-IMS. Moreover, adding 2 % fat could effectively enhance the aroma of the chicken soup, and the soup exhibited the highest concentration of free amino acids (211.29 μg/mL) and nucleotides (27.55 mg/100 mL). However, the taste activity value of 5′-nucleotides was below 1, suggesting that fat addition had minimal impact on the umami taste of white soup. The study demonstrates that appropriate fat supplementation can enhance the aroma of chicken white soup and lays a theoretical groundwork for the advancement of premium-quality chicken white soup with rich aroma.

1. Introduction

The process of stewing chicken soup facilitates the release of nutritional components and flavor compounds, such as flavor peptides, nucleotides, and free amino acids from the chicken, enhancing the taste and promoting easy digestion and absorption (Xiao et al., 2021). Flavor is a crucial factor influencing consumer acceptance and preference, particularly in the case of soups. Furthermore, the generation of flavor compounds in chicken soup involved a complex interplay of processes, including lipid oxidation and thermal degradation, ribonucleotide reactions, thiamine interactions, sugar-amino acid (or peptide) reactions, as well as amino acid and peptide pyrolysis. Additionally, secondary reactions could have taken place between the products of these primary reactions, further contributing to the enhancement of the chicken soup flavor profile. Zhang et al. (2018) noted that different heating modes could affect the flavor quality of chicken soup. Our previous research also showed that different stewing times influenced the formation of flavor substances in chicken soup (Guan et al., 2023). Qi et al. (2020) found that the addition of exogenous gelatin improved the flavor intensity of chicken soup during the stewing process. The flavor profile of chicken soup significantly influenced its palatability and consumer acceptance, serving as a key distinguishing feature of this culinary offering (Zhang et al., 2021). Given consumers' emphasis on flavor preferences, even minor alterations in the taste of chicken soup can have a substantial impact on consumer decisions and purchasing behavior. Accordingly, the evaluation and study of chicken soup flavor held significance in advancing the commercial production of premium-quality chicken soup.

Fat played a crucial role in the food matrix, contributing significantly to soup flavor and texture attributes, thus impacting the overall palatability of food products. Serving as a carrier and reservoir of aroma compounds, fat enhanced sensory stimulation during consumption and served as a precursor for specific flavors. Furthermore, the quantity and composition of fat, as well as its physical state, played a crucial role in modulating the dynamic release of flavor compounds during eating. Tuorila et al. (1995) reported that fat interacted in complex ways with volatile and nonvolatile ingredients, thus affecting the timing of flavor release of a product. Arancibia et al. (2015) also demonstrated fat content significantly affected the nasal release time of the most lipophilic compound (linalool) in lemon-flavored dairy desserts. Additionally, volatile compounds produced by the oxidation of fats during heating process, such as alcohols, aldehydes, ketones, and esters, play a key role in forming specific flavors (Han et al., 2023). Carrapiso (2007) indicated that increased fat content led to a general elevation in volatile

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compound concentrations in sausages. Altering the fat content causes a shift in the overall sensory perception of a blend of flavor compounds belonging to diverse chemical classes. Moreover, the concentration of nutrients and flavor compounds was found to be low in plain soup without adding other ingredients (Meng et al., 2022). The optimal quantity of added fat could enhance the structural attributes and impart a velvety taste to the food. However, excessive fat supplementation could intensify lipid and protein oxidation, thereby compromising the quality and sensory properties of the products. Consequently, the impact of fat content on the flavor profile of chicken soup held paramount importance in the industrial manufacturing of chicken soup.

Chicken skeleton is the main by-product of chicken processing, containing nutrients such as protein, vitamins, and minerals. After a long time of stewing, the protein and fat in the chicken skeleton are emulsified in the state of boiling, forming a milky chicken soup. However, the fat content on the chicken skeleton is relatively low, which makes the flavor of chicken white soup is insufficient. Therefore, it is particularly important to add a certain amount of fat in the soup during the stewing process. This study employs GC–MS, GC-IMS, *E*-nose, high-performance liquid chromatography (HPLC) analysis, amino acid analyzer, and electronic tongue (E-tongue) to investigate the volatile and non-volatile flavor compounds in chicken white soup with varying fat content. The objective is to establish a theoretical foundation for enhancing the flavor of chicken white soup and facilitating its industrial advancement.

2. Materials and methods

2.1. Materials and reagents

Chicken skeletons devoid of head, neck, wings, legs, feet, breast meat, and visible fats were sourced from a local market in Jinzhou, Liaoning, China. They were obtained by slaughtering white-feathered chickens that had been fed for 46 days. 37 fatty acid methyl esters (FAMEs), cyclohexanone, and n-alkanes (C6-C26) were obtained from Sigma-Aldrich Co. Ltd. (Shanghai, China). Methanol and n-hexane obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China) were of HPLC grade. Potassium hydroxide, ethyl acetate, chloroform, sulfosalicylic acid, and perchloric acid acquired from Aladdin Chemical Reagent Co., Ltd. (Shanghai, China) were analytical grade.

2.2. Preparation of chicken fat

The abdominal fat (1000 g) from white-feathered chickens fed 46 days was washed, drained, and cut into pieces. Subsequently, the fat was put in the pot and heated at 800 W for 20 min. After the water was evaporated and the fat was outflowed, the fat was heated at 1400 W for 20 min (Xia et al., 2021). The resulting liquid fat was then filtered through two layers of gauze to remove solid impurities and stored at −18 °C. *prior* to utilization, the chicken fat was thawed in a water bath (40 °C) for 30 min.

2.3. Cooking of chicken white soup

The chicken white soup was prepared following the method outlined by Guan, Feng, et al., 2024). The chicken skeleton was cut into small pieces. Add cold water, boil over high heat for 5 min, skim off the foam, and pour away the water. The pre-treated chicken skeletons were placed into a pot containing water twice the weight of the chicken skeleton, boiled on an induction cooker with a power of 1600 W (100 ± 0.22 °C) for 30 min, and then simmered for 120 min at 800 W (98 ± 0.17 °C). The resulting soup was divided evenly into six portions. Subsequently, a precise quantity of chicken fat (0 %, 1 %, 2 %, 3 %, 4 %, and 5 %, *W*/W) was added to each portion based on our preliminary experimental results, and the mixture was simmered in a stainless steel pot by a C21-SDHCB46 Supor induction cooker with a power of 800 W (98 ± 0.47 °C) for 1 h. Throughout the stewing process, boiling water was periodically added to the initial water level of the pot to compensate for evaporation. The volume of soup with varying fat additions maintained consistent during the formation of white soup. Three independent repetitions were performed.

2.4. Fatty acid analysis

The total lipids were extracted following the procedure described by Lin et al. (2020) and were then converted into fatty acid methyl ester derivatives according to the method of Diao et al. (2017) with minor modification. Total lipids (50 mg) were dissolved in 2 mL of n-hexane. Then, 0.4 mL of sodium methoxide regent (2 M) was added and mixed for 1 min using a vortex mixer. Next, saturated sodium chloride (2 mL) was added to the mixture and shaken vigorously for at least 15 s. After 10 min of precipitation, 1 μL of the clear supernatant was injected into the gas chromatograph (GC, Thermo Fisher Inc., Waltham, Massachusetts, USA) equipped with an Agilent SP-2560 capillary column (100 m × 0.25 mm × 0.2 μm) and a flame ionization detector. Nitrogen served as the carrier gas at a flow rate of 1 mL/min. The initial column temperature was set at 140 °C for 2 min, increased to 200 °C at a rate of 6 °C/min and held for 2 min; subsequently raised to 230 °C at a rate of 2 °C/min and held for 2 min; then elevated to 250 °C at a rate of 4 °C/min and maintained for 2 min. The detector temperature was 250 °C. The fatty acids were identified by comparison with the retention times of the standard FAME mixture. The quantification of different fatty acids was achieved by determining the area ratio of GC peaks between the external standard and the various fatty acids. The fatty acid composition was expressed in μg/mL of soup.

2.5. E-nose analysis

Aromatic information for the chicken white soups was acquired using a PEN3 portable *E*-nose with ten sensors (Airsense Analytics, Schwerin, Germany). The temperature during the detection was kept at 25 ± 1 °C. Each sample of chicken soup (5 g) was placed in a headspace vial, sealed with plastic wrap, and equilibrated for 30 min in a 50 °C water bath. The detection time was set at 120 s, with a cleaning time of 120 s. Data collected between 100 and 110 s were utilized for principal component analysis (PCA) conducted using the Win Muster software included with the E-nose.

2.6. GC–MS analysis

The volatile flavor compounds present in chicken white soup with varying fat content were extracted using a HS-SPME (headspace solid-phase microextraction) device equipped with a 75 μm CAR/PDMS (carboxen/polydimethylsiloxane) fiber. 4.5 g of chicken soup and 10 μL of cyclohexanone standard (dissolved in ethanol) were mixed in a 20-mL headspace vial. The volatile compounds were adsorbed with a CAR/PDMS fiber at 55 °C for 30 min, then desorbed at 250 °C for 5 min. Separation was performed using a GC–MS equipment from Shimadzu Enterprise Management Co., LTD, China equipped with an Rtx-5MS capillary column (30 m × 0.25 mm × 0.25 μm). The mass spectrometer operated within a mass range of m/z 30 to 550. Electron ionization mode was employed with an electron impact energy of 70 eV.

The volatile compounds were identified by searching the NIST/Wiley MS library and using the retention index (RI). The RI value was calculated by running C6-C26 n-alkanes under the same chromatographic conditions. The peak area of each compound was determined by the software system for search results with a matching degree exceeding 800 (total value 1000). A semi-quantitative approach was employed for the quantitative analysis of volatile flavor substances, utilizing cyclohexanone as the internal standard. The concentration of each substance was calculated according to the following formula (Zeng et al., 2020).

$$C_i = \frac{S_i \times M_o}{S_o \times M_i}$$

where C_i represented the content of identified compound (ng/g); S_0 and S_i represented the peak areas of the internal standard and the identified compound, respectively; M_0 was the mass of the internal standard (ng); M_i was the mass of the soup (g).

2.7. GC-IMS analysis

The volatile components from all samples were analyzed using GC-IMS equipment from Flavor Spec®, Dortmund, Germany. The test conditions were employed using the method described by Pu et al. (2019) with minor modification. A 2.0 g sample was placed in a 20 mL headspace sample vial and incubated at 60 °C for 20 min, with a rotation speed set at 500 rpm. Each 500 μL sample was inserted into the GC injection port. A FS-SE-54-CB-1 capillary column (15 m × 0.53 mm, 1 μm) was used. Nitrogen was utilized as the carrier gas and the drift gas. The flow rate of carrier gas through the column was maintained at 2 mL/min for 2 min, then linearly increased to 5 mL/min within 8 min, to 100 mL/min within 5 min, and finally increased to 140 mL/min within 15 min. The flow rate of the drift gas in the drift tube was maintained at 150 mL/min.

The identification of volatile flavor compounds was carried out using the NIST library and IMS database search software, combined with retention indices and drift times. The reporter plugin accompanying the instrument was used to draw two-dimensional and three-dimensional spectra, and the Gallery plot plugin was employed to craft fingerprint spectra of the volatile compounds.

2.8. E-tongue analysis

25 g sample was diluted to a total volume of 250 mL and filtered through 0.45 μm and 0.22 μm filters. Subsequently, 35 mL of the filtered and clarified chicken soup sample was transferred into the sample cup of the electronic tongue (SA402B, Insent Inc., Atsugi-chi, Japan) and positioned on the automatic injector of the electronic tongue following a predetermined sequence. The electronic sensor underwent an initial cleaning in the cleaning solution for 90 s. This was followed by the addition of the first reference solution for sensor cleansing for 120 s. Subsequently, the second reference solution was introduced for sensor cleaning for another 120 s. Following the cleaning process, the sensor was calibrated to the equilibrium position for 30 s and then moved into the sample cup for a 30-s testing cycle. After each test, the sensor underwent sequential rinsing in two reference solutions for 3 s each. The same sample was tested four times. The initial experimental data was discarded, and the average of the remaining three datasets was calculated for the analysis of taste components.

2.9. Free amino acids analysis

The analysis of free amino acids (FAAs) in chicken white soup was conducted following a previously established protocol (Lv et al., 2024). Each sample of white soup (2 g) was combined with 4 mL of sulfosalicylic acid solution (3 g/100 mL) and incubated at 4 °C for 12 h. Subsequently, the mixture was centrifuged at 10000 ×*g* for 15 min. An additional 2 mL of n-hexane was introduced, followed by vortex mixing for 60 s. The resulting supernatant was filtered through a 0.22 μm filter and then injected into a L-8800 amino acid analyzer (Hitachi, Tokyo, Japan) for analysis.

2.10. 5′-nucleotide analysis

The extraction of 5′-nucleotides was carried out following the method established by Meng et al. (2022) with certain adaptations. A volume of 10 mL of soup from each sample was centrifuged (4 °C, 10000 ×*g*, 15 min), and the resulting supernatant was thoroughly mixed with ethyl acetate in a 1:1 ratio (V:V) at 4 °C, followed by centrifugation at 10000 ×*g* for 20 s. Subsequently, 30 mL of a 5 % perchloric acid solution (*W/V*) was introduced to the mixture and homogenized using a high-speed disperser at 10000 rpm for 20 s. The disperser was rinsed with 10 mL of 5 % perchloric acid, and this rinse was combined with the homogenate. The combined solution was then subjected to centrifugation at 4 °C, 10000 ×*g* for 10 min. The resulting precipitate was washed with 10 mL of 5 % perchloric acid, followed by another round of centrifugation under the same conditions as previously described. The supernatants from both centrifugation steps were combined. This resulting supernatant was filtered using medium-speed filter paper, and the pH was adjusted to 5.4 using a 1 mol/L potassium hydroxide solution. The volume was adjusted to 100 mL, and the sample was subsequently filtered through a 0.22 μm aqueous filter membrane before analysis by HPLC.

The HPLC analysis was conducted following the methodology outlined by Qi et al. (2017) with some adjustments. The key chromatographic conditions of the HPLC system included the use of an X Bridge C18 column (5 μm, 4.6 × 250 mm) maintained at a column temperature of 30 °C, UV detection wavelength set at 254 nm, sample injection volume of 10 μL, and a flow rate of 0.8 mL/min. The mobile phase consisted of methanol as eluent A and 0.05 mol/L potassium dihydrogen phosphate buffer at pH 5.4 as eluent B. The mobile phase was filtered through a 0.45 μm filter and subjected to 30 min of ultrasonic degassing at room temperature. Gradient elution separation was achieved using a binary mobile phase, with the ratio of potassium dihydrogen phosphate buffer to methanol changing over time as follows: 0 min: 0 %/100 %; 11 min: 10 %/90 %; 18 min: 0 %/100 %; 23 min: 0 %/100 %. The total detection time for the analysis was 23 min.

The taste activity value (TAV) quantified the impact of an individual compound on the overall taste profile. A substance was considered to have minimal taste contribution when its TAV was below 1, whereas a TAV exceeding 1 indicated a significant contribution to the taste. TAV was determined by calculating the ratio of a substance's concentration in the chicken soup to its threshold value typically established in a simple matrix.

2.11. Sensory evaluation

Sensory evaluation was performed according to the method of Yue et al. (2024). 10 g of chicken white soup with different fat addition was randomly placed into disposable sensory cups. The chicken soups were maintained at 45 °C and randomly distributed to sensory evaluators who were healthy, non-smoking, and had no symptoms of rhinitis. Before evaluating the next chicken soup sample, the evaluator gargled with pure water. 10 panelists (5 women and 5 men, aged between 22 and 24 years) were selected to assess the color, aroma, taste, and overall acceptability of chicken soups, using a 10-point hedonic scale ranging from 10 (like very much) to 1 (dislike very much) for each sensory attribute. The evaluators scored separately without interference with each other, and the average value was taken as the result. Ethical permission for sensory research was not required in Bohai University. Prior to the sensory evaluation, all participants signed an informed consent and volunteered to join.

2.12. Statistical analysis

All experiments were repeated thrice, and the results were expressed as the mean ± SD. Statistical analysis was performed by one-way analysis of variance (ANOVA) and Duncan's multiple range test at $P < 0.05$ with IBM SPSS Statistics 19. PCA and loadings plot analysis were processed using Origin 2019b software. The heat map was generated using the online tool (https://www.chiplot.online/#Line-plot).

3. Results and discussion

3.1. Fatty acid analysis

Fatty acids (FAs) were known to play a crucial role in determining the flavor profile of meat, including meat soups. Serving as important precursors to meat flavor, FAs were closely associated with the distinctive flavor attributes of meat soups. A comprehensive analysis identified a total of 24 FAs in chicken soups, comprising 13 saturated fatty acids (SFAs), 6 monounsaturated fatty acids (MUFAs), and 5 polyunsaturated fatty acids (PUFAs). Fig. 1A illustrates that the levels of SFAs, MUFAs, and PUFAs exhibited significant variations across chicken white soups with different fat additions ($P < 0.05$). Notably, unsaturated fatty acids (UFAs) were found to predominate over SFAs in all examined chicken white soups. Furthermore, the chicken white soup with a 2 % fat addition displayed the highest total fatty acid content (5293.43 μg/mL), which was 17.6 % ($P < 0.05$) higher than 1 % fat addition. This may be because chicken soup was an emulsion (Qi et al., 2023), and when the added fat was 2 %, it was fully incorporated into the soup to participate in emulsification, thereby increasing the fatty acid content in the soup. However, as the added fat content increased to 3.0 %, the total fatty acid content significantly decreased to 3892.45 (μg/mL) ($P < 0.05$). This phenomenon may be attributed to the excessive fat impeding the emulsification process of the chicken soup (Guan, Feng, et al., 2024), causing the added fat to not be adsorbed by the emulsifier and forming an oil layer on the surface of the soup, resulting in a reduction in the retained fat content within the soup (Qi et al., 2023). Another reason may be that the fat on the surface of soup was more easily oxidized, forming a large number of free radicals to further oxidize some unsaturated fatty acids in the soup into epoxide or ether-linked dimers and oligomers (Gardner, 1989). Furthermore, findings by Han et al. (2023) demonstrated the pivotal role of UFAs in the generation of meat flavor compounds through moderate thermal oxidation processes. The formation of chicken white soup flavors primarily occurs via the oxidation and hydrolysis of unsaturated fatty acids. Compounds such as heptanal, octanal, nonanal, 2-decenal, and 2-nonenal are generated from oleic acid as a result of lipid oxidation and degradation, contributing pleasant aromas (Chen et al., 2019). Similarly, pentanal, hexanal, (*E*)-2-octenal, and (*E, E*)-2,4-decadienal originate from linoleic acid through oxidation and hydrolysis pathways. Yang et al. (2011) emphasized the significance of hexanal concentration in the flavor development of cooked meat.

In order to investigate the variations in fatty acid types and levels in chicken white soups with different fat additions, a heat map was generated (Fig. 1B). In the heat map representation, deeper red hues indicated lower content, while deeper blue hues signified higher content. The chicken white soup containing 2 % added fat exhibited elevated levels of oleic acid (1187.21 μg/mL) and linoleic acid (866.88 μg/mL). These fatty acids were known contributors to the flavor profile of the chicken white soup.

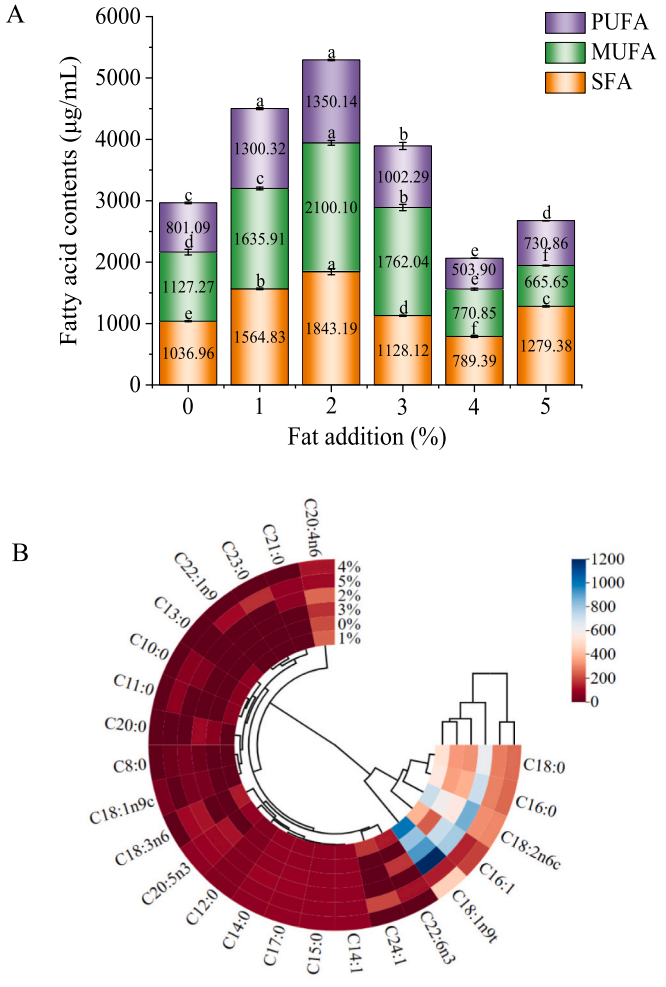

Fig. 1. Contents analysis (A) and heat map (B) of fatty acids in chicken white soups with varying fat additions.

3.2. E-nose analysis

As a significant technology in intelligent sensing, electronic nose (E-nose) had the capability to differentiate and classify various samples by leveraging the rapid response attributes of distinct sensors to specific volatile compounds (Xie et al., 2024). The response of E-nose sensors to flavor compounds present in chicken white soups with varying fat additions was illustrated through a heat map representation (Fig. 2A). In the heat map, deeper red shades indicated lower response values, while deeper blue hues signified higher response values. The diverse colors within the heat map highlighted the distinct aroma profiles of chicken soup samples with different fat additions. Notably, the W5S sensor (sensitive to nitrogen oxide compounds) and W1W sensor (responsive to terpenes and organosulfur compounds) exhibited strong responses across all six chicken white soup samples. This suggested the presence of these compounds in the samples, indicating their potential significant contribution to the volatile profile of the chicken soups. However, there was no significant differences in the responses of W3C (ammonia and aromatic compounds), W5C (alkane, aromatic compounds), and W2W (organic sulfide) sensors across all samples. This implied that the samples may contain lower levels of alkanes, ammonia, aromatic compounds, and organic sulfides. Moreover, the highest response values for W5S and W1W sensors were observed in the 2 % chicken soup samples, indicating a potentially higher presence of nitrogen oxides, terpenes, sulfides, and pyrazine compounds compared to the other samples. This suggested that an appropriate amount of chicken fat may enhance the release of volatile compounds. These results further suggested that the aroma profile of the 2 % chicken soup sample significantly differs from that of the other samples.

The relationship between the samples and *E*-nose sensors was further elucidated through PCA, with the results presented in Fig. 2B. PC1, PC2, and PC3 explained 45.4 %, 18.4 %, and 16.9 % of the total variance, respectively. The cumulative contribution of the three principal components accounted for 80.7 % of the variance, indicating the accuracy of the PCA results in interpreting the odor data across all samples. These outcomes highlighted the E-nose sensors' efficacy in successfully discriminating between chicken white soups with different fat additions. To delve deeper into the distinctions in aroma compounds among the chicken white soups with varying fat additions, aroma compound analysis was conducted using GC–MS and GC-IMS.

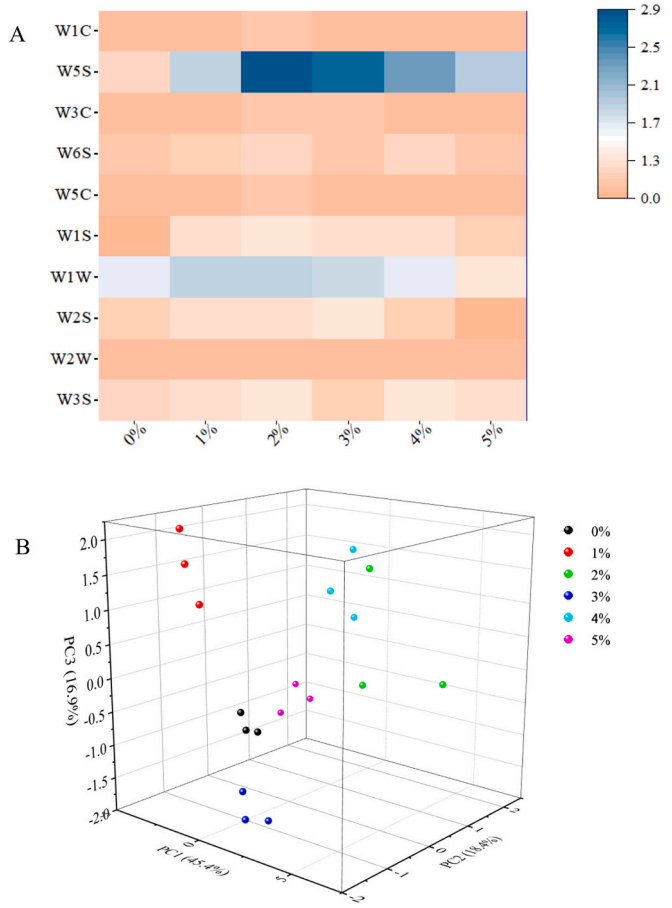

Fig. 2. Heat map (A) and PCA analysis (B) for E-nose result of chicken white soups with varying fat additions.

3.3. GC–MS analysis

Food flavor played a critical role in influencing consumer acceptance and consumption patterns. In this study, the volatile flavor components present in chicken white soups with varying fat additions were analyzed using GC–MS. The fat content was found to have a notable impact on the types and concentrations of specific volatile flavor compounds in chicken white soups. A total of 105 compounds were identified in the chicken white soup samples through GC–MS analysis, encompassing 5 esters, 54 alkanes, 11 alcohols, 4 ketones, 18 aldehydes, 7 hydrocarbons, 5 alkenes, and 1 furan (Fig. 3A). These findings suggested that lipids play a significant role in shaping the overall aroma profile of chicken soup. As the amount of fat added increased, the concentration of volatile compounds in the chicken soup also increased. Compared to the white soup without fat (26,374.12 ng/g), the content of volatile flavor compounds of the soup with 1 % fat addition was significantly increased to 29,601.98 ng/g. Particularly, when the fat addition reached 2 %, the content increased to the maximum (Fig. 3B). The phenomenon may be attributed to the interaction between oxidative degradation of chicken fat and Maillard reaction (Sun et al., 2023), which produced more compounds. However, when the fat addition increased to 4 %, the content of volatile compound decreased, which may be due to a decrease in fat dissolved into the soup. Therefore, the optimal amount of fat added to chicken white soup to enhance flavor appears to be 2 %. This result could also be seen from the heatmap of various volatile compounds contents in chicken white soups based on different fat additions (Fig. 3C).

Additionally, as depicted in Fig. 3B, the predominant flavor components identified in chicken white soup were primarily aldehydes, which were predominantly derived from unsaturated fatty acids or from the decomposition of alkoxy radicals during lipid oxidation (Mottram, 1998). Hence, the generation of aldehydes was closely associated with the lipid content of chicken white soup. The levels of aldehyde flavor compounds in chicken white soup varied significantly across different fat supplementation levels ($P < 0.05$). Verbeke et al. (2010) also observed a correlation between aldehydes and fat content. Linear aldehydes were generated through the oxidation of unsaturated fatty acids, whereas branched-chain aldehydes stem from the breakdown of amino acids. In particular, certain short-chain fatty acid aldehydes (C_5-C_9) were believed to play a crucial role in the flavor profile of chicken soup. Among the 13 aldehydes identified in chicken soup, notably higher contents were observed for nonanal, hexanal, heptanal, octanal, (*E*)-2-octenal, (*E*)-2-hexenal, (*E*)-2-nonenal, (*E, E*)-2,4-decadienal, (*E*)-2-decenal, and (*E, E*)-2,4-decadienal. Hexanal exhibited grassy aroma; heptanal presented fatty, greasy, and fruity characteristics; octanal imparted a fruity, fatty taste with a robust aroma post-dilution; while nonanal delivered a potent fatty and sour taste (García-González et al., 2013). Most aldehydes possessed a low flavor threshold and exhibited a distinctive fatty aroma at lower concentrations, yet at concentrations surpassing a certain threshold, they may yield acidic or other odors (Calkins & Hodgen, 2007). The aldehyde content in the study tended to diminish with increased fat supplementation, potentially attributed to conversion into acids or alcohols.

Alcohol primarily arose from the oxidation of linoleic acid degradation products. While alcohols had a lesser impact on meat flavor compared to aldehydes, they synergized with aldehydes and significantly contributed to the overall meat flavor profile (Wang et al., 2021). The alcohol content varied significantly across different levels of fat supplementation, thereby influencing the flavor profile of chicken white soup. Among them, 1-octene-3-ol imparted a mushroom aroma and served as a key flavor compound in chicken soup. Additionally, four kinds of ketones were detected in chicken white soup. Ketones originate from the degradation of amino acids via Strecker reactions and the oxidative thermal breakdown of fatty acids, thereby imparting a fruity and creamy taste to meat products (Wang et al., 2019).

The levels of ketones in chicken white soup varied significantly with different fat supplementation levels, exerting a notable impact on the flavor profile of the soup. Notably, 4-methyl-2-pentanone was consistently present in all fat supplementation levels of chicken white soup, with its content showing no significant differences with increasing fat content, indicating its enduring and stable aroma. Ester compounds were formed through the esterification of alcohols from fats and free fatty acids generated by oxidation. Alkanes, which result from lipid oxidation, had a high flavor threshold and therefore made minimal contributions to the overall flavor of chicken white soup. Among other compounds, furans, a class of compounds with lower odor threshold and pleasant aroma, might also affect the odor of chicken soup (Qi et al., 2017). Alkenes were produced through the cleavage and degradation of fatty acids, with many of these compounds possessing lengthy carbon chains that impart minimal aroma and flavor to the soup, yet played a vital role as flavor coordinators (Meng et al., 2022). The collective flavor of chicken soup was not dependent on one or a few substances, but rather on the combination of all volatile and non-volatile compounds present.

The flavor impact of volatile compounds could be evaluated using the odor activity value (OAV), which represented the ratio of the compound's concentration in the sample to its reported odor threshold in the aqueous phase. Volatile compounds with an OAV equal to or greater than 1 were recognized as key flavor contributors, exerting a substantial influence on the overall flavor profile of the sample, while an OAV < 1 suggested a minor contribution (Xie et al., 2024). As shown in Table 1, the 13 volatiles pentanal, hexanal, (*E*)-2-hexenal, heptanal, (*E*)-2-heptenal, octanal, (*E*)-2-octenal, nonanal, (*E*)-2-nonenal, decanal, (*E*)-2-decenal, (*E, E*)-2,4-decadienal, 1-octen-3-ol were identified as key aromatic constituents in chicken white soup. Consequently, aldehydes were

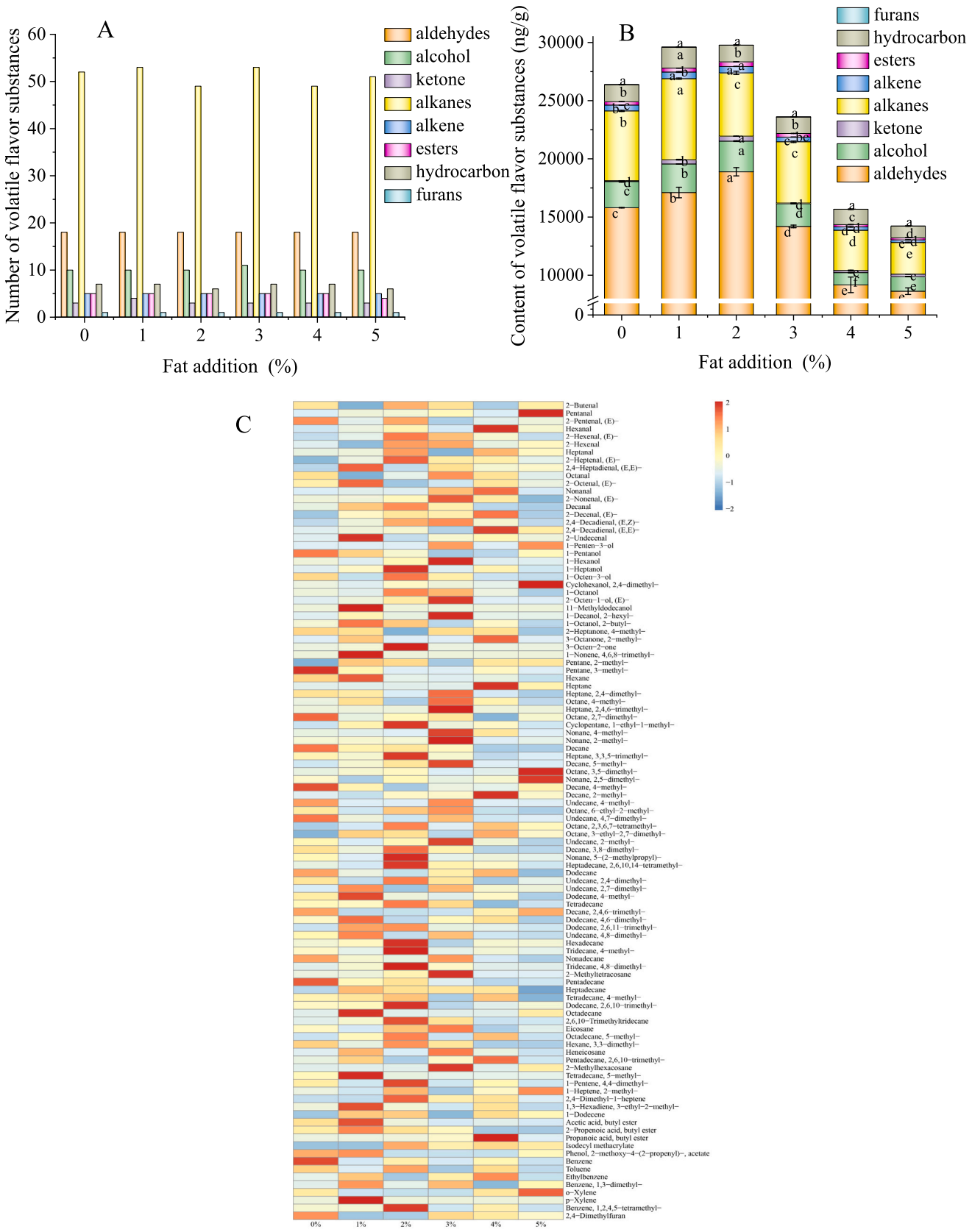

Fig. 3. Volatile components of chicken white soups with varying fat additions detected by GC–MS. Clustered column graph of volatile compound species (A); Stacked graph of volatile compound content (B); Heatmap analysis of volatile compounds (C).

Table 1
OAVs of volatile compounds of chicken white soups with varying fat additions.

Volatile flavor compounds	Retention time/min	Retention index	Odor threshold (ng/g)	Fat addition					
				0 %	1 %	2 %	3 %	4 %	5 %
Pentanal	3.058	754	12	15.77 ± 0.02^{a}	15.53 ± 0.21^{a}	12.69 ± 0.24^{b}	15.07 ± 0.43^{a}	9.77 ± 0.00^{c}	9.60 ± 1.64^{c}
Hexanal	5.503	793	5	790.98 ± 5.34^{b}	781.17 ± 11.09^{b}	937.86 ± 21.12^{a}	766.63 ± 5.51^{b}	468.66 ± 51.96^{c}	440.01 ± 14.70^{c}
(*E*)-2-Hexenal	7.149	847	19.2	13.61 ± 0.00^{a}	13.23 ± 0.46^{a}	13.23 ± 2.98^{a}	9.71 ± 2.33^{ab}	7.13 ± 0.81^{bc}	3.42 ± 0.00^{c}
Heptanal	9.438	899	3	205.11 ± 3.65^{a}	197.76 ± 4.08^{ab}	194.00 ± 9.96^{ab}	184.62 ± 0.43^{b}	162.05 ± 9.22^{c}	153.10 ± 5.14^{c}
(*E*)-2-Heptenal	11.979	942	13.5	196.75 ± 1.63^{b}	193.73 ± 6.44^{b}	250.33 ± 17.74^{a}	159.33 ± 10.50^{c}	100.78 ± 10.20^{d}	96.03 ± 6.09^{d}
Octanal	14.22	1003	0.7	1149.98 ± 38.38^{b}	1354.79 ± 0.78^{a}	1321.27 ± 17.81^{a}	957.77 ± 51.98^{c}	599.78 ± 37.85^{d}	580.63 ± 17.23^{d}
(*E*)-2-Octenal	16.54	1049	3	558.67 ± 26.02^{a}	555.70 ± 47.62^{a}	543.46 ± 4.50^{ab}	478.88 ± 10.49^{b}	193.58 ± 29.98^{c}	186.35 ± 15.88^{c}
Nonanal	18.348	1101	1	2113.33 ± 15.70^{b}	2569.40 ± 30.69^{a}	2195.26 ± 24.14^{b}	1696.82 ± 195.07^{c}	1195.99 ± 262.35^{d}	928.56 ± 9.12^{d}
(*E*)-2-Nonenal	20.272	1232	0.08	4213.06 ± 256.08^{c}	5329.97 ± 256.70^{b}	6947.71 ± 329.38^{a}	4112.68 ± 732.02^{c}	2723.48 ± 422.26^{d}	1991.79 ± 21.64^{d}
Decanal	21.793	1198	2	43.61 ± 1.39^{a}	43.86 ± 2.84^{a}	42.13 ± 3.36^{a}	41.29 ± 2.13^{a}	29.35 ± 0.83^{b}	21.56 ± 0.73^{c}
(*E*)-2-Decenal	23.503	1356	0.3	1228.13 ± 4.06^{c}	2145.23 ± 98.72^{b}	2809.43 ± 151.82^{a}	1875.50 ± 127.43^{b}	1027.61 ± 240.69^{cd}	892.29 ± 14.23^{d}
(*E, E*)-2,4-Decadienal	25.142	965	0.07	20,059.34 ± 1285.03^{ab}	22,702.10 ± 1545.63^{ab}	26,913.58 ± 1624.14^{a}	20,562.15 ± 903.91^{ab}	17,777.27 ± 3650.88^{b}	18,889.21 ± 2169.65^{b}
1-Pentanol	4.612	763	4000	0.02 ± 0.00^{a}	0.02 ± 0.00^{a}	0.02 ± 0.00^{a}	0.02 ± 0.00^{a}	0.01 ± 0.00^{b}	0.01 ± 0.00^{b}
1-Hexanol	8.167	865	330	0.37 ± 0.01^{ab}	0.38 ± 0.00^{ab}	0.44 ± 0.02^{a}	0.32 ± 0.09^{bc}	0.23 ± 0.00^{cd}	0.20 ± 0.00^{d}
1-Octen-3-ol	13.231	978	1	1339.41 ± 49.56^{b}	1384.41 ± 2.86^{ab}	1474.44 ± 74.47^{a}	1170.09 ± 35.86^{c}	632.15 ± 3.11^{e}	767.67 ± 1.46^{d}
Toluene	4.54	674	1550	0.05 ± 0.01^{ab}	0.06 ± 0.00^{a}	0.05 ± 0.01^{ab}	0.04 ± 0.00^{bc}	0.03 ± 0.01^{cd}	0.03 ± 0.00^{d}

Results are expressed as mean ± standard deviation ($n = 3$); Different letters in the same line represent significant differences in volatile flavor compounds of chicken white soup ($P < 0.05$); Thresholds for volatile flavor compounds are obtained from references (Qi et al., 2017) and a search of the website http://www.odour.org.uk. All thresholds are expressed as thresholds for flavor compounds in water.

likely to play a significant role in shaping the aroma profile of chicken white soup. It was worth mentioning that most aldehydes and 1-octen-3-ol in chicken white soup showed high OAVs when the fat addition was 2 %. However, as the fat addition continued to increase, their OAVs began to decline. This might be because saturated and monounsaturated aldehydes and 1-octen-3-ol were generated from lipid oxidation (Han et al., 2019). With greater fat additions, there wasn't enough protein in the soup to emulsify the fat, causing some fat droplets re-aggregated into clusters and floated on the surface of the soup, thereby reducing the amount of fat dissolved in the soup (Wang et al., 2023).

3.4. GC-IMS analysis

Based on the results of electronic nose and GC–MS analyses, four fat additions of 0 %, 1 %, 2 % and 3 % were selected for GC-IMS analysis. GC-IMS database matching was employed to identify the volatile flavor compounds present in chicken white soup. Fig. 4A and B showed the two-dimensional and three-dimensional GC-IMS spectra of chicken white soup with different fat addition, providing a direct representation of the differences in flavor compounds. The X, Y, and Z axes corresponded to drift time, retention time, and peak intensity, respectively. The red vertical line at the X axis 1.0 denoted the reaction peak following normalization. Each distinct color spot reflected the concentration of the corresponding volatile flavor compounds, with red and white indicating high and low concentrations, respectively. A compound might manifest as one, two, or more bright spots representing the monomer, dimer, or trimer of the substance, contingent upon its concentration and properties. While chicken white soup samples with different fat addition levels exhibited similar volatile flavor compounds, their peak intensitied vary across the different fat addition levels.

To visually compare the variations and specific distribution of volatile flavor compounds in chicken white soup samples with different fat additions, a volatile flavor compound fingerprint map was generated using the "gallery plot" function of GC-IMS software (Fig. 4C). Each row in the map corresponded to a sample, each column represented a specific compound, and the color gradient from light to dark signified the content level from low to high. A total of 72 volatile flavor compounds were identified in the chicken white soup, including their monomeric and dimeric forms. This composition comprised 9 esters, 21 alcohols, 9 ketones, 15 aldehydes, 3 alkene, 4 acids, 4 pyrazines, 2 ethers, 3 phenols, 2 furan and 4 other substances. As depicted in Fig. 4C, certain volatile substances (A region), such as 2-heptanone, (*Z*)-3-hexene-1-ol and (*E*)-2-octenal, exhibited decreased levels following fat addition, potentially due to the overshadowing of characteristic flavor compounds by the presence of chicken fat flavor. Conversely, the content of 2-methyl-1-butanol, propyl acetate, benzaldehyde, methylpyrazine, and (*Z*)-3-hexenol (B region) was elevated in the soup containing 2 % fat, thereby enhancing the flavor profile of the chicken white soup.

3.5. E-tongue analysis

The E-tongue utilized electronic sensors to mimic human taste perception and detect taste characteristics. The radar map presented the response values of the E-tongue in chicken white soups with varying fat additions (Fig. 5A). It was observed that the sourness and saltiness of chicken white soup across the six different fat levels consistently fall below the threshold of detectability, indicating that fat did not affect salt and sour tastes. Barylko-Pikielna et al. (1994) also reported that the taste qualities of sodium chloride and citric acid were not affected by the type of fat emulsion, whether oil-in water or water-in-oil. Additionally, most taste parameters on the diagram overlap, indicating that the taste profiles of the chicken soups with different fat additions were not distinctly separable.

PCA was a widely used statistical method for visualizing and quantifying differences between samples. In this study, PCA was employed to model and differentiate between various fat additions in chicken white soup (Fig. 5B). The interpretation rates of total variance for PC1 (70.1 %) and PC2 (16.4 %) combined reached 86.5 %, indicating that the extracted principal component features encapsulate a significant portion of the information present in the original sample data (Peng et al.,

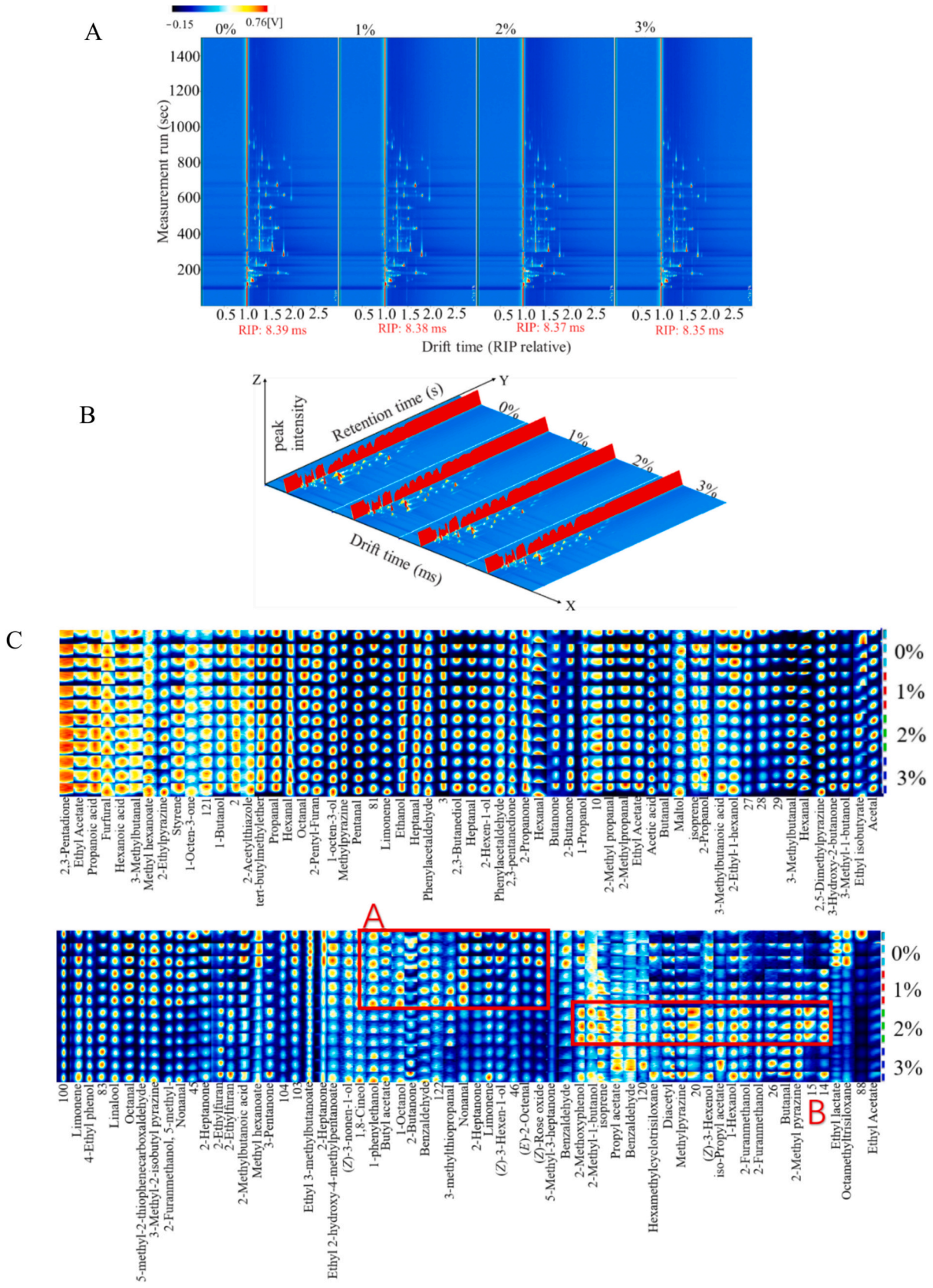

Fig. 4. Two-dimensional spectra (A), three-dimensional spectra (B), and fingerprint (C) of GC-IMS data of chicken white soups with varying fat additions.

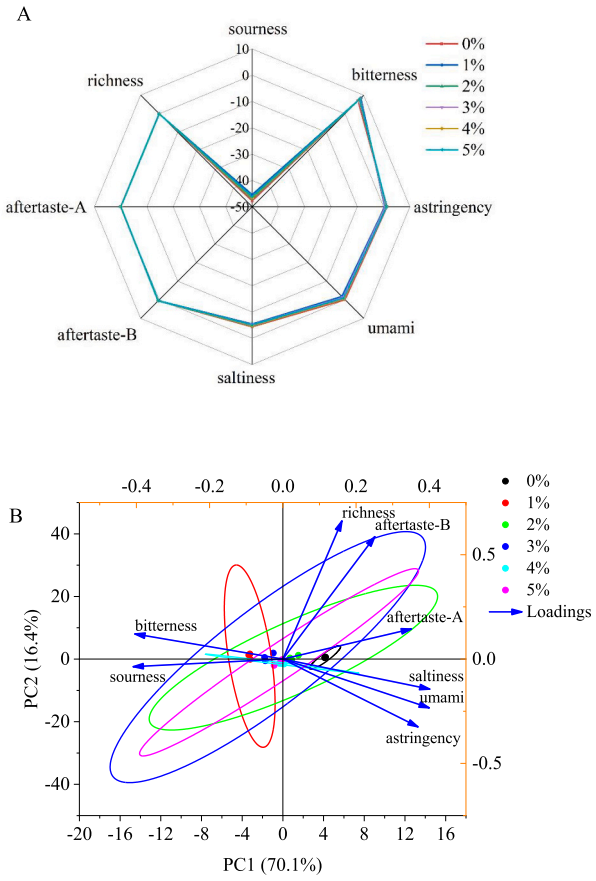

Fig. 5. Radar map (A) and PCA (B) of electronic tongue response value in chicken white soups with varying fat additions. Aftertaste-A is aftertaste astringency; Aftertaste-B is aftertaste bitterness.

2023). As depicted in Fig. 5B, the chicken soups with different fat additions were clustered closely together in spatial regions, while they were separated from the soup without fat addition. This suggested that the soups with fat addition shared relatively similar taste components, whereas the soup without fat had slightly different from the others in terms of taste characteristics. Moreover, PC1 exhibited positive correlations with umami, saltiness, richness, astringency, aftertaste–astringency (aftertaste-A), and aftertaste–bitterness (aftertaste-B), while displaying negative correlations with sourness and bitterness. However, the arrows' lengths were comparable, suggesting that each taste attribute contributed equally to the overall taste profile of the chicken soup. Consequently, the electronic tongue analysis did not effectively differentiate the taste characteristics of chicken white soup with varying fat additions, highlighting the necessity for further analysis to comprehensively assess its taste attributes.

3.6. Free amino acid analysis

FAAs served as pivotal flavor compounds in food, constituting the foundation of food's characteristic taste. The identification and concentration determination of FAAs in chicken white soup were conducted using an automatic amino acid analyzer. The 17 FAAs detected in chicken white soup samples with varying fat additions were categorized into four groups based on their taste properties (umami, sweet, bitter, or tasteless) (Table 2). Glutamate, glycine, alanine, and aspartic acid emerged as key determinants of food taste, collectively known as flavor amino acids, with particular emphasis on the significance of aspartic acid and glutamate in enhancing soup quality. Aspartate and glutamate, being representative umami amino acids with flavors akin to monosodium glutamate, contributed to the umami profile of chicken white soup. Glycine, serine, alanine, threonine, and arginine imparted pleasant sweetness and umami notes, while the combination of alanine and glutamate enhanced umami intensity in meat products. Conversely, tyrosine, lysine, methionine, valine, isoleucine, and leucine introduce slight bitterness to the soup (Zhou et al., 2020).

As indicated in Table 2, with increasing fat additions, the total amino acid concentration in chicken soup showed an initial increase followed by a decrease pattern. Compared to the chicken soup without fat addition (163.80 μg/mL), the highest concentration (211.29 μg/mL) was achieved when the fat addition was 2 %. This escalation could be attributed to the oxidation of chicken fat, leading to the generation of abundant free radicals that facilitate protein degradation and subsequent production of free amino acids (Ma et al., 2021). In a study by

Table 2
Analysis of concentration of free amino acids in chicken white soups with varying fat additions.

Concentration of free amino acids (μg/mL)	Fat addition					
	0 %	1 %	2 %	3 %	4 %	5 %
Aspartic acid (Asp)	11.62 ± 0.22^{e}	14.44 ± 0.22^{ab}	14.91 ± 0.28^{a}	14.33 ± 0.30^{bc}	13.80 ± 0.13^{c}	12.83 ± 0.08^{d}
Glutamic acid (Glu)	30.77 ± 0.42^{d}	39.93 ± 0.66^{a}	40.01 ± 0.78^{a}	38.83 ± 1.12^{ab}	38.14 ± 0.22^{b}	34.81 ± 0.55^{c}
∑ Umami AA	42.38 ± 0.64^{d}	54.37 ± 0.88^{a}	54.92 ± 1.06^{a}	53.15 ± 1.43^{ab}	51.94 ± 0.35^{b}	47.64 ± 0.64^{c}
Threonine (Thr)	11.09 ± 0.14^{e}	13.73 ± 0.22^{bc}	14.26 ± 0.25^{a}	13.82 ± 0.28^{ab}	13.31 ± 0.13^{c}	12.13 ± 0.00^{d}
Serine (Ser)	15.48 ± 0.28^{c}	20.03 ± 0.19^{a}	20.07 ± 0.41^{a}	19.55 ± 0.50^{a}	19.36 ± 0.21^{a}	17.31 ± 0.34^{b}
Proline (Pro)	8.09 ± 0.12^{d}	9.92 ± 0.08^{b}	10.62 ± 0.23^{a}	9.83 ± 0.34^{b}	9.64 ± 0.10^{b}	8.73 ± 0.01^{c}
Glycine (Gly)	14.19 ± 0.23^{c}	18.59 ± 0.35^{a}	18.40 ± 0.38^{a}	18.04 ± 0.45^{a}	17.85 ± 0.04^{a}	16.38 ± 0.13^{b}
Alanine (Ala)	21.08 ± 0.27^{d}	26.15 ± 0.23^{ab}	27.42 ± 0.59^{a}	26.21 ± 1.16^{ab}	25.32 ± 0.23^{b}	23.01 ± 0.08^{c}
∑ Sweet AA	69.92 ± 1.04^{d}	88.40 ± 0.91^{ab}	90.76 ± 1.87^{a}	87.44 ± 2.73^{ab}	85.48 ± 0.71^{b}	77.55 ± 0.54^{c}
Valine (Val)	4.71 ± 0.04^{d}	5.73 ± 0.01^{ab}	6.04 ± 0.11^{a}	5.74 ± 0.26^{ab}	5.64 ± 0.09^{b}	5.22 ± 0.11^{c}
Methionine (Met)	3.01 ± 0.05^{c}	3.54 ± 0.06^{a}	3.70 ± 0.05^{a}	3.64 ± 0.16^{a}	3.46 ± 0.02^{ab}	3.29 ± 0.15^{b}
Isoleucine (Ile)	2.59 ± 0.01^{d}	3.26 ± 0.06^{b}	3.45 ± 0.08^{a}	3.29 ± 0.04^{ab}	3.20 ± 0.01^{b}	2.76 ± 0.12^{c}
Leucine (Leu)	5.66 ± 0.08^{d}	7.13 ± 0.05^{b}	7.43 ± 0.17^{a}	7.11 ± 0.12^{b}	6.95 ± 0.01^{b}	6.17 ± 0.19^{c}
Tyrosine (Tyr)	6.55 ± 0.18^{c}	7.09 ± 0.50^{bc}	8.26 ± 0.01^{a}	8.79 ± 0.75^{a}	8.70 ± 0.32^{a}	7.81 ± 0.47^{b}
Phenylalanine (Phe)	9.87 ± 0.18^{c}	11.82 ± 0.11^{a}	11.97 ± 0.28^{a}	11.65 ± 0.25^{a}	11.69 ± 0.43^{a}	10.64 ± 0.20^{b}
Lysine (Lys)	7.34 ± 0.18^{d}	9.91 ± 0.26^{a}	9.36 ± 0.09^{b}	9.49 ± 0.18^{ab}	9.41 ± 0.24^{b}	8.57 ± 0.11^{c}
histidine (His)	2.70 ± 0.03^{c}	3.32 ± 0.04^{b}	3.52 ± 0.08^{a}	3.38 ± 0.04^{ab}	3.30 ± 0.06^{b}	2.82 ± 0.07^{c}
Arginine (Arg)	8.62 ± 0.17^{d}	11.35 ± 0.11^{a}	11.34 ± 0.28^{a}	11.12 ± 0.17^{ab}	10.87 ± 0.04^{b}	9.97 ± 0.15^{c}
∑ Bitter AA	51.04 ± 0.93^{c}	63.13 ± 4.07^{a}	65.04 ± 0.96^{a}	64.19 ± 1.97^{a}	63.20 ± 0.55^{a}	57.22 ± 0.66^{b}
Cysteine (Cys)	0.47 ± 0.00^{c}	0.46 ± 0.02^{c}	0.57 ± 0.00^{a}	0.52 ± 0.03^{b}	0.48 ± 0.03^{bc}	0.41 ± 0.01^{d}
∑ Other AA	0.47 ± 0.00^{c}	0.46 ± 0.02^{c}	0.57 ± 0.00^{a}	0.52 ± 0.03^{b}	0.48 ± 0.03^{bc}	0.41 ± 0.01^{d}
Total AA	163.80 ± 2.60^{d}	206.35 ± 5.88^{ab}	211.29 ± 3.89^{a}	205.30 ± 6.10^{ab}	201.09 ± 1.64^{b}	182.81 ± 1.83^{c}

Results are expressed as mean ± standard deviation (n = 3); Different lowercase letters (a-d) in the same row indicate significant differences ($P < 0.05$).

Chen et al. (2023), it was observed that the essential free amino acid content in yogurt increased by 0.346 times upon the addition of Perilla seed oil, suggesting a potential relationship between the composition of Perilla seed oil and its impact on amino acid synthesis. Notably, there were no significant differences observed in the concentrations of umami, sweet, and bitter amino acids in chicken soup samples with 1 %, 2 %, and 3 % fat additions. Nevertheless, upon adding 4 % fat to the chicken white soup, there was a decrease in the levels of umami and sweet amino acids. Subsequently, with a further increase in fat addition to 5 %, the concentration of bitter amino acids decreased. This decline could be attributed to certain amino acids becoming encapsulated within the fat, resulting in the absence of fat-soluble amino acids in the analysis (Sun et al., 2022). On the other hand, fat that was not soluble in soup was more prone to be oxidized, and the resulting carbonyl compounds reacted with the nucleophilic amino groups of amino acids (Zamora & Hidalgo, 2011).

3.7. 5′-nucleotides analysis

5′-nucleotides (5′-AMP, 5′-GMP, and 5′-IMP) served as primary flavor nucleotides in chicken soup, playing a crucial role in enhancing the umami taste and contributing to the distinctive flavor profile of the soup. These nucleotides had been recognized as freshness enhancers, imparting a unique flavor to chicken soup. Table 3 showed the nucleotide contents in chicken soups prepared with varying fat additions. It was observed that as the amount of added fat increases, the content of flavor nucleotides in the chicken soup initially rises and then declines. Specifically, when 2 % fat was added, the umami taste of the chicken soup was most pronounced. This phenomenon might be attributed to the optimal production of free radicals resulting from fat oxidation, which activated endogenous enzymes leading to the breakdown of ATP and subsequent production of flavor nucleotides (Liu et al., 2007). However, when the fat addition was over 2 %, 5′-nucleotide content began to decline, which may be due to excessive fat affecting the ATP enzymatic degradation and the diffusion of nucleotides in the soup, thereby reducing their presence in the soup (Pérez-Palacios et al., 2017).

TAV was commonly utilized to assess the taste impact of compounds, with a TAV exceeding 1 indicating a significant contribution to food taste. As shown in Table 3, the concentration of 5′-nucleotides was relatively low and their TAVs were all below 1, suggesting that the presence of nucleotides alone did not directly influence the taste of chicken soup. However, they exerted a synergistic effect on flavor enhancement. The interaction between nucleotides and various sweet amino acids (such as serine, glycine, and alanine) enhanced the umami taste (EI-Aleem et al., 2017).

3.8. Sensory evaluation

As presented in Table 4, compared with chicken soup without fat addition, the color and taste of chicken soup with 2 % fat addition did not change significantly ($P>0.05$), but the aroma significantly increased ($P < 0.05$), and the overall acceptability also increased. However, when the fat addition was over 2 %, the score of color, taste and aroma decreased. Additionally, more fat could not dissolve better into the soup and floated on the surface, resulting in a decrease in the overall acceptability. Overall, the chicken white soup with 2 % fat addition was acceptable to the consumers.

4. Conclusions

The concentrations of fatty acids, amino acids, nucleotides, and flavor compounds in chicken white soup exhibited a significant increase with escalating fat addition ($P < 0.05$), reaching peak levels at a 2 % fat addition. Through the integration of GC–MS, GC-IMS, and electronic nose analyses, it was determined that a 2 % fat addition effectively enhanced the flavor profile of chicken white soup. Notably, aldehydes emerged as the key flavor components in chicken soup according to the OAV results. A more comprehensive understanding of the volatile compounds in chicken white soup was achieved through the collaborative analysis of GC–MS and GC-IMS methodologies. This study successfully enhanced the flavor characteristics of chicken white soup, offering a theoretical foundation for addressing the issue of low flavor compound concentrations in chicken white soup.

Table 4
Sensory evaluation of chicken white soups with varying fat additions.

Fat addition	Color	Aroma	Taste	Acceptability
0 %	8.83 ± 0.29^{a}	8.67 ± 0.15^{b}	8.15 ± 0.13^{a}	7.42 ± 0.14^{ab}
1 %	8.67 ± 0.29^{a}	8.70 ± 0.26^{b}	8.33 ± 0.29^{a}	7.67 ± 0.29^{ab}
2 %	8.35 ± 0.41^{a}	9.40 ± 0.17^{a}	8.16 ± 0.14^{a}	7.92 ± 0.38^{a}
3 %	7.75 ± 0.25^{b}	8.82 ± 0.08^{b}	7.83 ± 0.29^{ab}	6.92 ± 0.38^{b}
4 %	6.35 ± 0.13^{c}	7.42 ± 0.14^{c}	7.33 ± 0.58^{bc}	5.92 ± 0.63^{c}
5 %	4.17 ± 0.30^{d}	6.42 ± 0.14^{d}	6.83 ± 0.29^{c}	4.33 ± 0.76^{d}

Results are expressed as mean ± standard deviation (n = 3); Different lowercase letters (a-d) in the same column indicate significant differences ($P < 0.05$).

Table 3
Analysis of 5′-nucleotide content and TAVs in chicken white soups with varying fat additions.

5′-nucleotide	Taste characteristics	Threshold value (mg/100 mL)	5′-nucleotide content (mg/100 mL)						TAVs in soup					
			0 %	1 %	2 %	3 %	4 %	5 %	0 %	1 %	2 %	3 %	4 %	5 %
5′-GMP	Umami (+)	12.5	0.17 ± 0.02^{c}	0.28 ± 0.01^{b}	0.48 ± 0.00^{a}	0.30 ± 0.00^{b}	0.36 ± 0.05^{b}	0.30 ± 0.05^{b}	0.01 ± 0.0^{c}	0.02 ± 0.01^{b}	0.04 ± 0.0^{a}	0.02 ± 0.0^{b}	0.03 ± 0.0^{b}	0.02 ± 0.0^{b}
5′-IMP	Umami (+)	25	9.49 ± 0.05^{e}	10.58 ± 0.10^{b}	10.75 ± 0.02^{a}	9.77 ± 0.01^{d}	10.23 ± 0.02^{c}	9.27 ± 0.03^{f}	0.38 ± 0.0^{e}	0.42 ± 0.0^{b}	0.43 ± 0.0^{a}	0.39 ± 0.0^{d}	0.41 ± 0.0^{c}	0.37 ± 0.0^{f}
5′-AMP	Sweet (+)	50	3.90 ± 0.01^{c}	3.99 ± 0.02^{a}	3.96 ± 0.00^{b}	3.87 ± 0.01^{d}	3.89 ± 0.00^{c}	3.82 ± 0.01^{e}	0.08 ± 0.0^{a}	0.08 ± 0.0^{a}	0.08 ± 0.0^{a}	0.08 ± 0.0^{a}	0.08 ± 0.0^{a}	0.08 ± 0.0^{a}
Hx	Bitter (−)	–	3.43 ± 0.03^{a}	3.42 ± 0.00^{a}	3.34 ± 0.01^{a}	3.41 ± 0.21^{a}	3.30 ± 0.00^{a}	3.29 ± 0.00^{a}	–	–	–	–	–	–
I	Bitter (−)	–	3.94 ± 0.01^{e}	4.27 ± 0.05^{b}	4.34 ± 0.01^{a}	4.00 ± 0.01^{d}	4.15 ± 0.00^{c}	3.85 ± 0.02^{f}	–	–	–	–	–	–
5′-ADP	–	–	4.42 ± 0.01^{d}	4.78 ± 0.11^{a}	4.67 ± 0.00^{b}	4.53 ± 0.00^{c}	4.80 ± 0.00^{a}	4.44 ± 0.01^{cd}	–	–	–	–	–	–
Total	–	–	25.35 ± 0.07^{d}	27.33 ± 0.21^{a}	27.55 ± 0.02^{a}	25.87 ± 0.22^{c}	26.73 ± 0.07^{b}	24.96 ± 0.08^{e}	–	–	–	–	–	–

Results are expressed as mean ± standard deviation (n = 3); Different lowercase letters (a-f) in the same row (separately for content and TAV) indicate significant differences ($P < 0.05$); The threshold of nucleotides was obtained according to the reference (Guan et al., 2024), and "-" represented that the threshold was not detected.

CRediT authorship contribution statement

Haining Guan: Writing – review & editing, Methodology, Conceptualization. **Wenxiu Zhang:** Writing – review & editing, Software. **Yanli Tian:** Writing – original draft, Investigation. **Siqi Leng:** Software, Formal analysis. **Shifa Zhao:** Investigation, Formal analysis. **Dengyong Liu:** Supervision, Funding acquisition. **Xiaoqin Diao:** Writing – review & editing, Methodology.

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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Data availability

Data will be made available on request.

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