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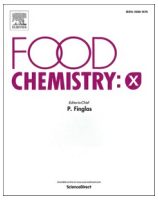

Quality properties of fish ball with abalone and its relationship with sensory properties

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ABSTRACT

In this work, whiteness, water-holding capacity, gel strength, textural profile analysis were performed to examine the quality of fish balls with abalone (FBA). In addition, a correlation between quality and sensory properties was established. The addition of abalone significantly increased the water holding capacity, gel strength and textural properties of FBA, and decreased their whiteness, the best overall quality was achieved at 9 % w/w abalone addition. The E-nose and E-tongue results revealed that the addition of abalone changed the flavour of FBA. HS-SPME-GC–MS identified 65 volatile organic compounds (VOCs) and proved to be effective in reducing fishy flavour. E-nose can distinguish between the VOCs in FBA. Moreover, Umami and 1-octen-3-ol can serve as important indicators to observe changes in the quality of FBA, as they were positively connected with WHC, gumminess, chewiness, resilience, a^*, hexanal, etc. The results provided a theoretical basis for the development of abalone and surimi products.

1. Introduction

Nemipterus virgatus, commonly known as the golden threadfin bream, is a common ingredient in surimi products, because of its tender meat, fast growth and reproduction rates, and consequent extensive use in fish farming (Agriculture 2023). Surimi products, such as fish balls, crab meat sticks and fish sausages, are highly processed, processing stages include washing, meat harvesting, rinsing, dehydration, molding, packaging and freezing (Yang, Wang, Wang, & Ye, 2014). Proteins in surimi improve the gelation properties of surimi products by aggregating, cross-linking and forming a three-dimensional network structure, which traps large amounts of water (Liu et al., 2021). To facilitate adaptation to consumer preferences and develop novel surimi products, producers add various plant- and animal-based components, to improve the textural properties and flavour of surimi. Addition of crab meat to surimi significantly promoted its flavour and color, and increased the fat content, that of some minerals and slightly decreased its texture quality (Liang, Lin, Zhu, Jiang, & Lu, 2020). Addition of diacylglycerol pre-emulsion to golden threadfin bream surimi improved its aroma, gel strength, hardness, and water-holding properties (Xu et al., 2022).

Abalone is a seafood product with high market demand and excellent nutritional quality, which is favored by consumers for its delicious taste, unique organoleptic properties, high nutritional value, and medicinal properties, i.e., anti-fatigue, antioxidant, and immunomodulation (Guo, Wang, He, Wei, Ma, & Xiong, 2020). It was initially marketed mainly as a raw product, which was time-consuming to prepare, had low commercial value and a very short shelf life. Abalone was also susceptible to disease and death during aquaculture, because of changes in water temperature and insufficient food supply. Abalone is now mainly processed into frozen, dried and canned products (Palma-Acevedo, Pérez-Won, Tabilo-Munizaga, Ortiz-Viedma, & Lemus-Mondaca, 2022; Pizarro-Oteiza, Giovagnoli-Vicuna, Briones-Labbarca, & Salazar, 2023) to extend its shelf life and distribution range. With the advancement of aquaculture technology and innovation in abalone processing, the shelf life of abalone products has been increased, the scale of distribution has increased and the utilization of raw materials improved.

Electronic nose (E-nose) and electronic tongue (E-tongue), which are fitted with liquid and gas sensors, respectively, simulate human taste

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and smell. Their benefits include quick detection, ease of usage, and high reproducibility; they are employed to digitally capture the flavor and aroma of food (Li et al., 2023). Aromas in substances can be extracted, separated, and detected using headspace solid phase microextraction gas chromatography spectroscopy (HS-SPME-GC–MS), which can also assess volatile organic molecules both qualitatively and quantitatively (Chen et al., 2021). Peng et al. (2023) utilized HS-SPME-GC-MS combined with E-nose and E-tongue to detect the flavor and indicated that differential metabolites could be used as characteristic markers to identify different grades of Jiuqu hongmei tea. Recent studies had applied HS-SPME-GC–MS and electronic senses to identified 182 volatile compounds on jujube wine quality (Cai et al., 2020).

However, little research has been reported on the incorporation of abalone into surimi products and the correlation between HS-SPME-GC–MS and E-nose in abalone products for discriminating flavor substances. The mutual influence of quality properties and sensory properties of fish balls with abalone (FBA) is an important factors in determining its market price, as well as determining consumer acceptance and aiming to improve product quality. In this study, the effects of adding surimi to fish balls on their color, water-holding capacity (WHC), gel strength, and textural profile analysis (TPA) were determined. Differences in the flavour and volatile composition of FBA were analyzed by E-nose, E-tongue and HS-SPME-GC–MS, coupled with principal components analysis (PCA), clustering heatmap, and radar diagram. Meanwhile, correlation analysis was performed between the E-nose and HS-SPME-GC–MS and between quality properties and sensory properties, respectively. As a newly developed product, the evaluation of FBA quality properties and sensory properties is of great significance for the development and innovation of new surimi products..

2. Materials and methods

2.1. Materials

The materials usage information of FBA is shown in Table 1, w/w of surimi. Live abalones, 55.0 ± 5.2 g mean weight, were slaughtered, shucked, eviscerated and minced. They were then stored at 4.0 ± 0.2 °C for no more than 24 h until further processing. Four abalone additions were used to prepare the fish balls: control (no addition), FBA-3 % (3:100), FBA-6 % (6:100), FBA-9 % (9:100), and FBA-12 % (12:100).

Table 1
The materials usage information of FBA.

Materials	Usage amount (g/100 g)				
	Control	FBA-3 %	FBA-6 %	FBA-9 %	FBA-12 %
Abalone	–	3.0	6.0	9.0	12.0
Lard oil	8.8	8.8	8.8	8.8	8.8
Egg white	4.0	4.0	4.0	4.0	4.0
Salt	2.0	2.0	2.0	2.0	2 0.0
Sesame oil	0.3	0.3	0.3	0.3	0.3
Cooking wine	0.3	0.3	0.3	0.3	0.3
Sugar	0.1	0.1	0.1	0.1	0.1
Monosodium glutamate	0.2	0.2	0.2	0.2	0.2
White pepper	0.1	0.1	0.1	0.1	0.1
Nemipterus virgatus surimi	100.0	100.0	100.0	100.0	100.0
Starch acetate	10.0	10.0	10.0	10.0	10.0
Soybean protein isolate	10.0	10.0	10.0	10.0	10.0
Emulsion pulp	2.1	2.1	2.1	2.1	2.1
Egg white powder	0.3	0.3	0.3	0.3	0.3
Meat essence powder	0.3	0.3	0.3	0.3	0.3
Fish essence	0.2	0.2	0.2	0.2	0.2
Composite phosphate	0.2	0.2	0.2	0.2	0.2

2.2. Preparation of fish balls with abalone

FBA were produced according to the following traditional recipe. Frozen surimi was thawed overnight in a refrigerator (BCD-649WDGK, Qingdao Haier, Qingdao, China) and homogenized for 3 min in a highspeed tissue blender (JJ-2B, Daluo Scientific Instruments Co., Ltd., Shanghai, China) at 5,000 rpm. After adding 2 % w/w of salt, blending was continued for 2 min, then sugar, egg whites, composite phosphate and abalone were added, followed by blending for 2 min. Ice cubes were appropriately added during blending to maintain the temperature below 4 °C. After blending, the fish paste was shaped into 3 cm diameter balls, which were then heated at 40 °C in a thermostatic water bath (HH-4, Changzhou Guohua Electric Appliance Co., Ltd., Changzhou, China) for 20 min. The resulting gelatinized fish balls were cooked (HB25D5L2W Steam Oven, Siemens Appliances, Shaoxing, China) at 90 °C for 10 min, then immediately cooled in ice-water and packaged with a vacuum-packing machine (DZ-350M, Shandong Mining Heavy Industry Co., Ltd., Jining, China) and stored at −18 °C for 6 months.

2.3. Determination of water-holding capacity

WHC was determined as described previously, with some modifications (Pizarro-Oteiza et al., 2023). An accurately weighed FBA sample (~2 g, m_1) was sandwiched between two layers of filter paper and centrifuged (Avanti J-E, Beckman Technologies, CA) at 10,000 rpm and 4 °C for 15 min. The filter paper wrapping was removed and the sample weighed again (m_2). Three measurements were taken for each set of samples and the WHC was calculated as follows:

$$WHC(\%) = \frac{m_2}{m_1} \times 100$$

2.4. Determination of gel strength

The fish balls were equilibrated to room temperature and cut into 20 × 20 mm cylinders, as above, then the gel strength were measured by a texture analyzer (TA.XT Express, Stable Micro Systems, Godalming, UK). The measurement parameters were set as follows: the P/50R metal probe was pressed vertically into the surface of the sample at a speed of 60 mm/min, a trigger force of 0.75 N and a puncture distance of 10 mm.

2.5. Textural profile analysis (TPA)

The thawed FBA were cut into 20 × 20 mm cylinders and their textural parameters (hardness, springiness, gumminess, cohesiveness chewiness and resilience) were determined with the texture analyzer. The measurement parameters were set as follows: metal cylindrical probe P/36R, pressed down twice, with 50 % compression at 5 s intervals, a pre-test rate of 3.0 mm/s, a test rate of 60 mm/min, a post-test rate of 3.0 mm/s, and an induction force of 5.0 g.

2.6. Color evaluation

Color evaluation was performed as described previously (Huang et al., 2023), with some modifications. The color values were carried out using a portable colorimeter (CR-10, Konica Corporation, Tokyo, Japan). Whiteness (W) was calculated using the following formula:

$$W = 100 - \left[(100\text{-}L^{*})^2 + a^{*2} + b^{*2}\right]^{1/2}$$

The L^* represents the lightness, a^* represents the redness/greenness, and b^* represents the yellowness/blueness.

2.7. Electronic nose measurement

E-nose assay was performed as described previously (Yu, Lu, Dong, & Xie, 2022), with some modifications. The E-nose analysis system (Pen 3,

AIRSENSE Analytics, Schwerin, Germany) was equipped with 10 semiconductor sensors: W1C (aromatic compounds), W5S (nitrogen oxides), W3C (amines, aromatic compounds), W6S (hydrocarbons), W5C (alkanes, aromatic compounds), W1S (methane (methyl group)), W1W (inorganic sulfide), W2S (broad range alcohols), W2W (organic sulfide), and W3S (long chain) Alkanes). Sample (5 g) was placed in a 50 mL headspace vial and allowed to stand for 30 min at room temperature to release volatile compounds. The measurement parameters were: equilibration time of 120 s before injection, headspace gas volume of 2,400 μL, with purification of the sensor system with clean air for 120 s after each 120 s sampling, until the signal returned to the baseline level.

2.8. Electronic tongue measurement

E-tongue assay was performed as described previously (Qian et al., 2023), with some modifications. The E-tongue system (SA402B, INSENT, Fukuoka, Japan) consisted of a sensor probe body, an artificial lipid membrane, an Ag/AgCl electrode and a pin-plug electrode tip. The CT0, CA0, AAE, AE1 and C00 sensors were used for measurement of saltiness, sourness, umami, astringency and aftertaste-A, bitterness and ftertaste-B, respectively. Each set of samples was heated at 90 °C and then accurately weighed (~10 g), stirred at 5,000 rpm for 1 min, and distilled water at 40 °C was added at a ratio of 1:10. The samples were centrifuged at 3,000 rpm for 10 min and the supernatant retained. An aliquot (70 mL) of each sample solution was taken and divided equally into two sampling cups for the assay, the assay time was 120 s.

2.9. HS-SPME-GC–MS analysis

HS-SPME-GC–MS (8860-5977B, Agilent, Beijing, China) was performed as described previously (Yu, Lu, Zi, Yang, & Xie, 2022), with some modifications. The minced fish ball sample (~3.0 g) was accurately weighed and placed in a 20 mL headspace vial, then saturated NaCl solution (6 mL) was added and the vial sealed. The vial was equilibrated with magnetic stirring at 50 °C for 15 min and a DVC/CAR/PDMS 50/30 μm headspace fiber (pre-activated for 60 min at 270 °C) added, volatiles were adsorbed for 40 min, then desorbed for 5 min in the GC injector. GC conditions: initial temperature 40 °C, increased to 120 °C at 3 °C/min, maintained for 5 min, then increased to 200 °C at 3 °C/min. VF-5 GC column (30 m × 0.25 mm × 0.25 μm), detector temperature 250 °C, carrier gas helium (99.999 %), flow rate 1 mL/min, inlet temperature 250 °C. Mass spectrometry conditions: transfer temperature 280 °C, ion trap temperature 220 °C, scanning range 30–550 *m/z*, detector temperature 250 °C, detector gas helium (99 999 %), flow rate 1 mL/min.

2.10. Statistical analysis

All experiments were performed as three replicates and the results were expressed as mean ± standard deviation. SPSS 20.0 software (SPSS Inc., Chicago, IL, USA) was used to statistically analyze the data. PCA was performed using SIMCA 14.1 (Umetrics, Sweden). The $p < 0.05$ was considered statistically significant. Graphing was performed using Origin 2022 (Origin Lab, Northampton, MA) and Gephi (version 0.9.2, Netbeans, France).

3. Results and discussion

3.1. Water-holding capacity analysis

The WHC is a crucial factor in determining the quality of food, since it has a significant impact on several quality attributes, including texture, flavor, and color. (Gokoglu, Yerlikaya, Ucak, & Yatmaz, 2017). Cooking weight loss results from the loss of water and leaching of water-soluble ingredients, such as gelatin, which is generated from gelation of collagen protein. The WHC of the fish balls increased ($p < 0.05$) with increased abalone addition (Fig. 1), to a maximum value of 94.27 ± 0.34 % at 9 % abalone addition, 3.38 % higher than control. However, at 12 % abalone addition, the decrease in the WHC from that at 9 % was not significant ($p > 0.05$).

The increase in the WHC resulting from abalone addition appeared to be related to the abundance of myogenic fiber proteins in abalone muscle, as well as its very low fat content. Heat-treated muscle proteins formed a very viscous sol–gel state during heat treatment, with an ordered three-dimensional network structure (Sun & Holley, 2011), which enhances their ability to adsorb and retain water. During heat treatment, lipid oxidation generated free radicals and lipid oxidation products, which attacked the amino acid side chains in abalone muscle, forming disulfide bonds and other linkages, which resulted in protein aggregation (Yu et al., 2022) and improved the WHC. Overall, 9 % abalone addition to FBA resulted in the highest WHC, with 12 % addition slightly lower.

3.2. Gel strength analysis

The three-dimensional network structure of surimi gels is maintained by both noncovalent (hydrophobic interactions, hydrogen bonding, electrostatic interactions) and covalent (disulfide and nondisulfide) interprotein cross-links (Davila, Pares, & Howell, 2007). The gel strength of FBA increased, then decreased with increased abalone addition, with a maximum value of 2509.87 g*mm at 9 % abalone addition (Fig. 1). The high content of myosin and low content of fat in abalone muscle the gel network appeared to have inhibited the gelatinization of starch granules, the filling effect of water absorption into the gel network by starch acetate would have increased the gel strength. Hydrophobic protein–protein interactions would also have contributed to the increased gel strength. Changes in the helical structure of the tail region of myoglutinin, when heated above 60 °C resulted in the formation of a stronger gel network, because of interactions between hydrophobic amino acid side chains (Tornberg, 2005). The increased gel strength may also be related to the presence of starch acetate, which contributes to the formation of a more compact, homogeneous and continuous network than natural starch (Cao, Wang, Yuan, Kong, Sun, & Liu, 2021). Overall, 9 % abalone addition to FBA resulted in the highest gel strength.

3.3. Textural profile analysis (TPA)

TPA is used to measure the textural properties of food, expressed as hardness, springiness, gumminess, cohesiveness, chewiness and resilience, and is an important indicator of consumer acceptance of food

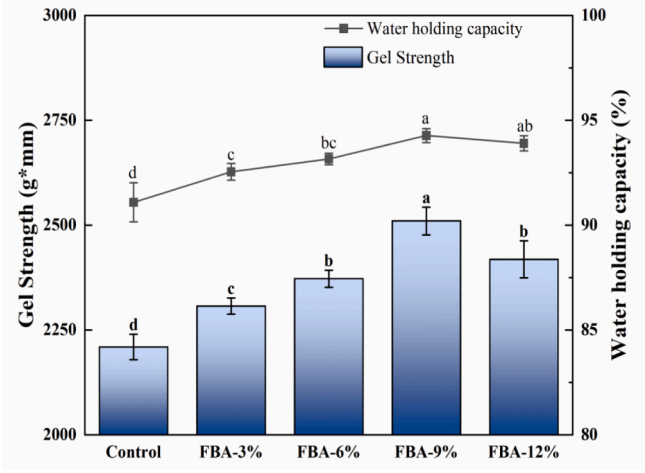

Fig.1. Water-holding capacity and gel strength of FBA with different abalone content.

products (Mei, Ting, Markus, & Ciaran, 2018). Table 2 showed that increased abalone addition to the fish balls resulted in increased hardness, springiness, gumminess, chewiness and resilience, but decreased cohesiveness ($p < 0.05$), compared with control. This may result from denaturation of collagen, paramyosin and myocardin during the second heating step (90 °C), involving longitudinal contraction of muscle fibers, increased myofibril diameter and decreased inter-myofibrillar porosity, which would enhance the shear-resistance and hardness of abalone muscle (Pathare & Roskilly, 2016). Transverse contraction of the fiber shaft occurs mainly at 40–60 °C, which widens the spaces between the fibers and the surrounding intramyocardium (Tornberg, 2005), decreasing cohesiveness. Similarly, the relative enhancement of electrostatic repulsion between protein molecules and the relaxation of the network structure contribute to decreased cohesion. The textural changes may also be influenced by the intrinsic structure of abalone muscle fibers, sarcoplasmic proteins and connective tissue. The muscle structure of abalone is an isotropic three-dimensional bundle of muscle fibers, surrounded by a relatively high connective tissue content, which is responsible for its greater chewiness. The structure of abalone muscle is very different from that of red meat, where muscle fibers are arranged in an anisotropic parallel structure and collagen surrounds the fibers and bundles of fibers. When biting through isotropic abalone muscle, rupture of the collagen matrix and fiber bundles occurred, and required more force than rupture of anisotropically oriented red meat fibers (Øiseth, Delahunty, Cochet, & Lundin, 2013). Heat treatment of edible abalone meat from 50 to 100 °C for 60 min resulted in the greatest increase in cohesion and reversibility at 90 °C (Zhu et al., 2011). The best TPA of FBA was obtained at 9 % abalone addition.

3.4. Color analysis

The color parameters, L^*, a^* and b^*, of FBA were determined and the whiteness calculated from them (Table 2), the whiteness value of FBA decreased significantly ($p < 0.05$) with increasing abalone addition. The control whiteness value was 67.59 ± 1.19, 9 % addition decreased the whiteness value of the control by 5.92 %, but that of the 12 % addition was not significantly lower ($p > 0.05$). The decrease in a^* after addition of abalone may be related to the green coloration of abalone muscle. β-carotene is the main pigment in abalone muscle and carotenoids bind to muscle proteins in mollusks (Kantha, 1989). Protein denaturation would have occurred during gelatinization and cooking of the fish balls, triggering oxidation and degradation of β-carotene, also increasing b^*. In addition, abalone is rich in iron and copper, and metal ions may oxidize and discolor β-carotene in abalone muscle. The increase in b^* may also result from non-enzymatic browning during heating, because of the presence of haemocyanin in abalone blood which binds Cu^{2+} ions and promotes auto-oxidation of phenolic compounds, further accelerating browning (Fan et al., 2023; Ma et al., 2023). In conclusion, the best whiteness of FBA was obtained at 9 % abalone addition.

3.5. Electric nose analysis

E-nose system is a commonly used tool for identifying and analyzing aromas (Yin & Zhao, 2019). PCA is a multivariate statistical analysis technique to assess similarities and differences between samples by identifying several principal component factors to represent the many complex variables present (Guo, Adelina, Hu, Zhang, & Zhao, 2022). Fig. 2A showed the response values of W1W, W2S and W3S increased with increasing abalone addition, i.e., the sulfur, alcohol, aldehyde, ketone, and alkane contents of fish balls significantly increased. This was in agreement with a previous report (Wang et al., 2014), that aldehydes acted as a major component of abalone aroma. Thermal oxidation and decomposition of fatty acids, especially polyunsaturated fatty acids, produces abundant volatile components in fish (Chung, Choi, Cho, & Kim, 2011). Abalone foot muscles contain mostly polar lipids, especially phospholipids (74.8 %) (Nelson, Nichols, & Leighton, 1999), the unsaturated fatty acids in phospholipids are very susceptible to lipid oxidation. Thus, the oxidative stability of abalone lipids is low, can alter the composition of aroma volatiles produced during heating. In addition, proteins can interact with flavour compounds through functional groups, such as amino acid side chains, amino termini and hydrophobic groups, which can affect the release and retention of flavour compounds (Xue, You, Zhang, Xiong, Yin, & Huang, 2021). According to the PCA plot (Fig. 2B), the variance contributions of the first two principal components, R2X[1] and R2X[2] were 55.9 % and 24.8 %, and accounted for 80.7 % of the variation in volatile composition between the samples. The control samples were located in the first quadrant, whereas most of the FBA samples were located in the second and fourth quadrants. The replicates of each sample were closely grouped, but the different samples were well separated, indicating that the reproducibility of the analysis was excellent and that addition of abalone significantly changed the aroma/flavour characteristics of fish balls.

3.6. Electric tongue analysis

The principle of E-tongue is similar to that of E-nose, in that the taste characteristics of the sample are represented by a combination of sensor responses (Peng et al., 2023). E-tongue system has been widely used to monitor the quality of food, beverages, cosmetics and pharmaceuticals, as well as for disease diagnosis, because it can differentiate highly complex samples, reduce matrix interference, and provide a rapid response (Zniber, Vahdatiyekta, & Huynh, 2023). According to Fig. 2C, the umami, saltiness, richness, and bitterness of the fish balls were higher ($p < 0.05$) with increased abalone addition. A known synergistic effect of taste interactions was that salty taste perception is amplified in high-umami foods, which enhances saltiness and umami (Sun et al., 2022). The formation of bitter taste in FBA may result from protein hydrolysis forming small, hydrophobic, bitter peptides (Thi Thu-Thao & Park, 2019). In the PCA plots of the E-tongue results (Fig. 2D), the first two principal components, (R2X[1] and R2X[2]) explained 57.2 % and

Table 2
Effect of different abalone content on the color and TPA of FBA.

Samples	L^*	a^*	b^*	Whiteness	Hardness (N)	Springiness	Gumminess (N)	Cohesiveness	Chewiness	Resilience
Control	67.586 ± 1.187^{a}	2.383 ± 0.307^{c}	13.250 ± 0.651^{c}	64.941 ± 0.315^{a}	28.846 ± 0.067^{c}	0.734 ± 0.014^{b}	19.207 ± 0.253^{b}	0.846 ± 0.024^{a}	17.915 ± 0.807^{c}	0.408 ± 0.011^{b}
FBA-3 %	66.088 ± 0.903^{b}	3.494 ± 0.339^{b}	13.920 ± 0.663^{b}	63.169 ± 0.867^{b}	29.319 ± 0.262^{c}	0.748 ± 0.020^{b}	20.161 ± 0.558^{ab}	0.840 ± 0.016^{ab}	18.506 ± 0.829^{bc}	0.422 ± 0.019^{ab}
FBA-6 %	65.842 ± 0.799^{b}	4.110 ± 0.317^{a}	13.910 ± 0.800^{b}	62.885 ± 0.968^{b}	29.487 ± 0.832^{c}	0.805 ± 0.012^{a}	20.422 ± 0.288^{ab}	0.818 ± 0.014^{abc}	19.419 ± 0.586^{b}	0.425 ± 0.004^{ab}
FBA-9 %	64.037 ± 0.225^{c}	4.383 ± 0.367^{a}	15.067 ± 0.228^{a}	60.761 ± 0.242^{c}	30.709 ± 0.376^{b}	0.825 ± 0.014^{a}	20.960 ± 0.863^{a}	0.810 ± 0.011^{bc}	20.932 ± 0.332^{a}	0.441 ± 0.007^{a}
FBA-12 %	63.398 ± 1.347^{c}	4.504 ± 0.370^{a}	15.714 ± 0.630^{a}	59.901 ± 1.064^{c}	31.909 ± 0.233^{a}	0.809 ± 0.038^{a}	21.138 ± 0.893^{a}	0.809 ± 0.020^{c}	20.898 ± 0.193^{a}	0.438 ± 0.007^{a}

Note: Different lowercase letters in the table represent significant differences in the data of indicators related to color and TPA, $p < 0.05$.

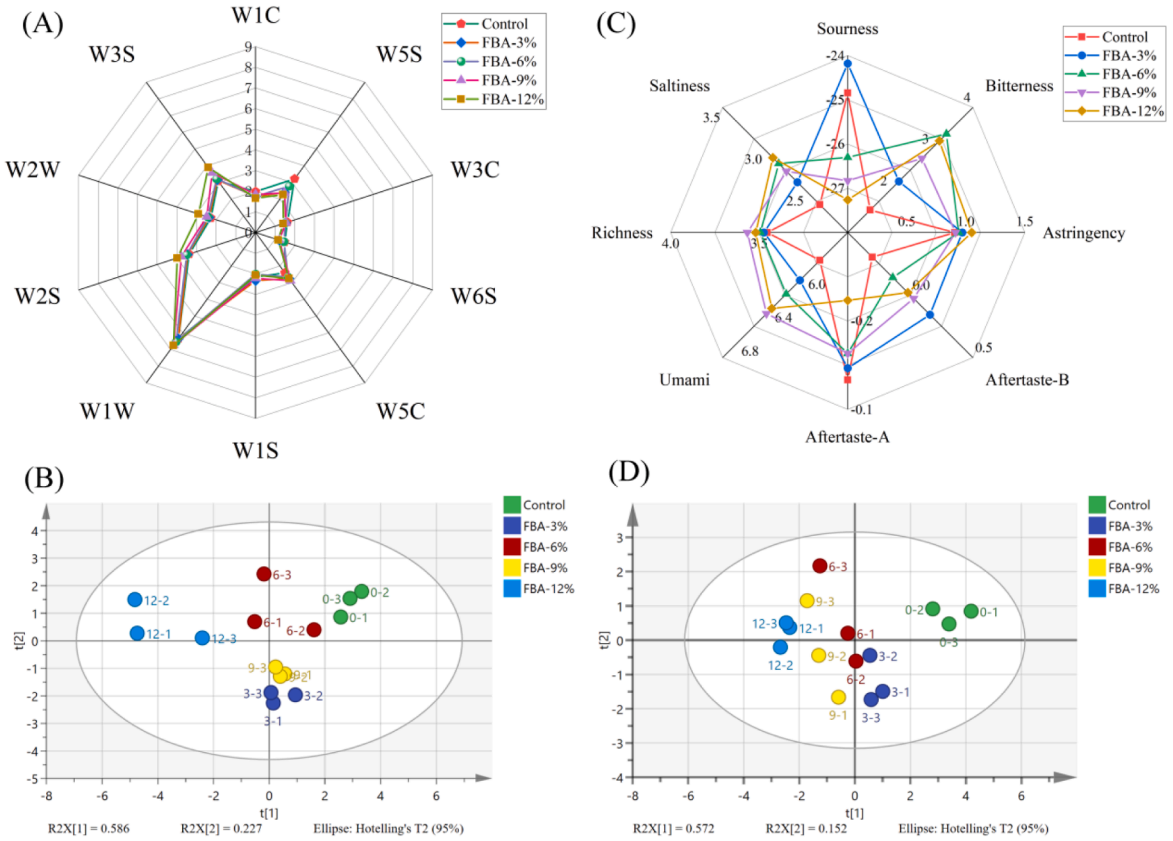

Fig.2. E-nose and E-tongue analysis of FBA with different abalone content. (A) Radar diagram of E-nose responses; (B) PCA of E-nose responses; (C) Radar map of the aroma attributes scores; (D) PCA of the aroma attributes scores.

15.2 % of the variance between samples, accounted for 72.4 % of the variation in taste. The control samples were closely grouped and well-separated from the other samples, indicating that addition of abalone significantly changed the taste of the fish balls. The other sample replicates were not closely grouped and the different samples were not well separated, indicating that there was little difference in taste between them. Therefore, HS-SPME-GC–MS was used to further analyze and identify the volatile organic compounds (VOCs) of FBA.

3.7. *HS-SPME-GC–MS analysis*

HS-SPME-GC–MS is commonly employed and exceptionally effective for analyzing the aroma of food, which enables the separation and identification of VOCs in complex samples (Chen et al., 2021). A total of 65 VOCs was identified from fish balls using HS-SPME-GC–MS, namely, 15 alcohols, 9 aldehydes, 6 ketones, 3 aromatic compounds, 4 esters, 11 hydrocarbons, 4 acids, 5 heterocyclic compounds, and 8 others (Table 3). Fig. 3 showed the relative contents of the 65 identified VOCs as a heatmap, with a hierarchical cluster analysis to visualize the relationships between the samples and compounds. The samples were clustered into three main groups: the control was in the first group, FBA-3 % and FBA-6 % were in the second group, FBA-9 % and FBA-12 % were in the third group. Alcohols, hydrocarbons and aldehydes were the main flavour compounds in FBA with relative content ranges of 20.91–33.44 %, 13.44–26.58 % and 10.68–20.59 %, respectively. This was in agreement with a previous report that the major volatile compounds in heated abalone meat were aldehydes, alkanes, alcohols, and ketones (Wang et al., 2014).

The major alcohols in FBA were 1-octen-3-ol (mushroom odor), 1-hexanol (grassy odor), 1-pentanol and ethanol. Alcohols are formed by lipoxygenase catalyzing the peroxidation of n-3 and n-6 polyunsaturated fatty acids (Selli & Cayhan, 2009). The 1-octen-3-ol is an important contributor to fishy odor, because of its low odor threshold (Sae-Leaw & Benjakul, 2014). The content of 1-octen-3-ol in FBA decreased ($p < 0.05$) with increased abalone content, and the 9 % addition reached the lowest level, suggesting that abalone addition can reduce the fishy odor of fish balls. The major aldehydes in FBA were hexanal, heptanal, octanal, benzaldehyde and phenylacetaldehyde. Hexanal is considered to be a characteristic fish odor compound (Ma et al., 2023), and when adding 12 % abalone, the decrease in the content of hexanal of FBA was not significant compared to 9 % addition ($p > 0.05$), indicating that abalone can partially mask the fishy odor of *Nemipterus virgatus* muscle. Lipid oxidation and the Maillard reaction are the two main formation pathways of odor-active aldehydes. Phospholipids and triglycerides are the major lipids in fish, the high degree of unsaturation and polar head group makes phospholipids good substrates for volatile flavour compound formation (Cui & Decker, 2016). Valeraldehyde, hexanal and octanal impart sweet, grassy and fruity odors to boiled shrimp(Hu, Wang, Liu, Cao, & Xue, 2021). Hydrocarbon volatile odor compounds are produced primarily by homolytic cleavage of alkoxy radicals in fatty acids, they typically have a high odor threshold and contribute little to the flavour of seafoods. Steaming appears to promote fat hydrolysis and oxidation, stimulating the release of more volatile compounds from fish (Nieva-Echevarria, Manzanos, Goicoechea, & Guillen, 2017).

Ketones are thermo-oxidative degradation products of unsaturated fatty acids or amino acids and contribute sweet, floral and fruity aromas (Oliva-Cruz, Mori-Culqui, Caetano, Gonas, Vilca-Valqui, & Chavez, 2021). Changes in ketone content after reheating may affect the aroma characteristics of FBA. The esters in FBA were mainly *n*-caproic acid vinyl ester, ethyl butyrate, formic acid, heptyl ester, and dibutyl phthalate, and decreased in content with increasing abalone addition ($p < 0.05$). Esters usually have a fruity aroma, they can be synthesized from

Table 3
Comparisons of the identified volatile compounds in fish balls with different abalone content by HS-SPME-GC–MS.

Volatile compounds	[a]CAS#	Formula	[b]Rt (min)	Relative content (%)				
				Control	FBA-3 %	FBA-6 %	FBA-9 %	FBA-12 %
Alcohols(15)								
Ethanol	64–017-5	C_2H_6O	1.789	3.55 ± 0.75	2.71 ± 0.52	3.15 ± 0.73	2.65 ± 0.23	2.71 ± 0.32
1-Penten-3-ol	616–25-1	$C_5H_{10}O$	5.661	2.36 ± 0.54	0.98 ± 0.13	1.20 ± 0.47	1.11 ± 0.22	1.55 ± 0.29
3-Methyl-1-butanol	123–51-3	$C_5H_{12}O$	6.865	2.01 ± 0.56	1.71 ± 0.37	2.06 ± 0.71	1.84 ± 0.36	1.77 ± 0.75
1-Pentanol	71–41-0	$C_5H_{12}O$	7.979	2.11 ± 0.13	3.81 ± 0.79	3.42 ± 0.81	3.18 ± 0.23	3.23 ± 0.44
1-Hexanol	111–27-3	$C_6H_{14}O$	10.663	4.19 ± 0.56	3.28 ± 0.26	3.24 ± 0.88	3.33 ± 0.78	3.22 ± 0.47
1-Octen-3-ol	3391–86-4	$C_8H_{16}O$	13.128	6.01 ± 1.49	5.25 ± 0.96	3.30 ± 0.36	3.16 ± 0.43	3.26 ± 0.56
1-Heptanol	53535–33-4	$C_7H_{16}O$	13.253	1.65 ± 0.57	1.86 ± 0.32	2.96 ± 0.24	1.86 ± 0.65	ND
cis-Hept-4-enol	6191–71-5	$C_7H_{14}O$	14.391	0.98 ± 0.33	0.88 ± 0.21	0.86 ± 0.17	0.67 ± 0.25	0.87 ± 0.49
3,7-Dimethyl-1,6-octadien-3-ol	78–70-6	$C_{10}H_{18}O$	15.477	ND	1.17 ± 0.67	1.17 ± 0.88	ND	ND
1-Octanol	111–87-5	$C_8H_{18}O$	15.779	2.23 ± 1.02	ND	ND	2.05 ± 0.64	2.22 ± 0.55
Dimethylsilanediol	1066–42-8	$C_2H_8O_2Si$	18.066	2.91 ± 0.76	3.34 ± 0.45	2.76 ± 1.23	3.77 ± 0.94	3.39 ± 0.36
3-Cyclohexene-1-ethanol	18240–10-3	$C_8H_{14}O$	18.455	2.05 ± 0.48	ND	0.65 ± 0.24	ND	ND
3-(Methylthio)-1-propanol	505–10-2	$C_4H_{10}OS$	18.888	0.59 ± 0.38	ND	0.52 ± 0.46	0.53 ± 0.21	1.45 ± 0.33
Benzyl alcohol	100–51-6	C_7H_8O	21.067	ND	1.47 ± 0.55	ND	1.68 ± 0.26	1.19 ± 0.43
Phenylethyl alcohol	1960–12-8	$C_8H_{10}O$	21.476	1.34 ± 0.66	1.21 ± 0.54	1.63 ± 0.31	1.55 ± 0.47	1.62 ± 0.58
Aldehydes(9)								
Valeraldehyde	110–62-3	$C_5H_{10}O$	2.705	2.21 ± 0.22	1.52 ± 0.67	1.56 ± 0.35	1.56 ± 0.83	1.80 ± 0.59
Hexanal	66–25-1	$C_6H_{12}O$	3.689	4.45 ± 0.43	3.42 ± 0.87	3.18 ± 0.45	2.97 ± 0.56	2.88 ± 0.78
Heptanal	111–71-7	$C_7H_{14}O$	6.031	2.32 ± 0.44	3.67 ± 0.52	3.81 ± 0.55	3.15 ± 1.30	3.10 ± 0.59
Octanal	124–13-0	$C_8H_{16}O$	8.688	1.44 ± 0.32	2.01 ± 0.67	2.24 ± 0.59	2.21 ± 1.04	2.33 ± 0.78
Benzeneacetaldehyde	144164-15-8	$C_{10}H_{12}O$	10.711	1.56 ± 0.69	1.59 ± 1.04	1.68 ± 0.67	1.99 ± 0.03	1.84 ± 0.27
Nonanal	124–19-6	$C_9H_{18}O$	11.382	1.24 ± 0.55	1.34 ± 0.64	1.11 ± 0.26	1.64 ± 0.87	2.01 ± 0.93
Benzaldehyde	100–52-7	C_7H_6O	14.322	2.11 ± 0.37	3.61 ± 1.04	3.69 ± 0.32	3.71 ± 0.56	4.01 ± 1.23
Decanal	112–31-2	$C_{10}H_{20}O$	14.825	1.56 ± 0.88	0.59 ± 0.31	0.68 ± 0.22	0.79 ± 0.43	0.84 ± 9.54
Piperonal	120–57-0	$C_8H_6O_3$	24.661	1.57 ± 0.22	1.02 ± 0.35	1.62 ± 0.65	1.76 ± 0.44	1.30 ± 0.56
Ketones (6)								
2,3-Butanedione	431–03-8	$C_4H_6O_2$	2.181	1.00 ± 0.36	ND	1.50 ± 0.44	ND	2.19 ± 0.87
2,3-Pentanedione	600–14-6	$C_5H_8O_2$	3.345	1.11 ± 0.43	1.51 ± 0.41	1.43 ± 0.78	3.72 ± 0.64	1.24 ± 0.34
2-Heptanone	110–43-0	$C_7H_{14}O$	5.973	ND	0.87 ± 0.29	1.96 ± 1.05	1.66 ± 0.47	3.67 ± 0.33
Acetoin	513–86-0	$C_4H_8O_2$	8.502	ND	ND	0.60 ± 0.23	ND	1.30 ± 0.87
3-Hydroxy-2-butanone	513–86-0	$C_4H_8O_2$	8.503	2.09 ± 0.39	ND	1.86 ± 0.56	1.38 ± 0.43	ND
3,5-Octadien-2-one	38284–27-4	$C_8H_{12}O$	15.666	0.86 ± 0.89	0.58 ± 0.21	ND	ND	ND
Aromatic (3)								
1-Methyl-4-(1-methylethyl)-benzene	99–87-6	$C_{10}H_{14}$	8.086	2.96 ± 1.42	1.83 ± 0.38	2.55 ± 0.11	3.75 ± 0.55	2.85 ± 0.69
Anethole	104–46-1	$C_{10}H_{12}O$	20.339	1.02 ± 0.55	0.54 ± 0.49	2.57 ± 0.32	ND	0.92 ± 0.37
Indole	120–72-9	C_8H_7N	26.570	1.42 ± 0.49	0.83 ± 0.22	1.33 ± 0.17	1.49 ± 0.19	0.81 ± 0.16
Esters (4)								
n-Caproic acid vinyl ester	3050–69-9	$C_8H_{14}O_2$	9.759	ND	1.31 ± 0.58	ND	ND	1.01 ± 0.33
Ethyl butyrate	105–54-4	C_6HO_2	10.214	2.42 ± 0.47	3.81 ± 1.01	1.82 ± 0.88	2.45 ± 0.36	1.03 ± 0.35
Formic acid, heptyl ester	112–23-2	$C_8H_{16}O_2$	13.245	2.43 ± 0.68	ND	ND	1.04 ± 0.11	1.12 ± 0.58
Dibutyl phthalate	84–74-2	$C_{16}H_{22}O_4$	28.616	ND	1.67 ± 0.33	1.75 ± 0.46	0.88 ± 0.42	0.46 ± 0.10
Hydrocarbons (11)								
3-Carene	13466–78-9	$C_{10}H_{16}$	5.052	1.65 ± 0.52	1.61 ± 0.37	3.79 ± 1.01	ND	ND
D-Limonene	5989–27-5	$C_{10}H_{16}$	6.243	2.83 ± 0.98	2.03 ± 0.23	3.21 ± 0.78	3.76 ± 0.69	3.09 ± 0.49
Styrene	100–42-5	C_8H_8	7.742	2.18 ± 0.89	1.30 ± 0.22	3.75 ± 0.49	ND	ND
(E,E,E)-1,4,8-dodecatriene	24252–85-5	$C_{12}H_{18}$	8.106	1.46 ± 0.76	1.21 ± 0.27	ND	ND	ND
7-Propylidene-bicyclo[4.1.0]heptane	82253–09-6	$C_{10}H_{16}$	8.391	1.29 ± 0.56	1.19 ± 0.49	1.39 ± 0.78	1.17 ± 0.39	1.13 ± 0.25
2,7-Dimethyl-octane	1072–16-8	$C_{10}H_{22}$	9.781	1.62 ± 0.26	ND	ND	ND	3.68 ± 1.05
3,5,5-Trimethyl-2-hexene	26456–76-8	C_9H_{18}	13.934	1.07 ± 0.54	3.72 ± 1.21	1.55 ± 0.69	1.29 ± 0.39	1.9 ± 0.25
Pentadecane	629–62-9	$C_{15}H_{32}$	14.186	ND	ND	ND	1.53 ± 0.66	ND
Caryophyllene	87–44-5	$C_{15}H_{24}$	16.100	3.50 ± 0.48	2.89 ± 0.60	1.86 ± 0.42	2.66 ± 0.38	2.65 ± 0.22
Humulene	6753–98-6	$C_{15}H_{24}$	17.707	ND	ND	0.10 ± 0.04	1.54 ± 0.27	ND
Spiro[2.9]dodeca-4,8-diene	62108–42-3	$C_{12}H_{18}$	18.461	ND	2.79 ± 0.53	ND	2.18 ± 0.67	1.68 ± 0.33
Acids(4)								
2-Octynoic acid	5663–96-7	$C_8H_{12}O_2$	1.678	1.22 ± 0.24	1.53 ± 0.84	ND	ND	1.25 ± 0.33
N-ethyl-amphetamine	72687–64-0	$C_{13}H_{19}NO$	19.644	ND	0.99 ± 0.48	ND	0.95 ± 0.59	1.01 ± 0.39
(p-Hydroxyphenyl)phosphonic acid	33795–18-5	$C_6H_7O_4P$	22.537	1.81 ± 0.68	1.50 ± 0.29	1.62 ± 0.48	1.51 ± 0.76	1.77 ± 0.25
Octanoic acid	124–07-2	$C_8H_{16}O_2$	23.406	0.89 ± 0.46	ND	ND	ND	ND
Heterocyclic compound (5)								
2-Pentylfuran	3777–69-3	$C_9H_{14}O$	7.248	1.84 ± 0.84	2.36 ± 0.58	2.71 ± 0.45	2.49 ± 0.25	3.28 ± 1.43
2,3-Dimethylpyrazine	5910–89-4	$C_6H_8N_2$	10.109	2.45 ± 0.47	2.47 ± 0.28	2.58 ± 1.03	2.59 ± 0.48	2.74 ± 0.29
Trimethylpyrazine	14667–55-1	$C_7H_{10}N_2$	11.635	2.39 ± 0.59	3.01 ± 1.06	2.52 ± 0.59	2.68 ± 0.87	2.70 ± 0.33
2,3-Diethylpyrazine	15707–24-1	$C_8H_{12}N_2$	12.901	1.25 ± 0.37	1.45 ± 0.27	1.58 ± 0.47	1.73 ± 0.39	2.05 ± 0.58
Methoxy-phenyl-acetaldehyde oxime	96301–79-0	$C_9H_{11}NO_2$	19.928	1.58 ± 0.26	1.93 ± 0.67	2.08 ± 1.28	2.23 ± 0.87	1.71 ± 0.39
Others (8)								
Carbamic acid, monoammonium salt	1111–78-0	$CH_6N_2O_2$	0.830	2.28 ± 0.48	2.16 ± 0.27	2.13 ± 0.69	2.58 ± 0.52	1.1 ± 0.38
(S)-l-alanine ethylamide	71773–95-0	$C_5H_{12}N_2O$	0.834	ND	1.31 ± 0.49	ND	ND	ND
Dodecamethylcyclohexasiloxane	540–97-6	$C_{12}H_{36}O_6Si_6$	11.154	ND	ND	ND	1.19 ± 0.25	1.02 ± 0.62
Tetradecamethylcycloheptasiloxane	107–50-6	$C_{14}H_{42}O_7Si_7$	15.459	ND	ND	ND	1.26 ± 0.39	1.28 ± 0.49
2-Acetylthiazole	24295–03-2	C_5H_5NOS	17.424	0.65 ± 0.59	ND	ND	ND	ND
Hexadecamethylcyclooctasiloxane	556–68-3	$C_{16}H_{48}O_8Si_8$	18.956	1.47 ± 1.01	1.65 ± 0.42	1.63 ± 0.74	1.6 ± 0.63	0.64 ± 0.58
N,N-Dibutyl-formamide	761–65-9	$C_9H_{19}NO$	19.640	0.82 ± 0.44	1.76 ± 0.59	1.72 ± 0.24	1.53 ± 0.58	0.42 ± 0.71
1,2-Benzisothiazole	272–16-2	C_7H_5NS	21.856	ND	1.75 ± 0.46	1.92 ± 0.94	ND	1.71 ± 0.29

[a] CAS: Chemical Abstracts Service registry number.
[b] Rt: Retention time in the capillary GC column.

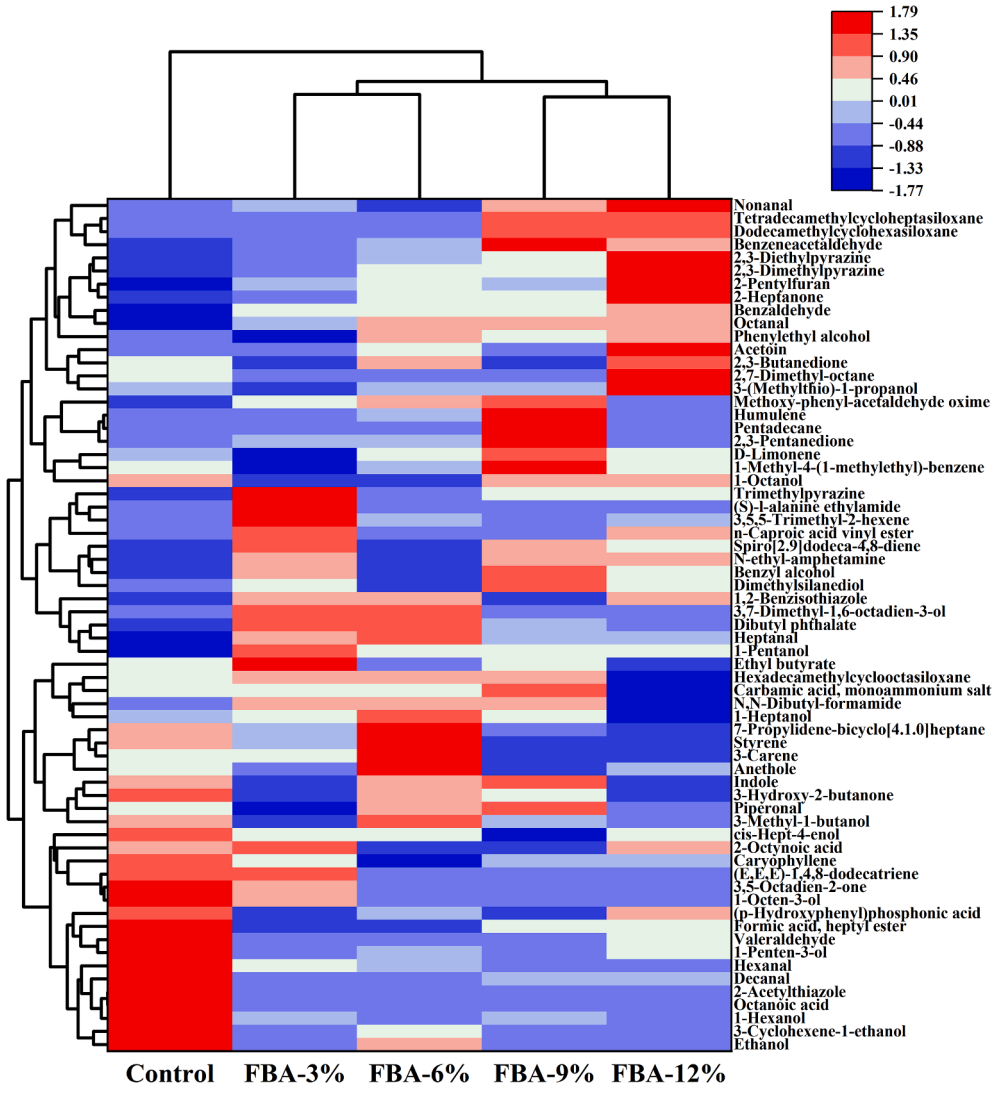

Fig.3. The heat map and clustering results of 65 VOCs of fish balls with different abalone content.

free fatty acids and alcohols, or by transesterification reactions of fatty acids in triglycerides with ethanol (Liu, Holland, & Crow, 2004). Microwaving, steaming, deep-frying and infrared heating reduce the content of esters in fish, which may be related to their low stability, esters readily undergo alcoholysis, aminolysis, ester exchange and reduction reactions under heating conditions, forming other volatile components (Xu et al., 2022). Three other aromatic compounds (1-methyl-4-(1-methylethyl)-benzene, anethole, and indole) were also identified in FBA at levels ranging from 2.11 to 7.06 %. These compounds are produced by catabolic transamination of the aromatic amino acids, tryptophan, phenylalanine and tyrosine (Giri, Osako, & Ohshima, 2010). 2-Pentylfuran, an important flavour compound in protein-based products, with a desirable sweet, meaty and caramelized flavour, can be produced by Maillard reactions between amino acids and reducing sugars and by lipid oxidation (Zhang et al., 2018). The acids contained in FBA were 2-octynoic acid, N-ethyl-amphetamine, (*p*-hydroxyphenyl) phosphonic acid and octanoic acid, and there was little overall variation in relative content with abalone addition. The acids may be hydrolysis products of triglycerides and phospholipids, or they may be produced by oxidation of alcohols and aldehydes. Three pyrazine derivatives were detected in FBA, namely 2,3-dimethylpyrazine, trimethylpyrazine, and 2,3-diethylpyrazine, with a total content of 4.68–8.69 %. Pyrazines are mainly produced by a Maillard reaction of α-amino ketones, they are highly odor-active, producing a high olfactory impact at very low concentrations, giving a pleasant aroma to the food, usually with a nutty, steamed or grilled flavour (Zhu et al., 2021).

3.8. Correlation analysis of electric nose and HS-SPME-GC–MS

Clarifying the relationship between the abundance of VOCs and the intensities of E-nose sensors can be used to evaluate the feasibility of using electronic noses for distinguishing VOCs in HS-SPME-GC–MS of FBA. Pearson's correlation analysis was performed between the top five volatile compounds by relative content from HS-SPME-GC–MS analysis of each sample and the response values of the 10 E-nose sensors (Shi et al., 2020; Zhang et al., 2021) (Fig. 4A).

The sensor responses of W1C, W3C and W5C were positively correlated with 1-methyl-4-(1-methylethyl)benzene and negatively correlated with 1-pentanol, heptanal, 2-heptanone and 3,5,5-trimethyl-2-hexene content. W1W and W2S were positively correlated with 1-

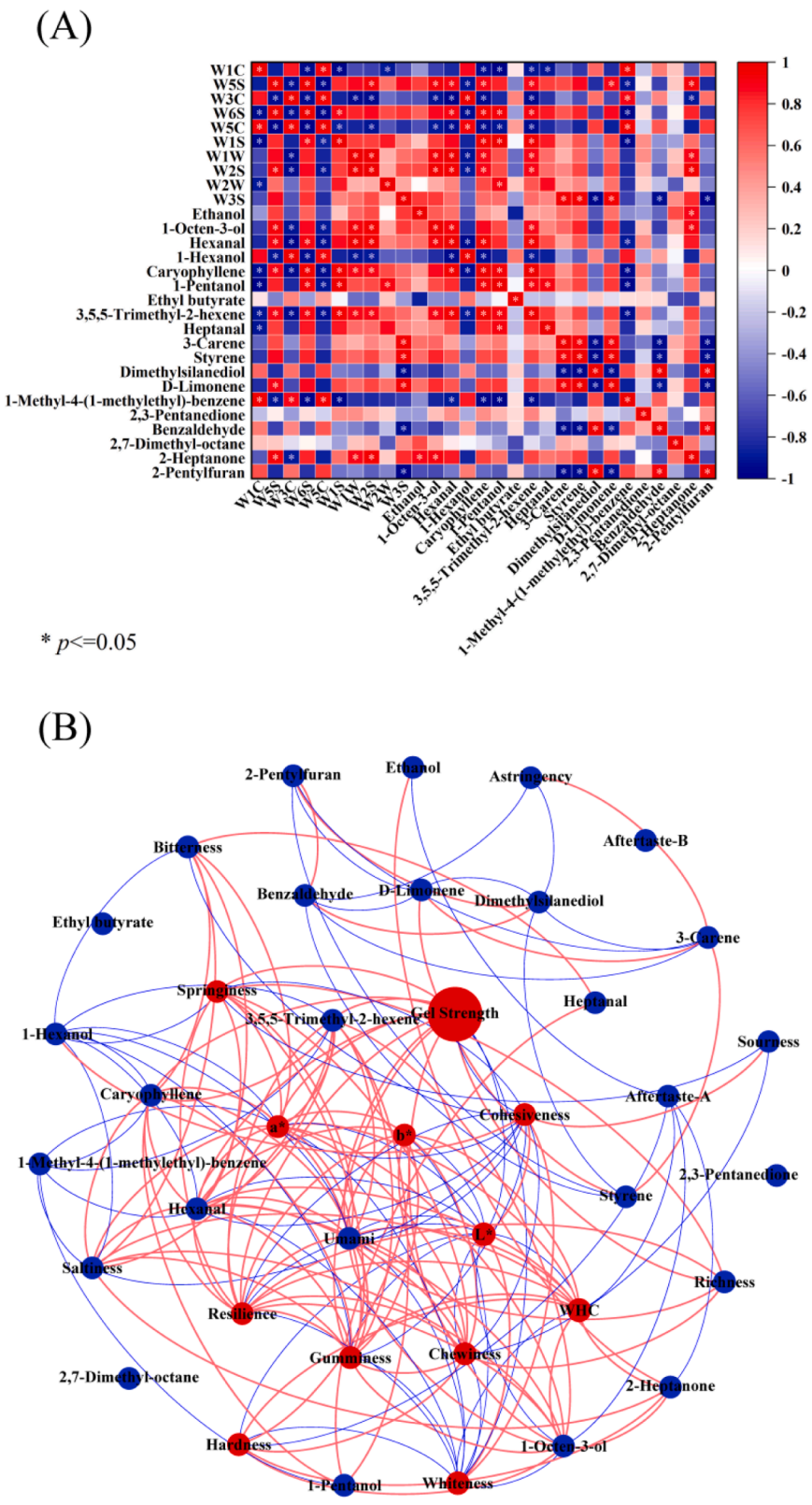

Fig.4. (A) Pearson correlation diagram between E-nose and main VOCs. (B) The association network diagram between quality properties and sensory properties. The red and blue circles represented quality properties and sensory properties, respectively. The red and blue lines represented positive and negative correlations, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

octen-3-ol, hexanal, caryophyllene, and 3,5,5-trimethyl-2-hexene content. W3S was positively correlated with styrene, 3-carene, and d-limonene, and negatively correlated with 2-pentylfuran, dimethylsilanediol, 1-methyl-4-(1-methylethyl)-benzene and benzaldehyde. The volatiles detected by W1C, W3C, W5C, W1W, W2S and W3S were in general agreement with their specifications, i.e., the electronic nose mainly detected alkanes, alcohols, aldehydes, ketones, and aromatic volatiles ($r \geq 0.80$, $p < 0.05$). The significant correlation between the characteristic FBA volatiles and the sensor signals indicated that the E-nose distinguished between the volatile compounds in FBA.

3.9. Correlation analysis of quality properties and sensory properties

For the purpose of in-depth investigation of correlation between quality and sensory properties of FBA, Pearson's analysis was performed and then Gephi software was used to generate a association network diagram (Fig. 4B). It can be been seen that hexanal, and caryophyllene were positively correlated with a^* values, and 1-pentanol, and hexanal were positively correlated with b^* values. This may be due to the fact that during lipid oxidation, unsaturated fatty acids are initially oxidised to form hydroperoxides catalysed by high temperatures, and alkoxy radicals are homolysed, which are readily degraded to many VOCs such as aldehydes, alcohols and alkanes(Varlet, Prost, & Serot, 2007). Gel strength was positively associated with hardness, springiness, gumminess, chewiness and resilience, and negatively asscociated with cohesiveness, which was consistent with the previous results of TPA. Saltiness was positively related with indicators such as 2-heptanone, gumminess, chewing, and a^*, while negatively related with cohesiveness, 1-hexanol and 1-methyl-4-(1-methylethyl)-benzene. Umami and 1-octen-3-ol can serve as important indicators to observe changes in the quality of FBA, as they were positively connected with WHC, gumminess, chewiness, resilience, a^*, hexanal, etc. Therefore, the relationship between the quality properties and sensory characteristics of FBA can be used to provide theoretical references for quality control, flavour prediction and indicators testing of innovative industrial surimi products.

Conclusion

The results showed that addition of 9 % w/w abalone resulted in the best overall quality, increasing the WHC to 93.90 %, the gel strength to 2509.86 g*mm, the hardness 30.71 N and the springiness to 0.83, and reducing the whiteness to 60.76 ($p < 0.05$). E-nose analysis suggested the change of abalone addition obviously affected the sulfur, alcohol and alkanes compounds of FBA. The E-tongue showed an increase in the freshness, saltiness, richness and bitterness of FBA, with increased abalone addition ($p < 0.05$). HS-SPME-GC–MS identified 65 VOCs, mainly alcohols (20.91–33.44 %), alkanes (13.44–26.58 %) and aldehydes (10.68–20.59 %), the contents of 1-octen-3-ol and hexanal decreased with increased abalone addition ($p < 0.05$), thereby reducing the fishy flavour of FBA. Pearson analysis demonstrated that the E-nose sensor responses, W1C, W3C, W5C, W1W, W2S and W3S were positively correlated with key VOCs, indicating that the E-nose can distinguish different VOCs in FBA. Meanwhile, a high correlation can be established between quality properties and sensory properties, such as umami and 1-octen-3-ol, which can be used to observe indicators including WHC, gumminess and b^*, etc. These findings provide a theoretical basis for the development of new surimi products.

CRediT authorship contribution statement

Shuyi You: Data curation, Formal analysis, Methodology, Writing – original draft. **Yan Tian:** Investigation, Methodology. **Wenqi Zhang:** Investigation, Methodology. **Baodong Zheng:** Supervision, Visualization. **Yi Zhang:** Conceptualization, Writing – review & editing. **Hongliang Zeng:** Formal analysis, Funding acquisition, Supervision, Writing – review & editing.

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.

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