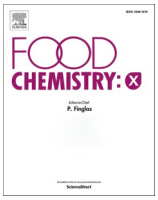
Food Chemistry: X 18 (2023) 100748

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x



Correlation between physicochemical properties and volatile compound profiles in tilapia muscles subjected to four different thermal processing techniques

Jiahui Chen [a,b], Cuiping Shi [a], Jiamin Xu [a,b], Xichang Wang [b], Jian Zhong [a,b,*]

[a] Xinhua Hospital, Shanghai Institute for Pediatric Research, Shanghai Key Laboratory of Pediatric Gastroenterology and Nutrition, Shanghai Jiao Tong University School of Medicine, Shanghai 200092, China

[b] National R&D Branch Center for Freshwater Aquatic Products Processing Technology (Shanghai), Integrated Scientific Research Base on Comprehensive Utilization Technology for By-Products of Aquatic Product Processing, Ministry of Agriculture and Rural Affairs of the People's Republic of China, Shanghai Engineering Research Center of Aquatic-Product Processing and Preservation, College of Food Science & Technology, Shanghai Ocean University, Shanghai 201306, China

ARTICLE INFO

Keywords:
Gas chromatography-based electronic nose
Headspace solid-phase microextraction–gas chromatography–mass spectrometry
Texture
Thermal processing
Tilapia muscle

ABSTRACT

This work studied the physicochemical properties and odor profiles of tilapia muscles after exposure to four types of thermal processing methods: microwaving, roasting, boiling, or steaming. The effect of thermal processing on textural properties followed a pH–water state–water content–tissue microstructure–mass loss–textural properties route, expressed in the following manner: microwaving > roasting > steaming ≈ boiling. After processing, muscle pH increased from 6.59 ± 0.10 to 6.73 ± 0.04–7.01 ± 0.06, and hardness changed from 1468.49 ± 180.77 g to 452.76 ± 46.94–10723.66 ± 2898.46 g. Gas chromatography-based E-nose analysis confirmed that these methods had significant odor fingerprint effects on the tilapia muscles. Finally, the combined analysis of headspace solid-phase microextraction–gas chromatography–mass spectrometry, statistical MetaboAnalyst, and odor activity value showed that the microwaved, roasted, steamed, and boiled tilapia muscles had, respectively, three (hexanal, nonanal, and decanal), four (2-methyl-butanal, 3-methyl-butanal, decanal, and trimethylamine), one (2-methyl-butanal), and one (decanal) relatively important volatile compounds.

1. Introduction

Thermal processing is an effective method to prepare food for human consumption. Traditional thermal processing methods include roasting, boiling, and steaming, and advances in the food industry have led to the development of many novel approaches such as microwave processing technology (Guo, Sun, Cheng & Han, 2017). All of these methods have different effects on the quality of foods (Hong, Chen, Wang, Chen & Kan, 2023), and they also impact allergenicity (Zhang et al., 2019) and the human gut microbiota (Pérez-Burillo et al., 2018).

Tilapia is the second most cultured fish in the world, with production spanning 140+ countries located primarily in Asia, Africa, and America. Not only does the species exhibit a fast growth rate, adaptability to a wide range of environmental conditions, and easy feeding on low trophic levels (Watanabe, Losordo, Fitzsimmons & Hanley, 2002), it can provide high-quality proteins and rich unsaturated fatty acids for human beings (Bi et al., 2019). Moreover, it can be processed into fillets that lack fish bones, which is especially suitable for consumption by the elderly and children. Therefore, it is commonly processed into frozen fillets (muscles) in factories and transported around the globe, mainly to Europe and America (Wu et al., 2020).

Many studies have already explored the effect of thermal processing methods on the quality of tilapia muscles. Steaming, boiling, and air frying have different effects on the metabolites in fresh tilapia muscle, according to the metabolomics method (Li et al., 2021). In this study, our group examined the effect of steaming, boiling, and roasting on the lipidomics profiles of frozen tilapia muscle (Wu et al., 2020), long-chain free fatty acids in frozen tilapia muscle (Wu et al., 2020), and lipid profile migration from frozen tilapia muscle to juice (Sun et al., 2021) using the lipidomics method. Further, we examined the effect of roasting, steaming, boiling, and microwaving on the aroma profiles of acidity regulator-treated frozen tilapia muscle (Chen et al., 2021). The key

* Corresponding author at: Xinhua Hospital, Shanghai Institute for Pediatric Research, Shanghai Key Laboratory of Pediatric Gastroenterology and Nutrition, Shanghai Jiao Tong University School of Medicine, Shanghai 200092, China.
E-mail address: jzhong@shsmu.edu.cn (J. Zhong).

https://doi.org/10.1016/j.fochx.2023.100748
Received 12 January 2023; Received in revised form 27 May 2023; Accepted 7 June 2023
Available online 12 June 2023

volatile compounds in soybean-fried tilapia included trimethylamine, hexanal, 2,3-dimethylpyrazine, dimethyl trisulfide, *trans*-2-octenal, 2,3-dimethyl-5-ethylpyrazine, (E)-2-nonenal, 2-propyl-pyridine, and (E,E)-2,4-decadienal (Liu et al., 2022). However, to the best of our knowledge, the effect of different thermal processing methods on the physicochemical properties and volatile compound profiles of tilapia muscles has not been illustrated.

The purpose of this research was to analyze the effect of four different thermal processing methods—roasting, steaming, boiling, and microwaving—on the physicochemical properties and volatile compound profiles of frozen tilapia muscles. First, the physical properties of raw and thermally processed muscles were measured. Second, the chemical properties of raw and thermally processed muscles were determined. Third, the sensory characteristics of raw and thermally processed muscles were analyzed using a gas chromatography-based electronic nose (GC-based E-nose) technique. Finally, volatile compound profiles were studied using headspace solid-phase microextraction–gas chromatography–mass spectrometry (HS-SPME–GC–MS), online statistical software MetaboAnalyst, and odor activity value analysis (OAV).

2. Materials and methods

2.1. Thermal processing of tilapia muscles

Frozen tilapia fillets were purchased from Hainan Xiangtai Fishery Co., Ltd. (Chengmai country, Hainan Province, China) and were stored at −18 °C in the laboratory. Tilapia fillets were naturally thawed (Fig. S1), and the center portions (1.5 × 1.5 cm, 4.9–5.1 g) were cut as tilapia muscles for subsequent thermal processing experiments; raw muscles were used as controls (Chen et al., 2021). Four processing methods were examined in the following manner: (1) microwaving—the tilapia sample was placed on a leaf-shaped porcelain dish, and the dish was positioned near the center of a commercial microwave oven (M1-L202B, Media Group, Guangdong Province, China) and was treated with a medium power level for 2 min; (2) roasting—a household electric oven (MG38CB-AA, Media Group) was heated for 15 min at 230 °C, and the tilapia sample was placed in aluminum foil, positioned in the center of the center layer of the oven at 230 °C, and treated for 10 min (the muscle was turned over after 5 min); (3) steaming—the sample was placed on a leaf-shaped porcelain dish, and the dish was positioned in the center of the steaming grid of a household electric cooker (MB-WFS5017TM, Media Group) with full hot steam and treated for 10 min; (4) boiling—the sample was put into boiled water (1000 mL) in a household electric cooker (MB-WFS5017TM, Media Group) and was treated for 10 min. All samples were immediately removed for subsequent analyses.

2.2. Analyses of physical properties

2.2.1. Morphology and color

The thawed and cut tilapia muscles were treated with different thermal processing methods, as described in section 2.1. After thermal processing, the samples were cooled in leaf-shaped porcelain dishes at room temperature for 10 min in the laboratory. The morphology and color changes of thermal processing tilapia muscles in the leaf-shaped porcelain dishes were examined with the naked eye and a digital camera.

2.2.2. Texture analysis

Texture properties of thermal processing tilapia muscle were analyzed using a TA.XT Plus C texture analyzer (Stable MicroSystems, UK) with a texture profile analysis (TPA) measurement mode (Xu, Shi, Wang & Wang, 2019). The diameter of the applied P/50 cylindrical Perspex probe was 50 m; tilapia samples were tested with a trigger loading of 5.0 g, a test speed of 1.0 mm/s, a sample deformation of 50%, and a holding time of 3.0 s between cycles.

2.2.3. Tissue microstructure

The microstructures of thermally processed tilapia muscles were observed using eosin staining and optical microscopy (Jiang, Nakazawa, Hu, Osako & Okazaki, 2019). Briefly, tilapia muscles were cut into 5 × 5 × 5-mm sections. The samples were fixed in a 4% paraformaldehyde solution, dehydrated in a gradient series (70%, 80%, 90%, and absolute) of ethanol solution, and embedded in paraffin wax using a JB-P5 embedding machine (Wuhan Junjie Electronics Co., Ltd., Wuhan City, Hubei Province, China). Cross sections (5 μm thick) were cut with a rotary microtome (RM2016, Leica, Shanghai, China), reshaped in warm water, mounted on glass slides, and dried for 24 h. The sections were dewaxed in five sequential solutions: xylene for 20 min, xylene for 20 min, absolute ethanol for 5 min, absolute ethanol for 5 min, and 75% ethanol solution for 5 min. Next, the sections were rinsed with water and stained with hematoxylin and then eosin. Finally, the sections were observed by an Eclipse E100 optical microscope (Nikon, Japan).

2.3. Analyses of chemical properties

2.3.1. pH determination

The pH of tilapia muscles was determined according to the Chinese national standard GB5009.237-2016. Briefly, tilapia muscle was cut into fragments measuring < 3 mm and mixed with 0.1 mol/L potassium chloride (1:10, mass ratio). The mixture was then mechanically sheared for 1 min at a homogenizing speed of 20,500 rpm using a T10 ULTRA-TURRAX® homogenizer (IKA, Guangzhou City, Guangdong Province, China). Finally, the pH of the homogenized mixture was determined using a pH meter (FE28, Mettler Toledo, Switzerland).

2.3.2. Mass loss percentage

The tilapia muscle sample was weighed before ($m1$) and after ($m2$) thermal processing. Then, the mass loss percentage was calculated:

$$Massloss(\%) = \frac{m1 - m2}{m1} \times 100 \quad (1)$$

2.3.3. Ash content percentage of raw muscle

The ash content percentage (%) of raw muscle was determined according to the Chinese national standard GB5009.4-2016. Briefly, the raw tilapia muscle sample was weighed before ($m1$) and after ($m2$) thermal processing. Then, a part ($m3$) of the thermally processed tilapia muscle sample was put in a constant-weight ceramic crucible and treated at 550 ± 25 °C to a constant weight ($m4$). Finally, the ash content percentage of raw muscle was calculated:

$$Ashcontent(\%) = \frac{m4 \times m2}{m3 \times m1} \times 100 \quad (2)$$

2.3.4. Water content percentage

The water content (%) of raw muscle was determined according to the Chinese national standard GB 5009.3-2016. Briefly, the raw tilapia muscle sample was weighed before ($m1$) and after ($m2$) thermal processing. Then, a part ($m5$) of the thermally processed tilapia muscle sample was put in a constant-weight weighing bottle and treated at 101–105 °C to a constant weight ($m6$). Finally, the water content percentage of raw muscle was calculated:

$$Watercontent(\%) = \frac{m6 \times m2}{m5 \times m1} \times 100 \quad (3)$$

2.3.5. Low-field nuclear magnetic resonance

The proton relaxation times and proton density images of the raw and thermal-processed tilapia muscles were analyzed using a MesoMR23-060H-I low-field nuclear magnetic resonance (LF-NMR) system (Niumag Electric Corporation, Shanghai, China) (Wang & Xie, 2019). Also, T_2 was measured using the Carr-Purcell-Meiboom-Gill pulse sequence, operating magnetic field was 0.5 T, proton resonance

frequency was 21 MHz, coil diameter was 70 mm, offset frequency was 172226.65 kHz, 90° pulse time was 19 μs, 180° pulse time was 37.04 μs, sampling frequency was 100 kHz, interval time was 2000 ms, the accumulative number was 8, and the echo number was 5000. Signal inversion data were collected, normalized, and used to generate pseudo-color images as the proton density of the raw and thermal-processed tilapia muscles.

2.4. GC-based E-nose analysis

Raw tilapia muscles were naturally thawed, and the center portions were then cut into muscles with a mass of 7.9–8.1 g. The tilapia muscles were treated with different thermal processing methods, as described in section 2.1. After thermal processing, the tilapia muscles were cooled at room temperature for 10 min and then cut into fragments (maximum sizes of <3 mm). The fragments were immediately put in 20-mL headspace bottles. The untreated tilapia muscles were used as controls.

The samples in the headspace bottles were examined using a Heracles II fast GC-based E-nose system (Alpha M.O.S., France) (Śliwińska, Wiśniewska, Dymerski, Wardencki & Namieśnik, 2016). The Heracles II system had a nonpolar chromatographic MXT-5 column and weak polar MXT-1701 column (length: 10 m; column diameter: 180 μm). Parameters were as follows: incubation temperature was 80 °C, incubation time was 20 min, and incubator speed was 500 rpm; injection volume was 5000 μL, injection speed was 125 μL/s, injection port temperature was 200 °C, and injection duration time was 45 s; initial trap temperature was 40 °C, trap shunt rate was 10 mL/min, trap duration time was 50 s, and the final temperature of the trap was 240 °C; the initial temperature of the column was 50 °C, the temperature of the column was raised to 80 °C at a speed of 1 °C/s and then to 250 °C at a speed of 3 °C/s, the acquisition time was 110 s, and the detector temperature was 260 °C; and the flame ionization detection gain was 12. Data were collected using Alphasoft V12.44 software (Alpha M.O.S.), and experiments were conducted in triplicate. Two chemometric methods—principal component analysis (PCA) and discriminant function analysis (DFA)—were applied to analyze the odor profiles of raw and thermally processed tilapia muscles. Afterwards, the software was used to extract Euclidean distance, percentage of dispersion, and fingerprint resolution index.

2.5. HS-SPME–GC–MS analysis

2.5.1. HS-SPME

Raw tilapia muscles (4.9–5.1 g) were thermally processed, cut into fragments, and put in 20-mL headspace bottles. Then, 5.0 mL of sodium chloride (0.18 g/mL) solution was added, and 5 μL of 2,4,6-trimethyl pyridine (TMP, 10 mg/g methanol) was added as an internal standard (Zhou, Chong, Ding, Gu & Liu, 2016). The bottles were immediately equilibrated at 50 °C at a magnetic speed of 600 rpm, and preconditioned SPME fibers (50/30 μm DVB/CAR/PDMS) were inserted in the bottles, with a fiber tip-sample distance of 10 mm. After 40 min, the fibers were inserted in the injection port (250 °C) of the GC–MS system (5977b-7890b, Agilent Technologies, California, USA). The volatile compounds were desorbed for 5 min.

2.5.2. GC–MS analysis

GC operational conditions were as follows (Wang, Zhang, Zhu, Wang & Shi, 2018): an elastic capillary column (HP-5MS (30-m length × 0.25-mm internal diameter × 0.25-μm film thickness; Agilent Technologies) was used; column temperature was 40 °C, which was raised to 100 °C at a speed of 5 °C/min, to 180 °C at a speed of 2 °C/min, to 250 °C at a speed of 5 °C/min, and then maintained for 5 min; and helium gas flow rate was 1.0 mL/min.

MS operational conditions were as follows (Koca & Cevikbas, 2015): MS spectra in the electron impact mode was generated at 70 eV, detector voltage was 1.2 kV, and the mass-charge ratio range was 45–550 *m/z*; in terms of temperature, source temperature was 230 °C, quadrupole temperature was 150 °C, and transmission line temperature was 280 °C.

2.5.3. Estimated concentrations of volatile compounds

The spectra of the detected chemicals were matched in NIST 17.0 library and Wiley MS library to identify volatile compounds with both matching and reverse matching degrees of >700.

The estimated concentration of each volatile compound in raw tilapia muscle was determined according to the following equation (Zhou et al., 2016):

$$\text{Estimated concentration } (\mu g/kg) = \frac{\text{Peak area ratio}\left(\frac{\text{Volatile compound}}{\text{TMP}}\right) \times \text{Mass of TMP}}{\text{Mass of raw tilapia muscle}} \times 1000 \text{ g/kg} \quad (4)$$

2.5.4. OAV analysis

The OAV method was used to evaluate the contributions of volatile compounds, according to the following equation (Wang et al., 2020):

$$OAVi = \frac{Ci}{OTi} \quad (5)$$

where *Ci* is the compound concentration, and *OTi* is the odor threshold of a compound in water. The volatile compounds with an OAV > 1 are considered significant contributors to the aroma characteristics.

2.6. Statistics

All of the samples were processed in triplicate. The datum was expressed as average value ± standard deviation. HS-SPME–GC–MS data were imported in the online statistical software MetaboAnalyst 5.0 (https://www.metaboanalyst.ca/) for partial least squares discriminate analysis (PLS-DA), variable importance in projection (VIP) scores, and heat map clustering analysis (Chong, Wishart & Xia, 2019; Shi et al., 2019; Pang et al., 2022). The statistical analysis module was one factor; data were normalized by sum and auto-scaled in MetaboAnalyst 5.0, and confidence regions (95%) were displayed.

3. Results and discussion

3.1. Physical properties of tilapia muscles after thermal processing

3.1.1. Morphological and color changes

As shown in Fig. S2, the thawed tilapia muscles were in the red. After microwaving, the muscles were damaged due to uneven internal heating in the rapid microwave heating process (Guo et al., 2017). The muscles were not damaged after other thermal processing. Further study (e.g., low power) is necessary to avoid tilapia muscle damage during the microwaving process. The muscle colors changed to yellow-white after microwaving, to grey-white on the side and brown on the upper/bottom after roasting, and to milk white after both steaming and boiling. Myoglobin is the main pigment for the red color of fresh tilapia muscles. Heating treatment induced the denaturation of myoglobin, and therefore the treated muscles might display white colors (Suman & Joseph, 2013). In addition, roasting might induce the formation of brown color on the tilapia muscle due to the Maillard reaction (Zhang, Ayed, Fisk & Liu, 2023).

3.1.2. Textural properties

The quality of aquatic products is primarily related to their textural properties, including hardness, springiness, cohesiveness, gumminess, and chewiness. TPA in the texture analyzer simulates the chewing process of food in the human mouth (Vacha, Stejskal, Vejsada, Kouril & Hlavac, 2013); the obtained textural properties are shown in Fig. 1A–F. Hardness changed from 1468.49 ± 180.77 g to 452.76 ± 46.94 (steamed), 479.32 ± 80.28 (boiled), 1272.50 ± 104.25 (roasted), and

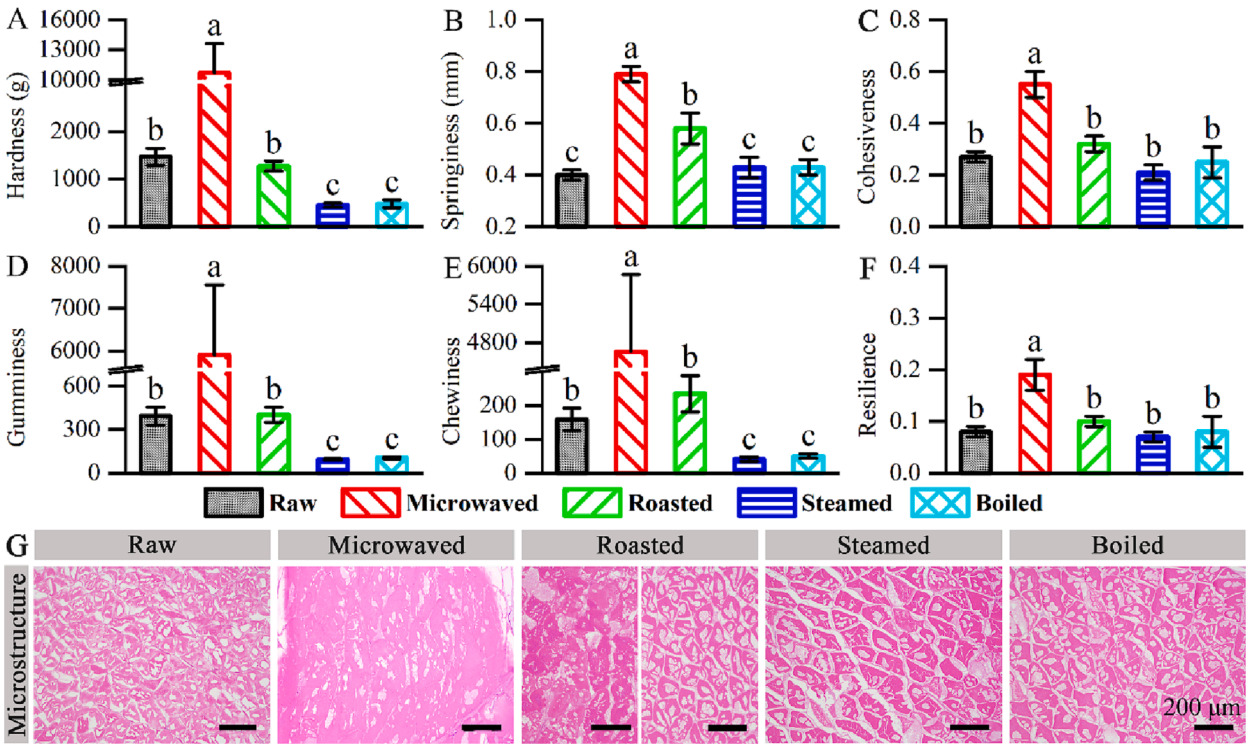


Fig. 1. Physical properties of thermally processed tilapia muscles. (A–F): Textural properties. Different letters above the columns indicate statistically significant differences at the 0.05 level. For hardness, gumminess, and chewiness results, the significance analyses of raw, roasted, steamed, and boiled samples were performed without the microwaved samples because they had the highest values (>20 times) compared to the others. (G): Tissue microstructures.

10723.66 ± 2898.46 (microwaved) g after processing. The orders of textural properties of tilapia muscles were dependent on the thermal processing methods, expressed in the following manner: microwaving > roasting > steaming ≈ boiling. This was consistent with our common feeling of hardness by teeth on the thermally processed fish muscles. Significance analyses confirmed that the microwaved and roasted samples had the highest and second-highest textural values, respectively, compared to the other two (indicated by the different letters above the columns in Fig. 1D–I). Hardness and springiness are the most important parameters for the quality of aquatic products (Xu et al., 2019). According to these two results (Fig. 1A–B), people could choose thermal processing methods appropriate for producing the desired level of hardness and springiness in chewing, expressed in the following manner: microwaving > roasting > steaming ≈ boiling.

3.1.3. Tissue microstructures

The microstructures of thermally processed tilapia muscles are shown in Fig. 1G. Raw muscle presented intact muscle cells, which were surrounded by endomysium. After microwaving, the muscle cells did not show clear morphology, which suggested the formation of significant muscle cell shrinkage and aggregation. After steaming and boiling, the muscle cells showed a similar morphology as raw muscle, with increased intercellular space compared to raw muscle. After roasting, some muscle cells (Fig. 1G: left image for roasted muscle) did not show clear morphology (formation of significant muscle cell shrinkage and aggregation), and some muscle cells (Fig. 1G: right image for roasted muscles) showed similar morphology, with increased intercellular space compared to raw muscle. Therefore, the muscle cell sizes of thermally processed tilapia muscles were dependent on the type of thermal processing method that was used, expressed in the following manner: microwaving < roasting < steaming ≈ boiling. According to the morphology and color analyses (Fig. S2), steaming and boiling were relatively mild heating treatment methods compared to roasting and microwaving. Moreover, steaming and boiling had larger water contents than roasting and microwaving (Fig. 2D). Therefore, the steaming and boiling had less—and similar—effects on the tilapia muscle microstructures than roasting and microwaving.

3.2. Chemical properties of tilapia muscles after thermal processing

3.2.1. pH determination

As shown in Fig. 2A, the pH values of raw, microwaved, roasted, steamed, and boiled tilapia muscles were 6.59 ± 0.10, 6.73 ± 0.04, 6.84 ± 0.01, 6.93 ± 0.01, and 7.01 ± 0.06, respectively. Heating treatment could induce a decrease of the acidic groups in the fish protein (Sobral, Cunha, Faria & Ferreira, 2018). Therefore, heating treatment had different abilities to disrupt the acidic groups in the fish proteins, expressed in the following manner: microwaving < roasting < steaming < boiling. Our previous work suggested that four classes of thermal processing methods had no obvious effects on the pH of acidity regulator-treated tilapia muscles (Chen et al., 2021). The acidity regulator consists of sodium bicarbonate, sodium citrate, sodium carbonate, DL-malic acid, and edible salt. It is generally used as a food additive for the preservation and flavor enhancement of jam and meat by maintaining or changing the pH of foods. Therefore, the acidity regulator pretreatment could inhibit the change of tilapia muscle pH after thermal processing.

3.2.2. Mass loss and ash content

As shown in Fig. 2B, the mass loss percentage order of tilapia muscles was dependent on the thermal processing methods, expressed in the following manner: microwaving > roasting > steaming > boiling; this finding was reversely consistent with tilapia muscle pH (Fig. 2A). As shown in Fig. 2C, the ash content order of tilapia muscles was dependent on the thermal processing methods, expressed in the following manner: raw ≈ microwaving ≈ roasting ≈ steaming > boiling. Ashes are the inorganic residues after either ignition or complete oxidation of organic substances in food (Hussain, Shukla, Dubey, Gautam & Tripathi, 2022).

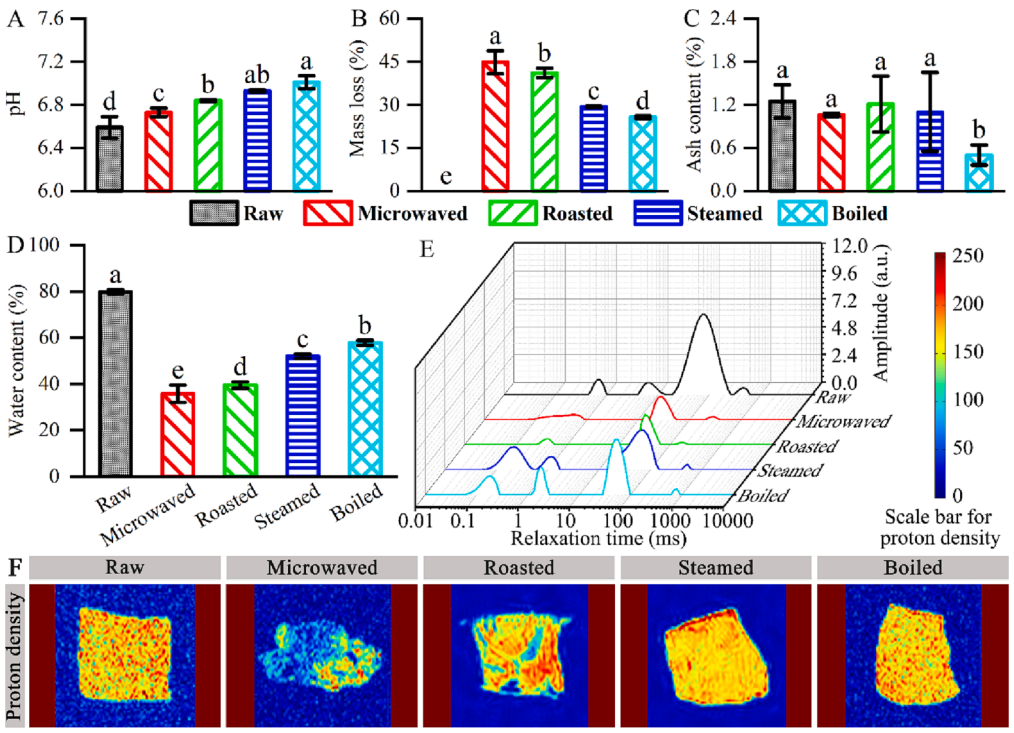


Fig. 2. Chemical properties of thermally processed tilapia muscles. (A): tissue pH. (B): Mass loss. (C): Ash contents. (D): Water contents. (E): Transverse relaxation times. The peaks with relaxation times of 0.1–1, 1–100, and 100–1000 ms are T_{21} (bound water), T_{22} (entrapped water), and T_{23} (free water). (F): Proton density images. Different letters above the columns indicate statistically significant differences at the 0.05 level.

The significant ash content decrease of boiled muscle may have resulted from the migration of inorganic substances such as calcium, phosphorus, and potassium (Joshi et al., 2017) from the tilapia muscle to the 1000 mL of soup.

3.2.3. *Water content and water state*

As shown in Fig. 2D, the water content order of the tilapia muscles was dependent on the thermal processing methods, expressed in the following manner: microwaving < roasting < steaming < boiling < non-treatment. The water content order was reversely consistent with the mass loss percentage results (Fig. 2B), which suggested that the mass loss might be primarily induced by the water loss. However, the water content order was consistent with the tilapia muscle pH results (Fig. 1B). Generally, the solution pH increased with the increase of water. Therefore, the water content after thermal processing might also affect the tilapia muscle pH (the isoelectric point of tilapia muscle), expressed in the following manner: microwaving < roasting < steaming < boiling.

The LF-NMR method is an efficient way to analyze the water state in a food (Nie et al., 2022). Bound water (closely associated with macromolecules), entrapped water (in tissue cells), and free water (between cells) are attributed to T_{21} (relaxation time of 0.1–1 ms), T_{22} (relaxation time of 1–100 ms), and T_{23} (relaxation time of 100–1000 ms), respectively, in the LF-NMR signals. In this work, LF-NMR was applied to study the water state in the thermally processed tilapia muscles (Fig. 2E). The microwaved and roasted muscles showed decreased bound (T_{21}), entrapped (T_{22}), and free (T_{23}) water amounts than the raw muscle. The steamed and boiled muscles showed decreased entrapped (T_{22}) and free (T_{23}) water amounts, but increased bound (T_{21}) water amounts compared to raw muscle. Some entrapped and free water molecules might change into bound water molecules during the steaming and boiling process; therefore, the water content of the steamed and boiled muscles was relatively higher than that of the microwaved and roasted muscles (Fig. 2D).

Proton density in the thermally processed muscles was shown in the pseudo-color images using LF-NMR (Fig. 2F). The proton contents (red area amounts) were dependent on the thermal processing methods, expressed in the following manner: microwaving < roasting < steaming < boiling < non-treatments; this was consistent with the water content results (Fig. 2D). In particular, the proton density image of roasted muscle showed that there was no water content in some areas, confirming muscle cell shrinkage and aggregation in some areas in the tissue microstructure image (Fig. 1G).

Previous work suggested that the water loss of a food item after cooking might induce a change in its textural properties (Lin et al., 2022). Our results (Figs. 1–2) suggested that textural properties changes after thermal processing involved a muscle pH–water state–water content–tissue microstructure–mass loss–textural properties route. Microwaving might induce the highest loss percentages of all the bound, entrapped, and free water (Fig. 2F), the highest water loss percentage (Fig. 2D–E), the largest muscle cell shrinkage and aggregation (Fig. 1F), the highest mass loss percentage (Fig. 2B), and therefore the highest textural properties (Fig. 1A–F). For the steamed and boiled tilapia muscles, even though significant water loss (Fig. 2D) and mass loss (Fig. 2B) occurred, the entrapped and free water molecules might change into bound water molecules (Fig. 2E–F); therefore, muscle cell morphology did not obviously change, and only the intercellular space increased for both the steamed and boiled muscles (Fig. 1G). Thus, the textural properties were similar and were the lowest among these thermally processed muscles. Roasting might induce significant loss of all bound, entrapped, and free water (Fig. 2E), as well as significant water loss (Fig. 2D) and mass loss (Fig. 2B). However, the water loss (Fig. 2F) and muscle cell shrinkage and aggregation (Fig. 1G) only occurred in some areas of the roasted muscle.

3.3. *Odor fingerprint change of tilapia muscles after thermal processing using GC-based E-nose analysis*

The fast GC-based E-nose technique combines the functions of GC and an electronic nose to imitate a human's olfactory function for identifying food odor characteristics—a so-called fingerprint—in a short

analysis time (1–3 min) and the highest discriminatory power (Li et al., 2022). Here, the technology was applied to analyze the odor fingerprints of the raw and thermally processed tilapia muscles using two chemometric methods (i.e., PCA and DFA).

As shown in the PCA plots (Fig. 3A), the first two components (PC1 was 56.378%, and PC2 was 29.488%) explained 85.866% of the total variance for the tilapia muscles. The points of the raw muscle were in the first and fourth quadrants; the points of the microwaved muscle were in the second quadrant; the points of the boiled and steamed muscles were in the third quadrant; and the points of the roasted muscle were in the second and third quadrants. All of the raw and thermal muscles showed significantly different odor characteristics; specifically, thermally processed muscles showed relatively close odor characteristics compared to raw muscle. The PC2 values were dependent on the thermal processing methods, expressed in the following manner: steaming < boiling < roasting < microwaving. The order was contrary to the pH (Fig. 2A) and water content (Fig. 2E), and further confirmed that pH could affect the flavor characteristics of tilapia muscles (Chen et al., 2021).

As shown in the DFA plots (Fig. 3B), the first two components (DF1 was 71.487%, and DF2 was 23.635%) explained 95.120% of the total variance for the tilapia muscles. The points of raw muscle were in the second quadrant; the points of the microwaved muscle were in the first quadrant; the points of the boiled and roasted muscles were in the first and fourth quadrants; and the points of the steamed muscle were in the fourth quadrant. All of the raw and thermal muscles showed significantly different odor characteristics.

According to the PCA and DFA results, Euclidean distances, percentages of dispersion, and fingerprint resolution indexes (%) between two tilapia muscle groups were obtained (Fig. 3C and Table S1). All of the percentages of dispersion were 0.00, confirming that all of the raw and thermal muscles showed significantly different odor fingerprint characteristics. The comparisons between raw and thermally processed

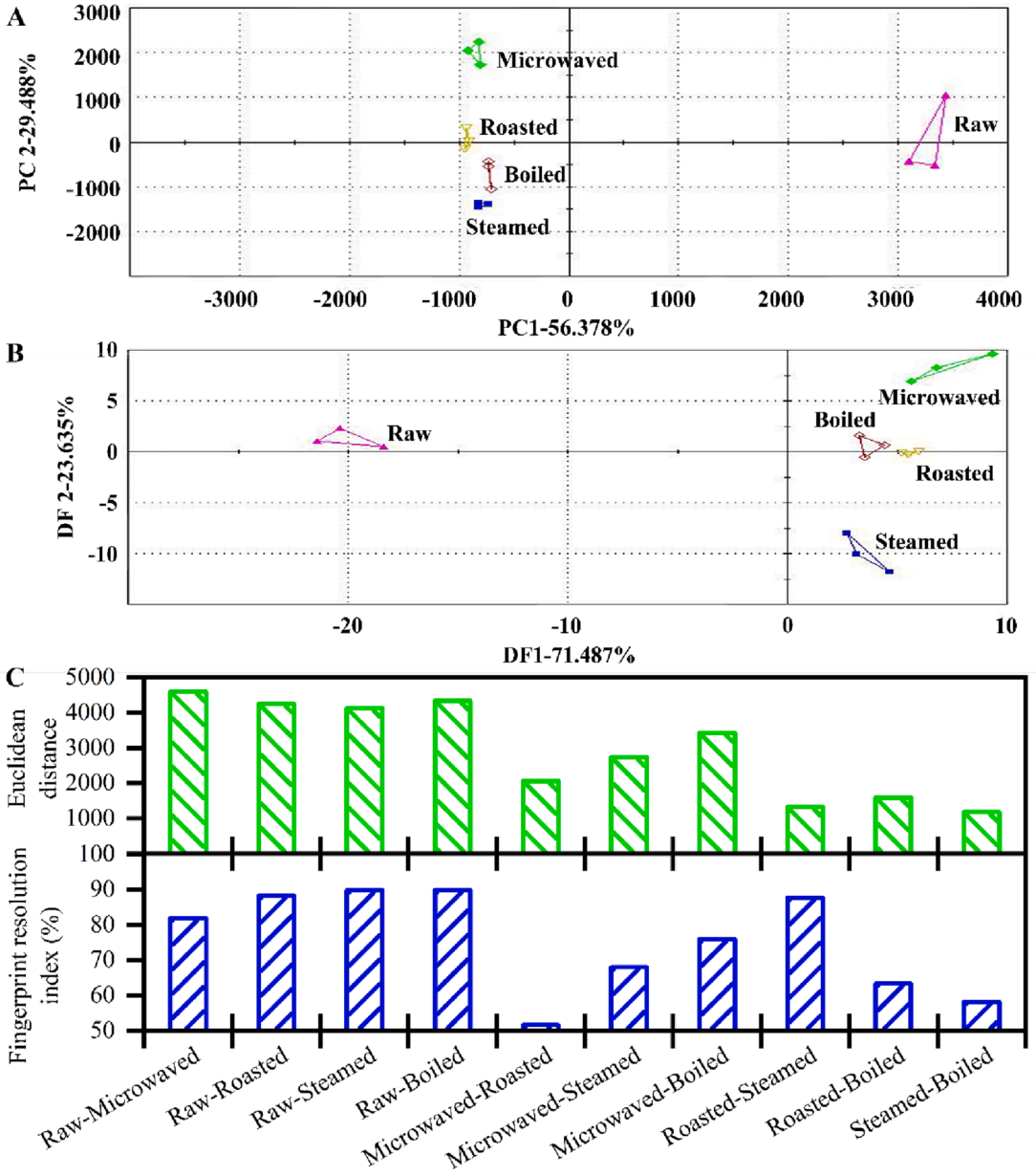


Fig. 3. Gas chromatography-based E-nose results of thermally processed tilapia muscles. (A): Principal component analysis (PCA). (B): Discriminant function analysis (DFA). (C): Euclidean distance and fingerprint resolution index (%) between two groups according to the PCA and DFA results. The experimental data (three parallel experiments) were directly analyzed by the software to obtain the Euclidean distance and fingerprint resolution index; therefore, no standard deviation was provided by the software for (C).

muscles had Euclidean distances of 4123.63–4589.40 and fingerprint resolution indexes of 81.92–89.99%. Therefore, the raw tilapia muscle had the biggest odor fingerprint difference from all of the thermally processed muscles, confirming that thermal processing could significantly change the odor fingerprint characteristics of food (Chen et al., 2021). The comparisons between microwaved and other thermally processed muscles had Euclidean distances of 2064.67–3427.08 and fingerprint resolution indexes of 51.60–75.96%. Therefore, the microwaved muscle had significant odor fingerprint differences from other thermally processed muscles. Finally, the steamed and boiled muscles had the minimum odor fingerprint difference (a Euclidean distance of 1180.72 and a fingerprint resolution index of 58.1%) among these tilapia muscle groups. So, according to the GC-based E-nose results, the thermal processing methods had a significant effect on the odor fingerprint characteristics of the tilapia muscles, expressed in the following manner: microwaving > roasting > steaming > boiling, which was consistent with the effect of thermal processing methods on the mass loss (Fig. 2B) and water loss (Fig. 2D) of the tilapia muscles.

3.4. Volatile compounds of tilapia muscles after thermal processing

3.4.1. Volatile compound characterization

An HS-SPME–GC–MS technique was applied to analyze the volatile compounds of raw and thermally processed muscles (Fig. 4 and Table S2). The raw tilapia muscle showed 4 aldehydes (365.11 ± 150.93 μg/kg), two ketones (6.45 ± 1.86 μg/kg), 7 alcohols (276.42 ± 30.27 μg/kg), 11 hydrocarbons (423.05 ± 101.10 μg/kg), and three other compounds (51.33 ± 27.59 μg/kg). The number of total volatile compounds was 27 (1122.35 ± 296.22 μg/kg). The detected volatile compounds were slightly different from acidity regulator-treated tilapia muscle (5 aldehydes, 231.35 ± 58.50 μg/kg; one ketone, 23.68 ± 8.84 μg/kg; one alcohol, 0.63 ± 0.57 μg/kg; one ester, 7.23 ± 2.21 μg/kg; 12 hydrocarbons, 208.45 ± 37.58 μg/kg; one other compound, 18.59 ± 13.44 μg/kg) (Chen et al., 2021). Therefore, an acidity regulator (ingredients: sodium bicarbonate, sodium citrate, sodium carbonate, DL-malic acid, and edible salt) could slightly adjust the volatile compound classes and significantly decrease the volatile compound concentrations in the raw tilapia muscle.

After thermal processing, the numbers (Fig. 4A) and estimated concentrations (Fig. 4B) of alcohols and hydrocarbons were significantly decreased. Therefore, the total numbers of volatile compounds (Fig. 4A) were decreased after thermal processing. The total estimated concentrations of volatile compounds did not show obvious changes after microwaving and roasting (Fig. 4B), whereas they did show obvious decreases after steaming and boiling (Fig. 4B). This was consistent with our common sense reasoning that microwaved and roasted food elicited a higher odor sensation in people than did steamed and boiled food. The low odor feeling of the steamed and boiled tilapia muscles may have resulted from the decrease of numbers and concentrations of volatile compounds, whereas high odor feeling of microwaved and roasted tilapia muscles may have resulted from the chemical transformation of some volatile compounds to others.

Except for microwaving, all other thermal processing methods increased aldehydes. Aldehydes are generally produced from lipid oxidation and degradation; as tilapia is a kind of low-lipid and high-protein fish, the numbers of aldehydes were significantly pork and beef meats (Wang, Zhu, et al., 2018). It might also have resulted from the fact that the instrument could not detect them due to the high detection limit. In addition, the flavor dissipated quickly during the microwaving process, so the volatile aldehydes might have dissipated during the thermal processing and consequently could not be detected by the instruments.

The thermal processing methods significantly decreased volatile alcohols, as only 1-octene-3-ol was detected in the microwaved and roasted tilapia muscles. Alcohols C4–C8 smell like wood, spices, green grass, fruits, mushrooms, and fat, and the smells increased with the increase of the carbon chain (García-González, Tena, Aparicio-Ruiz & Morales, 2008). Moreover, the presence of alcohols might play important roles in the formation of tilapia muscle flavor during thermal processing.

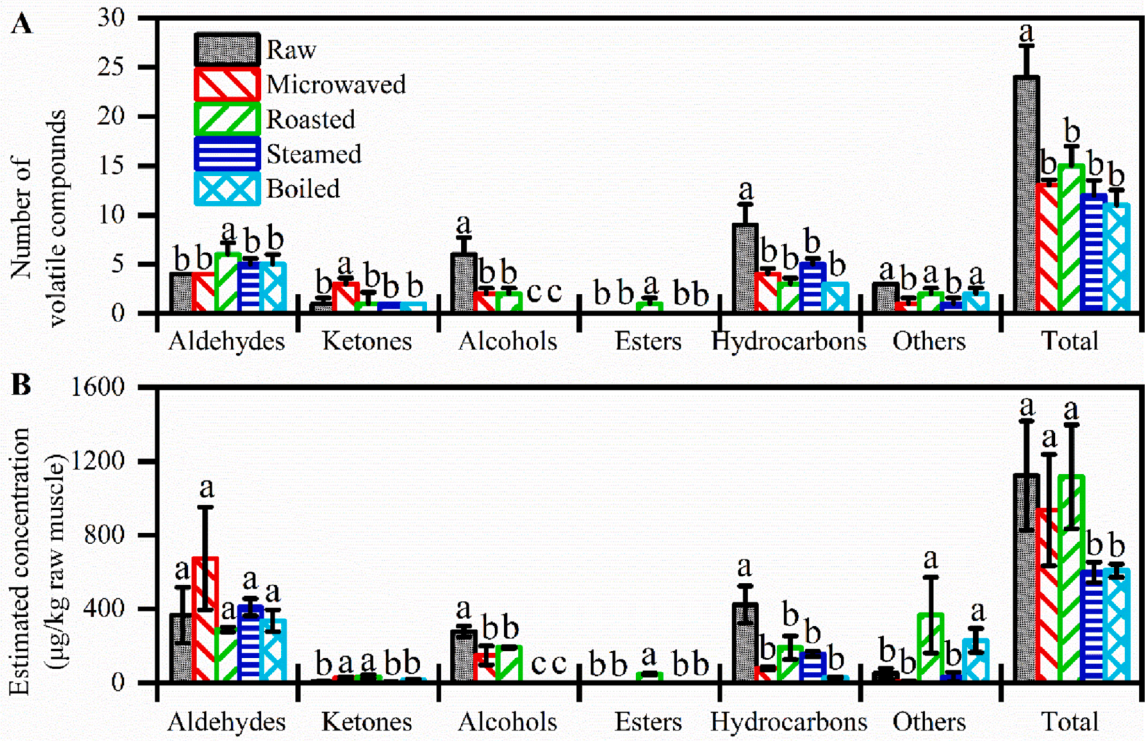


Fig. 4. Numbers (A) and estimated concentrations (B) of volatile compounds in thermally processed tilapia muscles. For each volatile compound class, different letters indicate significant difference ($p < 0.05$).

3.4.2. Statistical analysis of volatile compounds

The obtained volatile compound classes and individual volatile compounds (Table S2) were statistically analyzed using online MetaboAnalyst 5.0 software (Chong et al., 2019; Shi et al., 2019; Pang et al., 2022) with PLS-DA (Fig. 5A–B), VIP (Fig. 5C–D), and heat map visualizations (Fig. 5E–F). PLS-DA can be applied to characterize and classify a data set such as volatile compound classes in the raw and thermally processed tilapia muscles using a multiple linear regression technique.

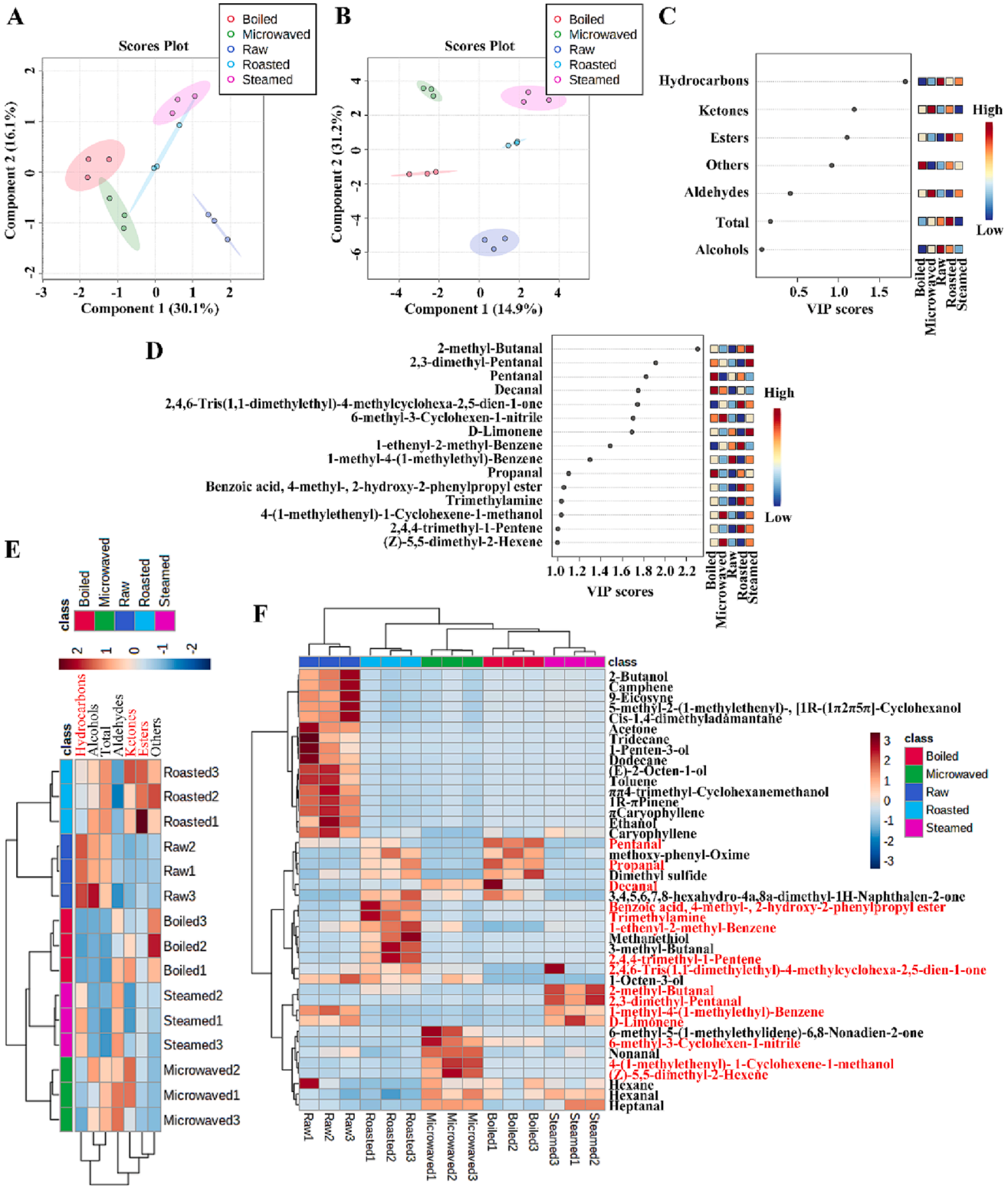


Fig. 5. Statistical analyses of volatile compound classes (A, C, and E) and individual compounds (B, D, and F) in thermally processed tilapia muscles using Metaboanalyst 5.0 software. (A–B): Partial least squares-discriminate analysis (PLS-DA) scores plots. (C–D): Variable importance in projection (VIP) scores. (E–F): Heat maps. The volatile compounds in red (E and F) were that with VIP scores of >1 in (C and D). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

VIP can be used to differentiate different groups with a score of >1, while heat map visualizations could directly provide intuitive visualizations of estimated concentrations of the volatile compounds in the raw and thermally processed tilapia muscles.

Statistical analyses of volatile compound classes in tilapia muscles are shown in Fig. 5A, C, and E. According to the PLS-DA scores plot (Fig. 5A), the volatile compound classes in the raw and thermally processed tilapia muscles were classified due to the cumulative contribution rate of 46.2% from the first two principal components. According to VIP score analysis (Fig. 5C), three volatile compound classes (hydrocarbons, ketones, and esters) with VIP scores >1 could be used to differentiate the raw and thermally processed tilapia muscles. Heat map visualization (Fig. 5E) confirmed that the raw and thermally processed tilapia muscles were classified, which was consistent with the PLS-DA results (Fig. 5A).

Statistical analyses of individual volatile compounds in tilapia muscles are shown in Fig. 5B, D, and F. According to the PLS-DA scores plot (Fig. 5B), the individual volatile compounds in the raw and thermally processed tilapia muscles were classified due to the cumulative contribution rate of 46.1% from the first two principal components. According to VIP score analysis (Fig. 5D), 15 volatile compounds with VIP scores >1 could be used to differentiate the raw and thermally processed tilapia muscles: five aldehydes (2-methyl-Butanal; 2,3-dimethyl-Pentanal; Pentanal; Decanal; Propanal); one ketone (2,4,6-Tris(1,1-dimethylethyl)-4-methylcyclohexa-2,5-dien-1-one); three others (6-methyl-3-Cyclohexen-1-nitrile; D-Limonene; Trimethylamine); four hydrocarbons (1-ethenyl-2-methyl-Benzene; 1-methyl-4-(1-methylethyl)-Benzene; 2,4,4-trimethyl-1-Pentene; (Z)-5,5-dimethyl-2-Hexene); one ester (Benzoic acid, 4-methyl-, 2-hydroxy-2-phenylpropyl ester); and one alcohol (4-(1-methylethenyl)- 1-Cyclohexene-1-methanol). Heat map visualization (Fig. 5F) confirmed that the raw and thermally processed tilapia muscles were clearly classified, which was consistent with the PLS-DA results (Fig. 5B). These chemicals might be primarily attributed to the metabolism of the main fatty acids (e.g., eicosapentaenoic and docosahexaenoic acids) in aquatic products (Wu et al., 2021).

3.4.3. OAVs of volatile compounds

OAV can be used to assess the relative importance of individual volatile compounds to the odor profile of a food (Giri, Osako & Ohshima, 2011; Pu, Shan, Zhang, Sun & Zhang, 2022). The volatile compounds with OAVs of >1 are considered relatively important compounds (Wang et al., 2016). As shown in Table 1, raw tilapia muscle had the relatively important compounds of four aldehydes (pentanal, OAV = 8.96; hexanal, OAV = 63.7; heptanal, OAV = 2.04; nonanal, OAV = 24.3) and one alcohol (1-octen-3-ol, OAV = 145).

Thermal processing methods had obvious effects on the OAVs of relatively important volatile compounds. Microwaving decreased the OAVs of two volatile compounds (one aldehyde: pentanal, from 8.96 to 0; one alcohol: 1-octen-3-ol, from 145 to 86.3) and increased the OVAs of four volatile aldehydes (hexanal, from 63.7 to 121; heptanal, from 2.04 to 4.92; nonanal, from 24.3 to 45.5; decanal, from 0 to 35.6). Roasting decreased the OVAs of three volatile aldehydes (hexanal, from 63.7 to 45.1; heptanal, from 2.04 to 1.24; nonanal, from 24.3 to 14.9) and one alcohol (1-octen-3-ol, from 145 to 123), whereas it increased the OAVs of four volatile aldehydes (pentanal, from 8.96 to 9.65; 2-methyl-butanal, from 0 to 13.8; 3-methyl-butanal, from 0 to 5.41; decanal, from 0 to 8.90) and one other compound (trimethylamine, from 0 to 6.45).

Steaming decreased the OAVs of two volatile aldehydes (pentanal, from 8.96 to 0; nonanal, from 24.3 to 12.0) and one alcohol (1-octen-3-ol, from 145 to 0), whereas it increased the OAVs of three volatile aldehydes (2-methyl-butanal, from 0 to 27.0; hexanal, from 63.7 to 71.3; heptanal, from 2.04 to 2.98). Boiling decreased the OAVs of all the

Table 1
Odor activity values (OAVs) of volatile compounds in raw and thermally processed tilapia muscles.

No.	Volatile compound	CAS	Formula	Molecular weight	Odor threshold (μg/kg)	Odor type[e]	Flavor type[e]	OAV				
								Raw	Microwaved	Roasted	Steamed	Boiled
	Aldehydes											
1	Propanal	123-38-6	C3H6O	58	15.1c	Ethereal	Musty	ND	ND	<1	ND	<1
2	Pentanal	110-62-3	C5H10O	86	1.57[c]	Fermented	Winey	8.96	ND	9.65	ND	16.4
3	2-methyl-Butanal	96-17-3	C4H8O	72	1.00[a]	Cocoa	Fusel	ND	ND	13.8	27.0	ND
4	3-methyl-Butanal	590-86-3	C4H8O	72	1.10[a]	Aldehydic	Fruity	ND	ND	5.41	ND	ND
5	Hexanal	66-25-1	C6H12O	100	5.00[a]	Green	Green	63.7	121	45.1	71.3	57.4
6	Heptanal	111-71-7	C7H14O	114	2.80[a]	Green	Green	2.04	4.92	1.24	2.98	<1
7	Nonanal	124-19-6	C9H18O	142	1.10[a]	Aldehydic	Aldehydic	24.3	45.5	14.9	12.0	11.0
8	Decanal	112-31-2	C10H20O	156	2.71[c]	Aldehydic	Waxy	ND	35.6	8.90	ND	24.6
	Alcohols											
9	1-Penten-3-ol	616-25-1	C5H10O	86	358[a]	Green	Green	<1	ND	ND	ND	ND
10	1-Octen-3-ol	3391-86-4	C8H16O	128	1.50[b]	Earthy	Mushroom	145	86.3	123	ND	ND
	Others											
11	Trimethylamine	75-50-3	C3H9N	59	2.40[a]	Fishy	Fishy	ND	ND	6.45	ND	ND
12	Dimethyl sulfide	75-18-3	C2H6S	62	2.6[d]	Cabbage, sulfur, gasoline	Cabbage	2.45	ND	7.68	1.48	6.42
13	Toluene	108-88-3	C7H8	92	1550[a]	Sweet	/	<1	ND	ND	ND	ND

Note: [a]Odor thresholds from ref. (Wang et al., 2016). [b]Odor thresholds from ref. (Giri et al., 2011). [c]Odor thresholds from ref. (Mu et al., 2017). [d]Odor thresholds from ref. (Yu et al., 2022). [e]Odor and flavor types from https://www.thegoodscentscompany.com.

relatively important volatile compounds in the raw muscle and increased the OAV of one volatile aldehyde (decanal, from 0 to 24.6). Therefore, three (hexanal, nonanal, and decanal), four (2-methyl-butanal, 3-methyl-butanal, decanal, and trimethylamine), one (2-methyl-butanal), and one (decanal) compound might be the relatively important volatile compounds for the odor profiles of the microwaved, roasted, steamed, and boiled, respectively, tilapia muscles.

Dimethyl sulfide was found in tilapia muscle. These kinds of sulfur-containing compounds are important flavor chemicals of meats and are mainly from Maillard reactions or amino acid pyrolysis (Mori, 1999). In fact, it could provide the smell of cabbage and sulfur for tilapia muscles. The roasted and boiled tilapia muscles had relatively high OAV values (7.68 and 6.42, respectively), which would be helpful for the formation of cabbage and sulfur after roasting and boiling.

4. Conclusions

This study examined the physicochemical properties and odor profiles of tilapia muscles after four types of thermal processing. All of the results suggested that textural properties changed after thermal processing, which involved a muscle pH–water state–water content–tissue microstructure–mass loss–textural properties route, expressed in the following manner: microwaving > roasting > steaming ≈ boiling. As such, people could choose appropriate thermal processing methods for tilapia muscles according to the desired chewing feeling in the mouth. Further work is necessary to run a consumer sensory analysis to evaluate the effect of the different thermal treatments on consumer preferences. GC-based E-nose results demonstrated that the thermal processing methods had a significant effect on the odor fingerprint characteristics of the tilapia muscles, expressed in the following manner: microwaving > roasting > steaming > boiling. This was consistent with the effect of thermal processing methods on the mass loss and water loss of the tilapia muscles. Finally, the volatile compound classes and individual volatile compounds were examined by HS-SPME-GC–MS, online statistical software MetaboAnalyst, and OAV analysis. The results confirmed that the four types of thermal processing methods had different effects on the odor profiles of tilapia muscles. Moreover, the microwaved, roasted, steamed, and boiled tilapia muscles showed three (hexanal, nonanal, and decanal), four (2-methyl-butanal, 3-methyl-butanal, decanal, and trimethylamine), one (2-methyl-butanal), and one (decanal) compound as the relatively important volatile compounds for their odor profiles. Even though chromatographic methods are mature, further appropriate method validation should be considered to confirm the results.

These findings significantly advanced our understanding of the effect of thermal processing methods on the physicochemical and volatile compound properties of tilapia fish muscles. In addition, our work could provide potential suggestions for food thermal processing methods, depending on the chewing sensation that people prefer. Finally, this work could be beneficial in expanding the consumption of boneless fish muscles. However, it should be noted that the detailed molecular mechanisms involved in the changes of physicochemical properties and volatile compound profiles of tilapia muscles after thermal processing remain unclear. Studies that incorporate novel analytical techniques are needed to explore this further.

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.

Data availability

Data will be made available on request.

Acknowledgments

This research has been supported by research grants from the National Key R & D Program of China (No. 2019YFD0902003) and the National Natural Science Foundation of China (No. 32272338).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2023.100748.

References

Bi, C., Li, X., Xin, Q., Han, W., Shi, C., Guo, R., … Zhong, J. (2019). Effect of extraction methods on the preparation of electrospun/electrosprayed microstructures of tilapia skin collagen. *Journal of Bioscience and Bioengineering, 128*, 234–240. https://doi.org/10.1016/j.jbiosc.2019.02.004

Chen, J., Tao, L., Zhang, T., Zhang, J., Wu, T., Luan, D., … Zhong, J. (2021). Effect of four types of thermal processing methods on the aroma profiles of acidity regulator-treated tilapia muscles using E-nose, HS-SPME-GC-MS, and HS-GC-IMS. *LWT, 147*, Article 111585. https://doi.org/10.1016/j.lwt.2021.111585

Chong, J., Wishart, D. S., & Xia, J. (2019). Using MetaboAnalyst 4.0 for comprehensive and integrative metabolomics data analysis. *Current Protocols in Bioinformatics, 68*, e86. https://doi.org/10.1002/cpbi.86

García-González, D. L., Tena, N., Aparicio-Ruiz, R., & Morales, M. T. (2008). Relationship between sensory attributes and volatile compounds qualifying dry-cured hams. *Meat Science, 80*, 315–325. https://doi.org/10.1016/j.meatsci.2007.12.015

Giri, A., Osako, K., & Ohshima, T. (2011). Effects of hypobaric and temperature-dependent storage on headspace aroma-active volatiles in common squid miso. *Food Research International, 44*, 739–747. https://doi.org/10.1016/j.foodres.2011.01.025

Guo, Q., Sun, D.-W., Cheng, J.-H., & Han, Z. (2017). Microwave processing techniques and their recent applications in the food industry. *Trends in Food Science & Technology, 67*, 236–247. https://doi.org/10.1016/j.tifs.2017.07.007

Hong, Q., Chen, G., Wang, Z., Chen, X., & Kan, J. (2023). Effects of different thermal processing methods on bioactive components, phenolic compounds, and antioxidant activities of Qingke (highland hull-less barley). *Food Science and Human Wellness, 12*, 119–129. https://doi.org/10.1016/j.fshw.2022.07.030

Hussain, N., Shukla, S. S., Dubey, A. D., Gautam, S., & Tripathi, J. (2022). Control of post-harvest storage losses in water chestnut (*Trapa bispinosa Roxburg*) fruits by natural functional herbal coating and gamma radiation processing. *Journal of Food Science and Technology, 59*, 2842–2854. https://doi.org/10.1007/s13197-021-05307-x

Jiang, Q., Nakazawa, N., Hu, Y., Osako, K., & Okazaki, E. (2019). Changes in quality properties and tissue histology of lightly salted tuna meat subjected to multiple freeze-thaw cycles. *Food Chemistry, 293*, 178–186. https://doi.org/10.1016/j.foodchem.2019.04.091

Joshi, V., Akhtar, M. S., Sharma, P., Singh Kushwaha, S., Baruah, D., Ciji, A., … Sarma, D. (2017). Himalayan fish manifest higher potential of quality nutrients for human health. *Journal of Aquatic Food Product Technology, 26*, 843–855. https://doi.org/10.1080/10498850.2017.1340916

Koca, S. B., & Cevikbas, M. (2015). Antifungal effect of Origanum onites essential oil as an alternative to formalin in the artificial incubation of narrow-clawed crayfish (Astacus leptodactylus Eschscholtz, 1823). *Aquaculture Research, 46*, 2204–2210. https://doi.org/10.1111/are.12374

Li, R., Sun, Z., Zhao, Y., Li, L., Yang, X., Cen, J., … Wang, Y. (2021). Application of UHPLC-Q-TOF-MS/MS metabolomics approach to investigate the taste and nutrition changes in tilapia fillets treated with different thermal processing methods. *Food Chemistry, 356*, Article 129737. https://doi.org/10.1016/j.foodchem.2021.129737

Li, Y., Fei, C., Mao, C., Ji, D., Gong, J., Qin, Y., … Lu, T. (2022). Physicochemical parameters combined flash GC e-nose and artificial neural network for quality and volatile characterization of vinegar with different brewing techniques. *Food Chemistry, 374*, Article 131658. https://doi.org/10.1016/j.foodchem.2021.131658

Lin, J., Zhang, Y., Li, Y., Sun, P., Ren, X., & Li, D. (2022). Improving the texture properties and protein thermal stability of Antarctic krill (*Euphausia superba*) by L-lysine marination. *Journal of the Science of Food and Agriculture, 102*, 3916–3924. https://doi.org/10.1002/jsfa.11741

Liu, M., Zhao, X., Zhao, M., Liu, X., Pang, Y., & Zhang, M. (2022). Characterization of the key aroma constituents in fried tilapia through the sensorics concept. *Foods, 11*, 494. https://doi.org/10.3390/foods11040494

Mori, H. (1999). Simultaneous determination of D-lactic acid and L-lactic acid using a flow system with two enzyme reactors and an octadecylsilica column in one line. *Analytical Letters, 32*, 1301–1312. https://doi.org/10.1080/00032719908542898

Mu, H., Wei, Z., Yi, L., Liang, H., Zhao, L., Zhang, W., & Mai, K. (2017). Dietary fishmeal levels affect the volatile compounds in cooked muscle of farmed large yellow croaker Larimichthys crocea. *Aquaculture Research, 48*, 5821–5834. https://doi.org/10.1111/are.13405

Nie, Y., Chen, J., Xu, J., Zhang, Y., Yang, M., Yang, L., … Zhong, J. (2022). Vacuum freeze-drying of tilapia skin affects the properties of skin and extracted gelatins. *Food Chemistry, 374*, Article 131784. https://doi.org/10.1016/j.foodchem.2021.131784

Pang, Z., Zhou, G., Ewald, J., Chang, L., Hacariz, O., Basu, N., & Xia, J. (2022). Using MetaboAnalyst 5.0 for LC–HRMS spectra processing, multi-omics integration and covariate adjustment of global metabolomics data. *Nature Protocols, 17*, 1735–1761. https://doi.org/10.1038/s41596-022-00710-w

Pérez-Burillo, S., Pastoriza, S., Jiménez-Hernández, N., D'Auria, G., Francino, M. P., & Rufián-Henares, J. A. (2018). Effect of food thermal processing on the composition of the gut microbiota. *Journal of Agricultural and Food Chemistry, 66*, 11500–11509. https://doi.org/10.1021/acs.jafc.8b04077

Pu, D., Shan, Y., Zhang, L., Sun, B., & Zhang, Y. (2022). Identification and inhibition of the key off-odorants in duck broth by means of the sensomics approach and binary odor mixture. *Journal of Agricultural and Food Chemistry, 70*, 13367–13378. https://doi.org/10.1021/acs.jafc.2c02687

Shi, C., Guo, H., Wu, T., Tao, N., Wang, X., & Zhong, J. (2019). Effect of three types of thermal processing methods on the lipidomics profile of tilapia fillets by UPLC-Q-Extractive Orbitrap mass spectrometry. *Food Chemistry, 298*, Article 125029. https://doi.org/10.1016/j.foodchem.2019.125029

Śliwińska, M., Wiśniewska, P., Dymerski, T., Wardencki, W., & Namieśnik, J. (2016). Evaluation of the suitability of electronic nose based on fast GC for distinguishing between the plum spirits of different geographical origins. *European Food Research and Technology, 242*, 1813–1819. https://doi.org/10.1007/s00217-016-2680-6

Sobral, M. M. C., Cunha, S. C., Faria, M. A., & Ferreira, I. M. (2018). Domestic cooking of muscle foods: Impact on composition of nutrients and contaminants. *Comprehensive Reviews in Food Science and Food Safety, 17*, 309–333. https://doi.org/10.1111/1541-4337.12327

Suman, S. P., & Joseph, P. (2013). Myoglobin chemistry and meat color. *Annual Review of Food Science and Technology, 4*, 79–99. https://doi.org/10.1146/annurev-food-030212-182623

Sun, R., Wu, T., Guo, H., Xu, J., Chen, J., Tao, N., … Zhong, J. (2021). Lipid profile migration during the tilapia muscle steaming process revealed by a transactional analysis between MS data and lipidomics data. *Npj Science of Food, 5*, 30. https://doi.org/10.1038/s41538-021-00115-1

Vacha, F., Stejskal, V., Vejsada, P., Kouril, J., & Hlavac, D. (2013). Texture profile analyses in tench (Tinca tinca L., 1758) from extensive and intensive culture. *Acta Veterinaria Brno, 82*, 421–425. https://doi.org/10.2754/avb201382040421

Wang, H., Zhang, J., Zhu, Y., Wang, X., & Shi, W. (2018). Volatile components present in different parts of grass carp. *Journal of Food Biochemistry, 42*, Article e12668. https://doi.org/10.1111/jfbc.12668

Wang, M.-Q., Ma, W.-J., Shi, J., Zhu, Y., Lin, Z., & Lv, H.-P. (2020). Characterization of the key aroma compounds in Longjing tea using stir bar sorptive extraction (SBSE) combined with gas chromatography-mass spectrometry (GC–MS), gas chromatography-olfactometry (GC-O), odor activity value (OAV), and aroma recombination. *Food Research International, 130*, Article 108908. https://doi.org/10.1016/j.foodres.2019.108908

Wang, S., He, Y., Wang, Y., Tao, N., Wu, X., Wang, X., … Ma, M. (2016). Comparison of flavour qualities of three sourced Eriocheir sinensis. *Food Chemistry, 200*, 24–31. https://doi.org/10.1016/j.foodchem.2015.12.093

Wang, X.-Y., & Xie, J. (2019). Evaluation of water dynamics and protein changes in bigeye tuna (*Thunnus obesus*) during cold storage. *LWT, 108*, 289–296. https://doi.org/10.1016/j.lwt.2019.03.076

Wang, X., Zhu, L., Han, Y., Xu, L., Jin, J., Cai, Y., & Wang, H. (2018). Analysis of volatile compounds between raw and cooked beef by HS-SPME–GC–MS. *Journal of Food Processing and Preservation, 42*, e13503.

Watanabe, W. O., Losordo, T. M., Fitzsimmons, K., & Hanley, F. (2002). Tilapia production systems in the americas: Technological advances, trends, and challenges. *Reviews in Fisheries Science, 10*, 465–498. https://doi.org/10.1080/20026491051758

Wu, S., Yang, J., Dong, H., Liu, Q., Li, X., Zeng, X., & Bai, W. (2021). Key aroma compounds of Chinese dry-cured Spanish mackerel (Scomberomorus niphonius) and their potential metabolic mechanisms. *Food Chemistry, 342*, Article 128381. https://doi.org/10.1016/j.foodchem.2020.128381

Wu, T., Guo, H., Lu, Z., Zhang, T., Zhao, R., Tao, N., … Zhong, J. (2020). Reliability of LipidSearch software identification and its application to assess the effect of dry salting on the long-chain free fatty acid profile of tilapia muscles. *Food Research International, 138*, Article 109791. https://doi.org/10.1016/j.foodres.2020.109791

Xu, N., Shi, W., Wang, X., & Wang, Z. (2019). Effect of ice water pretreatment on the quality of Pacific White Shrimps (*Litopenaeus vannamei*). *Food Science & Nutrition, 7*, 645–655. https://doi.org/10.1002/fsn3.901

Yu, P., Yang, Y., Sun, J., Jia, X., Zheng, C., Zhou, Q., & Huang, F. (2022). Identification of volatile sulfur-containing compounds and the precursor of dimethyl sulfide in cold-pressed rapeseed oil by GC–SCD and UPLC–MS/MS. *Food Chemistry, 367*, Article 130741. https://doi.org/10.1016/j.foodchem.2021.130741

Zhang, D., Ayed, C., Fisk, I. D., & Liu, Y. (2023). Effect of cooking processes on tilapia aroma and potential umami perception. *Food Science and Human Wellness, 12*, 35–44. https://doi.org/10.1016/j.fshw.2022.07.016

Zhang, T., Shi, Y., Zhao, Y., Wang, J., Wang, M., Niu, B., & Chen, Q. (2019). Different thermal processing effects on peanut allergenicity. *Journal of the Science of Food and Agriculture, 99*, 2321–2328. https://doi.org/10.1002/jsfa.9430

Zhou, X., Chong, Y., Ding, Y., Gu, S., & Liu, L. (2016). Determination of the effects of different washing processes on aroma characteristics in silver carp mince by MMSE-GC-MS, e-nose and sensory evaluation. *Food Chemistry, 207*, 205–213. https://doi.org/10.1016/j.foodchem.2016.03.026