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Research Article

A Study on the Formation and Change of Yesso Scallop Odor Characteristics by GC-O-MS, Sensory Evaluation, and Flavor-Precursor Analysis

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Scallops are exposed to drying and hypoxia for a long duration in the supply chain, leading to quality deterioration and changes in odor characteristics. In this study, quality deterioration of Yesso scallop was simulated under different conditions to explore the formation and change of its unique aroma. Its volatile components were analyzed by partial least squares (PLS) regression, GC-O, and smell threshold, and its odor characteristics were analyzed with reference to flavor precursors. The sensory descriptors selected comprehensively described the odor characteristics of Yesso scallop. The 16 most relevant volatile components for each odor characteristic were identified, and a new star-mark grading method was established to evaluate the role of volatile components in the formation of odor characteristics. The possible odor precursors were determined, providing preliminary information on the generation of pleasant and unpleasant odor characteristics by Yesso scallops. Thus, our results provide a scientific basis for the further study and control of the odor characteristics of aquatic products.

1. Introduction

Yesso scallops (*Mizuhopecten yessoensis*) are one of the most important economic shellfish in China's aquaculture industry and naturally distribute along the coastlines of the Far East of Russia, northern Japan, and the northern part of the Korean Peninsula. As one of the major cultured shellfish groups, Yesso scallops provide abundant minerals, essential amino acids, and high-quality protein in addition to its characteristic flavor, making it highly attractive to customers [1].

Fresh live Yesso scallops have a faint smell of seafood and develop a strong unique flavor during the cooking process. However, scallops are exposed to drying and hypoxia for a long duration in the supply chain, leading to quality deterioration and changes in odor characteristics; specifically, the pleasant odor characteristics of cooked scallops are lost, while their unpleasant odor characteristics increase. Several studies have been conducted to evaluate the effects of environmental stress (dryness, hypoxia, and air exposure) on the immune system of scallops; these studies indicate that environmental stress influence the activity of scallops, which may cause changes in odors [2].

At present, research on the mechanisms by which the aromas of aquatic products form and change is mainly focused on the application of GC-MS or GC-O in combination with sensory evaluation, flavor precursor determination, and other technical means to analyze their volatile components [3]. The volatile components of Yesso scallops are mainly aldehydes, ketones, alcohols, aromatics, and sulfur-containing compounds, as well as many other small-molecule compounds [4]. By establishing a reliable sensory analysis method, the quantitative sensory evaluation results can be used for chemometric analysis along with instrumental measurements of various physical and chemical indicators of scallops, including volatile components [5].

The formation of unpleasant odors from animal-origin food is mainly due to degradation by endogenous enzymes or microorganisms, oxidation of lipids and fatty acids, diet, and environmental pollution. For example, the lipids of aquatic products are easy to oxidize during processing and storage, generate hydroperoxides, and then decompose into small molecules such as aldehydes and ketones, thus leading to changes in the flavor, texture, and color of aquatic products [6]. The components produced by different formation mechanisms are also different and are related to the type and content of flavor precursors in food raw materials [7]. Water-soluble flavor precursors, such as free amino acids, free fatty acids, and reducing sugars, have been identified [8]. These flavor precursors produce various flavor substances under the action of microorganisms, enzymes, oxygenation, and the Maillard reaction [9]. Changes of flavor precursors lead to changes in food flavor.

In this study, the odor characteristics of Yesso scallops were divided into pleasant and unpleasant odors, and the volatile components mostly related to these two odor characteristics were identified. Then, the correlation, GC-O smell, and odor threshold were combined to establish a standard star-mark method to further classify the volatile components. Finally, on the basis of the abovementioned results, two types of possible flavor precursors were analyzed to complete a preliminary exploration of the mechanisms by which odor characteristics form and change upon quality deterioration in the supply chain. The results provide a scientific basis for further research into flavor loss and flavor-precursor removal, as well as a method for studying the odor characteristics of aquatic products.

2. Materials and Methods

2.1. Sample Treatment. At 5:00 am in Huangsha Port, Sheyang County, Yancheng City, Jiangsu Province, China, 100 live scallops, 8–10 cm in size, were purchased and transported to the laboratory in crushed ice. Among them, 25 scallops (adductor muscle and main edible parts) were taken for immediate treatment and analysis (alive in excellent condition) and 25 scallops were taken for analysis after steaming (cooked in excellent condition). The remaining 50 were subjected to simulated environmental stress. After dry exposure (anoxic) was placed at room temperature (~25°C on average) for 24 h, 25 shellfish columns were taken for direct analysis (alive in poor condition) and 25 shellfish columns were taken for analysis after steaming (cooked in poor condition).

2.2. Quantitative Description of Sensory Analysis. We referred to the Chinese National Standard (GB/T 16291 Sensory Analysis-General Guidance for Selection, Training, and Monitoring of Assessors) to establish, select, and train sensory teams. With reference to the sensory descriptors of scallops, which were established by Yang et al. [10], the sensory team finally selected six odor descriptors, among which "stench," "earthy-musty," and "sulfur" described unpleasant odors, while "scallop aroma," "cooked meat," and "potato mud" described pleasant odors, as shown in Table 1.

After training, the sensory team analyzed the sensory characteristics of scallops in different conditions using the quantitative description analysis method, and scored each sensory description quantitatively by formulating olfactory reference materials. For example, the scale for quantitative description and analysis of "stench" with reference materials is shown in Figure 1.

2.3. Analysis of Volatile Components. The eluent from the GC capillary tube flows into the MS unit and olfactometer, respectively, at a 1 : 1 split ratio for qualitative, relative quantitative, and olfactory analysis of volatile components. The specific methods were as follows:

2.3.1. Qualitative and Quantitative Analysis of GC-MS Volatile Components. The method outlined in the study by Wu et al. [11] was used to analyze the volatile components of the scallop column samples. The equipment used were an Agilent 7890A gas chromatography-mass spectrometer, a MonoTrap RCC18 was used as the solid phase extraction integral collector, and 2,4,6-trimethylpyridine was used as the internal standard. For qualitative analysis, the volatile components were qualitatively determined with reference to the NIST and Wiley spectral libraries, and only the results with positive and negative matching degrees greater than 800 (the maximum value is 1000) were reported. For relative quantitative analysis, 2,4,6-trimethylpyridine was added as an internal standard before sample adsorption, and the relative content of each volatile odor substance was calculated.

2.3.2. GC-O Analysis of the Odor Characteristics of Volatile Components. Using a Gerstel ODP-2 olfactometer, GC-O olfactory testing was conducted by sensory team members. Each sample was smelled once by each team member, and the odor characteristics and retention time for each volatile component were recorded. The odor characteristics were limited to the six sensory descriptors described above. At least two sensory officials had to identify the same odor characteristic at the same retention time before recording it as a valid result [12, 13].

2.4. Analysis of Odor Precursors

2.4.1. Determination of Free Amino Acids by HPLC. With reference to the Chinese National Standard GB/T 30987-2020, the method for determination of free amino acids was performed using an Agilent 1260 high-performance liquid chromatography instrument.

Free amino acid content was calculated using the following formula:

$$\mathbf{W} = \frac{(\mathbf{C} - \mathbf{C_0}) \times \mathbf{V} \times \mathbf{N}}{\mathbf{m}}, \tag{1}$$

where W is the target free amino acid content in the sample (mg/kg), C is the concentration of the target substance in the sample determination solution (mg/L), C_0 is the

Table 1: Descriptors of sensory analysis for the quantitative description of scallops.

No.	Sensory descriptors	Odor description
1	Stench	The fishy bad smell of aquatic products
2	Earthy-musty	Moldy soil smell of quality deteriorated scallops
3	Sulfur	Bad pungent smell
4	Scallop aroma	Unique pleasant smell of scallops
5	Cooked meat	Aroma of cooked meat
6	Potato mud	Aroma of mashed potatoes

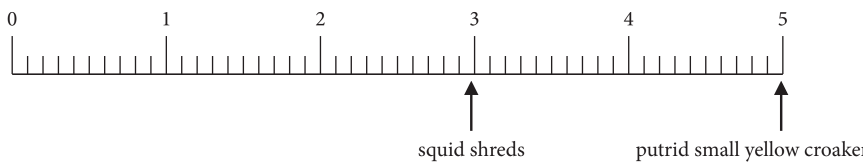


Figure 1: Quantitative description analysis diagram for "stench."

concentration of the target substance in the blank control (mg/L), V is the sample volume (mL), N is the dilution ratio, and M is the sample quantity (g).

2.4.2. Determination of Free Fatty Acids by GC-MS. Free fatty acids were determined using the methods of Honicky et al. [14] and Sims et al. [15] using an Agilent 7890A gas chromatography-mass spectrometer [14, 15].

Free fatty acid content was calculated using the following formula:

$$\mathbf{W} = \frac{(\mathbf{C} - \mathbf{C_0}) \times \mathbf{V} \times \mathbf{N}}{\mathbf{m}} \times k \times 10^{-4}, \quad (2)$$

where W is the content of free fatty acids in the sample (g/100 g), C is the concentration of fatty acid methyl ester in the sample determination solution (mg/L), C_0 is the concentration of the target substance in the blank control (μg/L), V is the constant volume (mL), K is the conversion coefficient of fatty acid methyl ester to fatty acid, N is the dilution ratio, 10^{-4} is the unit conversion factor, and M is the sample weight (g).

2.5. Data Analysis. Quantitative description of sensory analysis and GC-MS instrument analyses results were analyzed by partial least squares regression (PLSR). Six PLSR analyses were performed for six sensory descriptors, using quantitative results of sensory description as the dependent variable, and relative content of each volatile component as the independent variable. Mintab 14.0 software was used for data analysis. Quantitative results of sensory description were made into a radar chart for better observation.

According to the PLSR standardization coefficient and load result analysis, the 16 most relevant volatile components were selected for each descriptor.

Then, the 16 volatile components mostly related to each descriptor was star rated, combined with the correlation with GC-O odor description and the size of the olfactory threshold. The number of asterisks obtained is used to grade each volatile component in degrees.

3. Results and Discussion

3.1. Quantitative Description and Analysis of Odor Characteristic Changes. In order to determine the formation and change mechanisms of the scallop odor characteristics, they were divided into pleasant and unpleasant odors.

The sensory team described the pleasant odor characteristics of scallops as "scallop aroma," "cooked meat," and "potato mud." The basic attributes of scallops are those of a meat product, so the basic odor of scallops is expressed as the aroma of cooked meat. Unlike animal meat, the aroma of scallops is lightly sweet but not greasy, supplemented by the flavor of mashed potato. Furthermore, scallops have a unique scallop aroma. The abovementioned three odor descriptors comprehensively describe the pleasant odor characteristics of scallops. It can be seen from the sensory analysis results (Figure 2) that the pleasant odor scores of samples in the poor alive condition are generally at a low level, while the scallop aroma score for samples in the excellent alive condition is relatively high, but drops rapidly upon quality deterioration. The quality deterioration has little effect on the "cooked meat" and "potato mud" characteristics of the live samples. After cooking, the pleasant odor characteristics of scallops in both poor and excellent conditions improve compared with those for the alive samples in the same state. After quality deterioration, the scallop aroma and cooked meat scores decrease rapidly, and the potato mud score decreases slightly.

The sensory team described the unpleasant odor characteristics as "stench," "earthy-musty," and "sulfur." Stench is a typical smell of seafood products after quality degradation. Sulfur is used to describe the pungent odor. The scallops after quality degradation also produce an unpleasant bad smell similar to that of moldy soil. These three descriptors comprehensively describe the characteristics of the unpleasant odor of scallops. According to the sensory analysis results (Figure 2), the unpleasant odor score of samples increases rapidly with the decline in quality, while the earthy-musty score increases slightly, and the sulfur score shows little change. The stench score of samples in poor condition decreases slightly after being cooked, and the

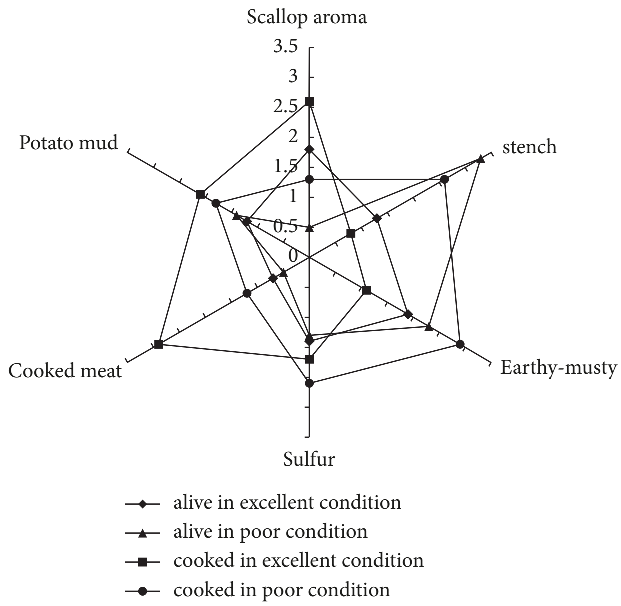


Figure 2: Radar chart of the sensory analysis results for odor characteristics of Yesso scallops under different conditions.

earthy-musty and sulfur scores increase significantly. After the scallops in excellent condition are cooked, the unpleasant odor characteristics are generally maintained at a low level, the stench and earthy-musty scores are decreased, and the sulfur score is increased.

In general, the sensory evaluation results for samples in different conditions are comparable to a certain extent. The quantitative results for different descriptors are somewhat inconsistent, so they were qualified by the correlation analysis with the results of the volatile component analysis.

3.2. Analysis and Comparison of Volatile Components for Yesso Scallops in Different Conditions. The volatile components of scallop samples for the four different conditions were detected, and the results are shown in Figure 3 and Table 2. Seventy-eight volatile compounds were identified from scallop samples in the four states, including 10 sulfur compounds labeled A1–A10, 17 hydrocarbons labeled B1–B17, five amines labeled C1–C5, 15 heterocyclic compounds labeled D1–D15, 14 aromatic compounds labeled E1–E14, seven alcohols labeled F1–F7, three ketones labeled G1–G3, and seven aldehydes labeled H1–H7.

The relative contents of sulfur compounds increase as a whole after cooking. High concentrations of sulfur compounds generally generate a pungent smell, but some sulfur compounds provide good flavor characteristics at low concentrations [17], such as a pleasant crab-like flavor. Sulfur compounds participate in the formation of the flavor of scallops after cooking. Nitrogen compounds are important flavor compounds in aquatic products, such as trimethylamine, which is an important fishy substance in aquatic products, and one of the indicators for evaluating the freshness of aquatic products [18]. It is generally believed that alcohols and alkanes have high odor thresholds and make little contribution to the formation of scallop flavor, but alkenes can act as precursors of aldehydes, ketones, and other compounds and are potential flavor compounds [19]. The low threshold value of aldehydes has an important influence on the odor characteristics of the scallop. The heterocyclic compounds of cooked scallop samples increase as a whole. Specifically, some pyrazine and furan compounds with barbecue-like flavors participate in the formation of cooked scallop aroma [20].

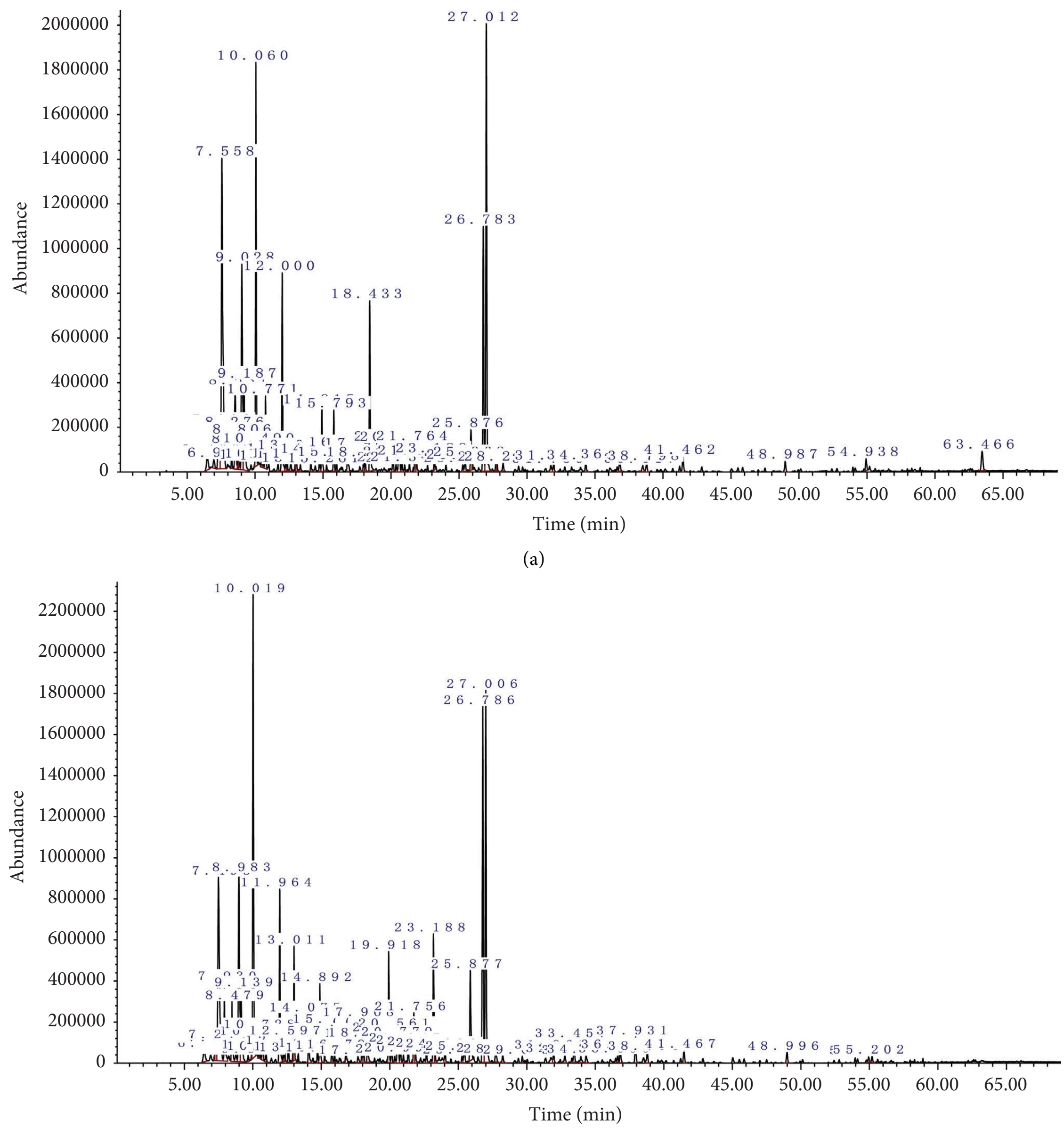
3.3. Correlation Analysis between Sensory Evaluation and Volatile Component Results. The results of sensory quantitative description analysis and volatile component quantitative analysis were analyzed by partial least square regression. First, all 78 volatile components were analyzed and six PLSR models were established. The R^2 values of all six models were greater than 0.7907 (stench), with a maximum value of 0.9621 (cooked meat). PLSR models of pleasant odors were significantly higher than unpleasant odors. These models can be used for correlation ranking of volatile components, not be used for predicting sensory characteristics.

According to the PLRS standardization coefficient and load result analysis (as shown in Figures 4 and 5), the 16 most relevant volatile components were selected for each descriptor, without considering the interaction between volatile components and only analyzing the role of individual volatile components in the formation of odor characteristics. Furthermore, with the 16 most relevant volatile components selected as the independent variable, six PLSR models were established. The R^2 value of all 6 models were greater than 0.9508 (sulfur flavor), indicating that the model can well reflect the correlation between sensory characteristics and volatile odor components.

At the same time, considering the accuracy and difficulty of quantifying GC-O results, a new standard star-marking method was used to further evaluate the role of each volatile component in the formation of odor characteristics. Based on the 16 volatile components, most related to each descriptor obtained by partial least squares regression and combined with the correlation with GC-O odor description and the size of the olfactory threshold, each volatile component was star rated. The number of asterisks obtained is used to grade each volatile component in degrees. The specific method is shown in Tables 3 and 4.

3.3.1. Analysis of Volatile Components Most Related to Unpleasant Odor Characteristics. The analysis results for the most relevant volatile components for "stench" are shown in Table 3, including one 4-star component (octanal), two 3-star components (trimethylamine and 2-methylbutyraldehyde), four 2-star components (dimethyl sulfide, 1-hydroxy-2-acetone, nonaldehyde, and 3-octanone), two 1-star components (2-methylnaphthalene and decane), and seven 0-star components (heptane, cyclohexene, 1,3-octadiene, isopropylamine, 2-butylthiophene, styrene, and cyclohexanol).

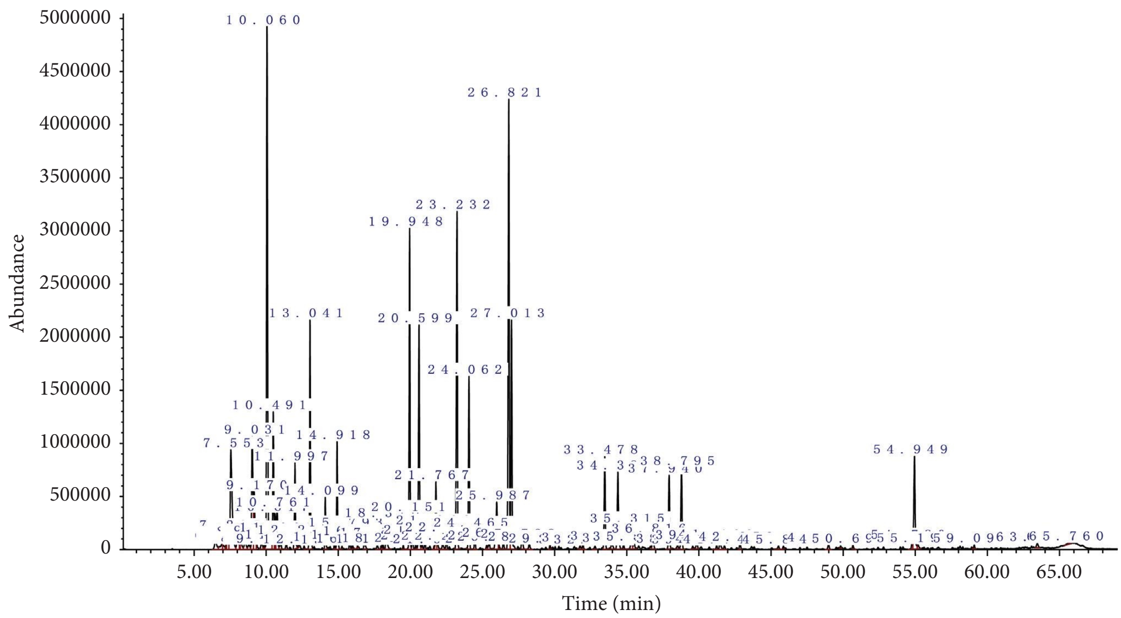
Among the most relevant volatile components for "earthy-musty," there are three 4-star components (methyl



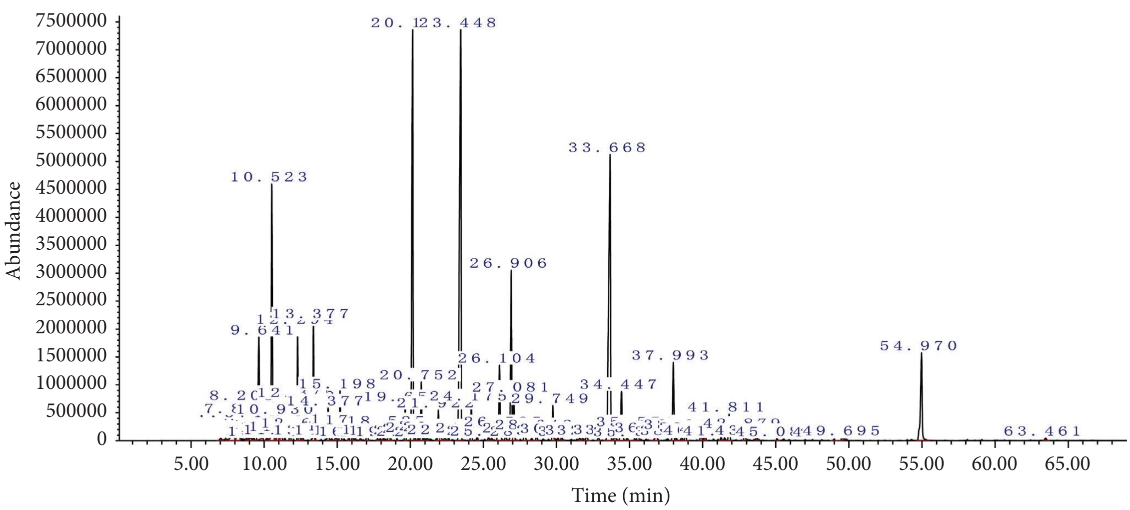
(a)

(b)

Figure 3: Continued.



(c)



(d)

Figure 3: GC-MS total ion current diagram for the volatile components of Yesso scallops in different conditions: (a) alive in excellent condition, (b) alive in poor condition, (c) cooked in excellent condition, and (d) cooked in poor condition.

mercaptan, decanal, and 2-methylbutyraldehyde), four 3-star components (3-octone, methylallyl disulfide, octanal, and nonaldehyde), two 2-star components (n-propylmercaptan and trimethylamine), one 1-star component (toluene), and six 0-star components (carbonyl sulfur, heptane, cyclohexene, 2-butylthiophene, n-pentanol, and cyclohexanol).

Among the most relevant volatile components for "sulfur," there is one 4-star component (methyl mercaptan), four 3-star components (methyl allyl disulfide, 2-methylbutyraldehyde, n-propylmercaptan, and octanal), two 2-star components (carbonyl sulfur and toluene), three 1-star components (dimethyl sulfoxide, heptane, and butyl benzene), and six 0-star components (octane, 1,4-diethyl-benzene, pentylbenzene, hexylbenzene, n-pentanol, and cyclohexanol).

3.3.2. Analysis of Volatile Components Most Related to Pleasant Odor Characteristics. The analysis results for the most relevant volatile components for "scallop aroma" are shown in Table 4, among which there are no 4-star, 3-star, and 2-star components, seven 1-star components (diallyl sulfide, 2-ethylpyridine, 1,4-dimethylbenzene, 1-penten-3-ol, diallyl disulfide, trichloromethane, and thiophene), and nine 0-star components (3-methyl-pentane, 1,2-dimethylhydrazine, urea, methylcyclothioethane, pyridine, 1,4-diethyl-benzene, 2,2-oxodiethanol, 2-octyne-1-ol, and 2,3-dimercaptopropanol).

Among the most relevant volatile components for "cooked meat," there are no 4-star components, three 3-star components (2-ethylfuran, 2,3,5-trimethylpyrazine, and 2-pentyl furan), three 2-star components (2,5-dimethylpyrazine,

Table 2: Comparison of volatile components in Yesso scallops in different conditions.

Name of compounds	Label	Threshold (μg/kg) [16]	Alive		Cooked		Odor description (GC-O)
			Excellent	Poor	Excellent	Poor	
Dimethyl sulfide	A1	0.12	0.171 ± 0.081	0.223 ± 0.067	0.112 ± 0.012	0.178 ± 0.023	Sulfur
Dimethyl trisulfide	A2	0.005	N.D	N.D	1.642 ± 0.143	0.929 ± 0.089	Sulfur, earthy-musty
Diallyl sulfide	A3	100	N.D	N.D	3.084 ± 0.621	0.244 ± 0.073	Sulfur
Diallyl disulfide	A4	30	N.D	N.D	3.648 ± 0.534	0.066 ± 0.016	Sulfur
Allyl methyl sulfide	A5	—	0.042 ± 0.011	0.132 ± 0.027	1.553 ± 0.122	0.226 ± 0.062	Sulfur
Methylallyl disulfide	A6	6.3	0.041 ± 0.008	N.D	0.058 ± 0.031	0.382 ± 0.084	Sulfur, earthy-musty
Carbonyl sulfide	A7	—	0.031 ± 0.010	0.044 ± 0.017	0.063 ± 0.019	0.077 ± 0.020	—
Dimethyl sulfoxide	A8	—	N.D	N.D	0.088 ± 0.023	0.097 ± 0.031	—
Methyl mercaptan	A9	0.2	N.D	N.D	N.D	0.043 ± 0.009	Sulfur, earthy-musty
N-propyl mercaptan	A10	3.1	N.D	0.044 ± 0.011	0.243 ± 0.065	0.451 ± 0.093	Sulfur
1,3-Pentadiene	B1	2500	0.044 ± 0.012	0.038 ± 0.014	N.D	0.019 ± 0.008	—
3-Methyl-pentane	B2	—	0.062 ± 0.021	0.057 ± 0.018	0.065 ± 0.009	0.017 ± 0.015	—
Hexane	B3	—	2.248 ± 0.834	2.096 ± 0.239	0.122 ± 0.013	1.166 ± 0.331	—
Trichloromethane	B4	90	0.346 ± 0.113	0.147 ± 0.067	0.174 ± 0.091	0.085 ± 0.027	—
Methylcyclopentane	B5	—	0.077 ± 0.019	0.052 ± 0.017	0.021 ± 0.009	0.019 ± 0.010	—
Heptane	B6	50000	N.D	0.011 ± 0.002	N.D	0.015 ± 0.008	—
Cyclohexene	B7	—	0.018 ± 0.007	0.051 ± 0.016	N.D	0.049 ± 0.012	—
Decane	B8	—	0.012 ± 0.002	0.085 ± 0.026	N.D	0.022 ± 0.005	Stench
1,3-Octadiene	B9	5600	0.192 ± 0.077	0.245 ± 0.101	0.089 ± 0.024	0.176 ± 0.075	—
Octane	B10	—	0.018 ± 0.004	0.035 ± 0.016	0.061 ± 0.031	0.058 ± 0.028	—
2,4-Octadiene	B11	20000	0.011 ± 0.008	0.032 ± 0.013	N.D	N.D	—
1,3,6-Octtriene	B12	—	0.021 ± 0.005	0.031 ± 0.017	N.D	N.D	—
1,3-Trans-5-mes-octotriene	B13	—	0.033 ± 0.009	0.182 ± 0.023	N.D	N.D	—
1-Vinyl-3-ethylene-cyclopentene	B14	—	0.013 ± 0.005	0.026 ± 0.002	N.D	N.D	—
2-Methylpropene	B15	—	N.D	N.D	0.036 ± 0.012	0.019 ± 0.003	—
1,2-Dimethyl-1,4-cyclohexadiene	B16	—	0.023 ± 0.011	0.114 ± 0.057	N.D	N.D	—
1,5-Dimethyl-1,4-cyclohexadiene	B17	—	0.031 ± 0.014	0.018 ± 0.006	N.D	N.D	—
Trimethylamine	C1	8~2.4	0.184 ± 0.055	1.138 ± 0.206	0.291 ± 0.034	1.166 ± 0.405	Stench
Isopropylamine	C2	5000	0.015 ± 0.008	0.049 ± 0.022	0.021 ± 0.011	0.016 ± 0.009	—
Oxalazide	C3	—	N.D	N.D	0.889 ± 0.312	0.213 ± 0.067	—
1,2-Dimethylhydrazine	C4	—	0.014 ± 0.007	N.D	N.D	N.D	—
Urea	C5	—	0.021 ± 0.011	N.D	N.D	N.D	—
Methylcyclothioethane	D1	—	N.D	0.045 ± 0.024	3.123 ± 0.602	0.055 ± 0.032	—
Thiophene	D2	84	0.024 ± 0.010	0.018 ± 0.005	0.113 ± 0.083	0.022 ± 0.009	—
Pyridine	D3	2000	0.010 ± 0.004	N.D	0.076 ± 0.029	0.028 ± 0.010	—
Isothiazole	D4	38	N.D	0.011 ± 0.003	0.542 ± 0.102	0.144 ± 0.089	—
2,5-Dimethylpyrazine	D5	1750	N.D	N.D	0.632 ± 0.208	0.187 ± 0.073	Cooked meat
2-Acetylthiazole	D6	3	0.011 ± 0.005	0.017 ± 0.003	0.065 ± 0.016	0.023 ± 0.008	—
1,3-Dithiane	D7	—	N.D	0.150 ± 0.085	2.847 ± 0.326	1.134 ± 0.098	—
2,3,5-Trimethylpyrazine	D8	23	N.D	N.D	0.085 ± 0.051	0.034 ± 0.011	Cooked meat
2-Ethylthiophene	D9	10	N.D	N.D	0.039 ± 0.019	0.029 ± 0.012	—
2-Butylthiophene	D10	—	0.014 ± 0.006	0.034 ± 0.009	0.021 ± 0.008	0.037 ± 0.012	—

Table 2: Continued.

Name of compounds	Label	Threshold (μg/kg) [16]	Alive		Cooked		Odor description (GC-O)
			Excellent	Poor	Excellent	Poor	
2-Acetyl-2-thiazoline	D11	0.12	N.D	N.D	0.142 ± 0.048	0.045 ± 0.013	Potato mud
3 - (2-butenyl) - thiophene	D12	—	0.076 ± 0.014	0.024 ± 0.009	N.D	N.D	—
2-Ethylpyridine	D13	—	0.012 ± 0.006	0.016 ± 0.007	0.083 ± 0.018	0.028 ± 0.009	Potato mud
2-Ethylfuran	D14	2.3	N.D	N.D	0.393 ± 0.095	0.126 ± 0.074	Cooked meat
2-Amylfuran	D15	5.8	N.D	N.D	0.467 ± 0.097	0.176 ± 0.083	Cooked meat
Tenzene	E1	3630	0.492 ± 0.071	0.545 ± 0.082	0.336 ± 0.078	0.392 ± 0.097	Earthy-musty
Toluene	E2	527	0.083 ± 0.029	0.135 ± 0.064	0.209 ± 0.072	0.341 ± 0.105	Sulfur
Ethyl benzene	E3	2205.3	0.080 ± 0.012	0.162 ± 0.081	0.048 ± 0.003	0.055 ± 0.012	—
1,3-Dimethylbenzene	E4	1100	0.045 ± 0.021	0.074 ± 0.023	N.D	N.D	—
Styrene	E5	2000	0.122 ± 0.043	0.321 ± 0.062	0.112 ± 0.081	0.232 ± 0.077	—
1,4-Dimethylbenzene	E6	530	0.114 ± 0.062	0.097 ± 0.041	0.388 ± 0.098	0.154 ± 0.052	Potato mud
Butylbenzene	E7	100	N.D	0.008 ± 0.003	0.019 ± 0.008	0.021 ± 0.007	—
1,2-Dimethylbenzene	E8	450.2	0.032 ± 0.015	0.038 ± 0.009	N.D	N.D	—
1,4-Diethyl benzene	E9	—	0.023 ± 0.008	N.D	0.012 ± 0.006	0.015 ± 0.002	—
1,2-Dichlorobenzene	E10	—	0.049 ± 0.005	0.024 ± 0.005	0.019 ± 0.008	0.020 ± 0.005	—
Amyl benzene	E11	—	N.D	N.D	0.023 ± 0.011	0.021 ± 0.008	—
Hexyl benzene	E12	—	N.D	N.D	0.032 ± 0.015	0.024 ± 0.009	—
Naphthalene	E13	60	0.044 ± 0.012	0.056 ± 0.011	0.048 ± 0.008	0.043 ± 0.007	—
2-Methylnaphthalene	E14	4	N.D	0.021 ± 0.001	N.D	N.D	—
1-Octene-3-ol	F1	358.1	0.017 ± 0.002	0.029 ± 0.014	0.082 ± 0.029	0.033 ± 0.011	Cooked meat
N-amyl alcohol	F2	150.2	0.019 ± 0.008	N.D	N.D	0.023 ± 0.010	—
Cyclohexanol	F3	2500	0.010 ± 0.009	0.024 ± 0.008	N.D	0.038 ± 0.015	—
1-Pentene-3-ol	F4	1.5	0.041 ± 0.018	0.029 ± 0.008	N.D	N.D	Earthy-musty
2,2-Oxodiethanol	F5	—	N.D	N.D	1.149 ± 0.183	N.D	—
2-Octyne-1-ol	F6	—	0.031 ± 0.011	N.D	N.D	N.D	—
2,3-Dimercaptopropanol	F7	—	N.D	N.D	0.056 ± 0.012	N.D	—
3-Octanone	G1	21.4	0.055 ± 0.012	2.255 ± 0.503	0.023 ± 0.006	2.023 ± 0.413	Earthy-musty
1-Hydroxy-2-acetone	G2	50	0.043 ± 0.010	0.112 ± 0.009	N.D	0.028 ± 0.004	Stench
2-Heptanone	G3	140	N.D	N.D	0.160 ± 0.072	0.039 ± 0.013	Cooked meat
Octyl aldehyde	H1	0.7	0.019 ± 0.007	0.079 ± 0.025	0.112 ± 0.062	0.311 ± 0.082	Stench
Decanal	H2	0.1	0.055 ± 0.023	0.122 ± 0.078	0.027 ± 0.008	0.114 ± 0.062	Earthy-musty
Nonanal	H3	1.1	0.048 ± 0.008	0.135 ± 0.094	0.028 ± 0.007	0.138 ± 0.073	Earthy-musty
Hexanal	H4	5	N.D	0.121 ± 0.078	0.091 ± 0.014	N.D	Earthy-musty
Benzaldehyde	H5	350	0.107 ± 0.056	0.060 ± 0.023	0.353 ± 0.063	0.213 ± 0.092	—
2-Methylpropanal	H6	—	N.D	0.011 ± 0.007	0.079 ± 0.025	0.027 ± 0.002	Potato mud
2-Methylbutyraldehyde	H7	1	0.055 ± 0.016	0.128 ± 0.043	0.025 ± 0.010	0.151 ± 0.061	Earthy-musty

Note. N.D: not detected; —: not retrieved or found.

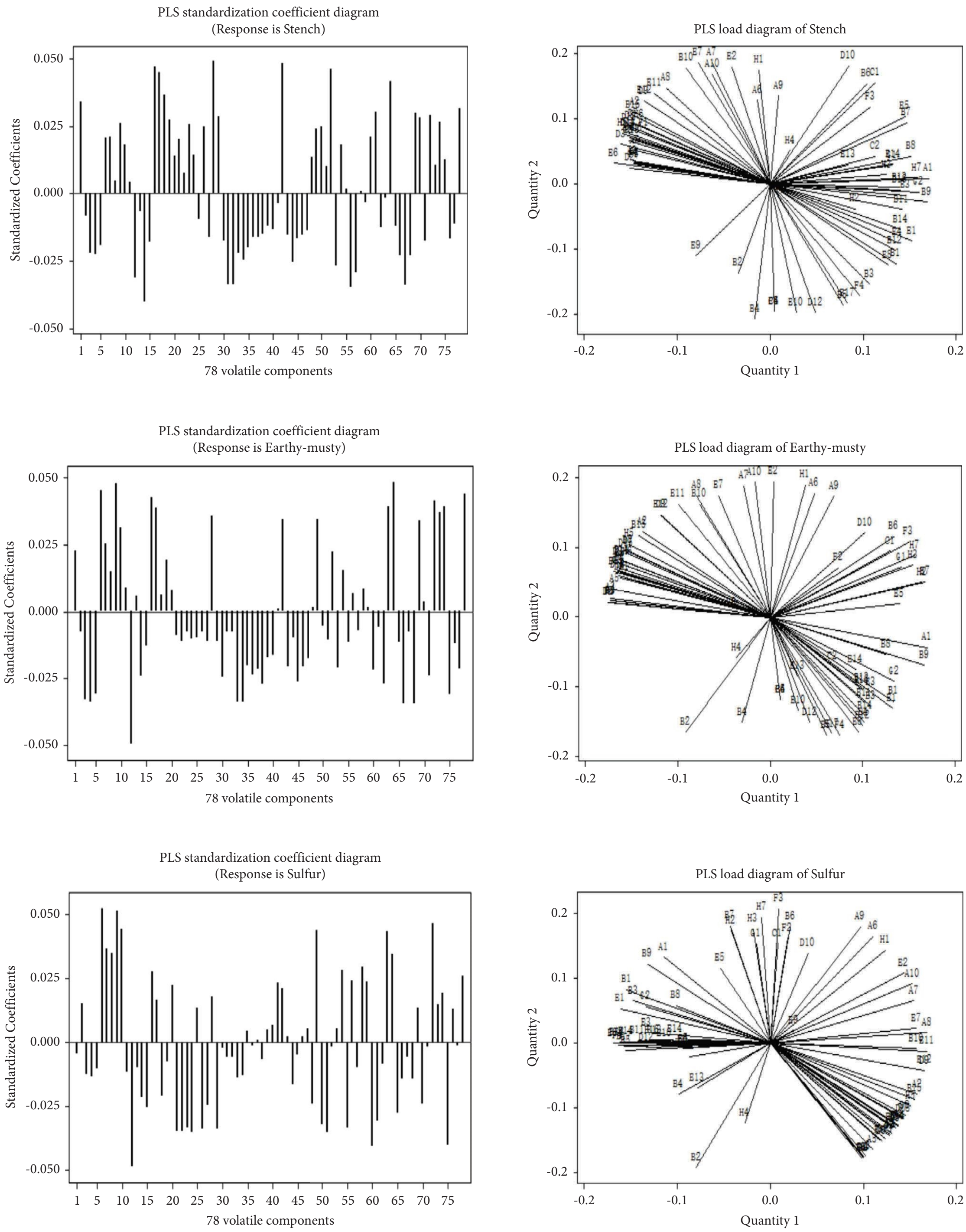


Figure 4: PLS between sensory evaluation of unpleasant odor and volatile components.

2-heptanone, and 1-penten-3-ol), six 1-star components (2-acetylthiazole, 2-methylpropionaldehyde, diallyl sulfide, diallyl disulfide, thiophene, and 2-ethylpyridine), and four 0-star components (allyl methyl sulfide, methyl cyclothioethane, 2,2-oxodiethanol, and 2,3-dimercaptopropanol).

Among the most relevant volatile components for "potato mud," there is one 4-star component (dimethyl trisulfide), one 3-star component (2-acetyl-2-thiazoline), four 2-star components (2-methylpropionaldehyde, 2-ethylpyridine, 1,4-dimethylbenzene, and 2,3,5-trimethylpyrazine), four 1-star components (1-pentene-3-ol, 2-ethylthiophene, 2-acetylthiazole, and butyl benzene), and six 0-star components (carbonyl sulfur, dimethyl sulfoxide, octane, 2-methylpropene, pentyl benzene, and hexyl benzene).

3.4. Preliminary Analysis of the Formation and Change Mechanisms of the Odor Characteristics of Yesso Scallops in Terms of Odor Precursors. Flavor precursors are the material

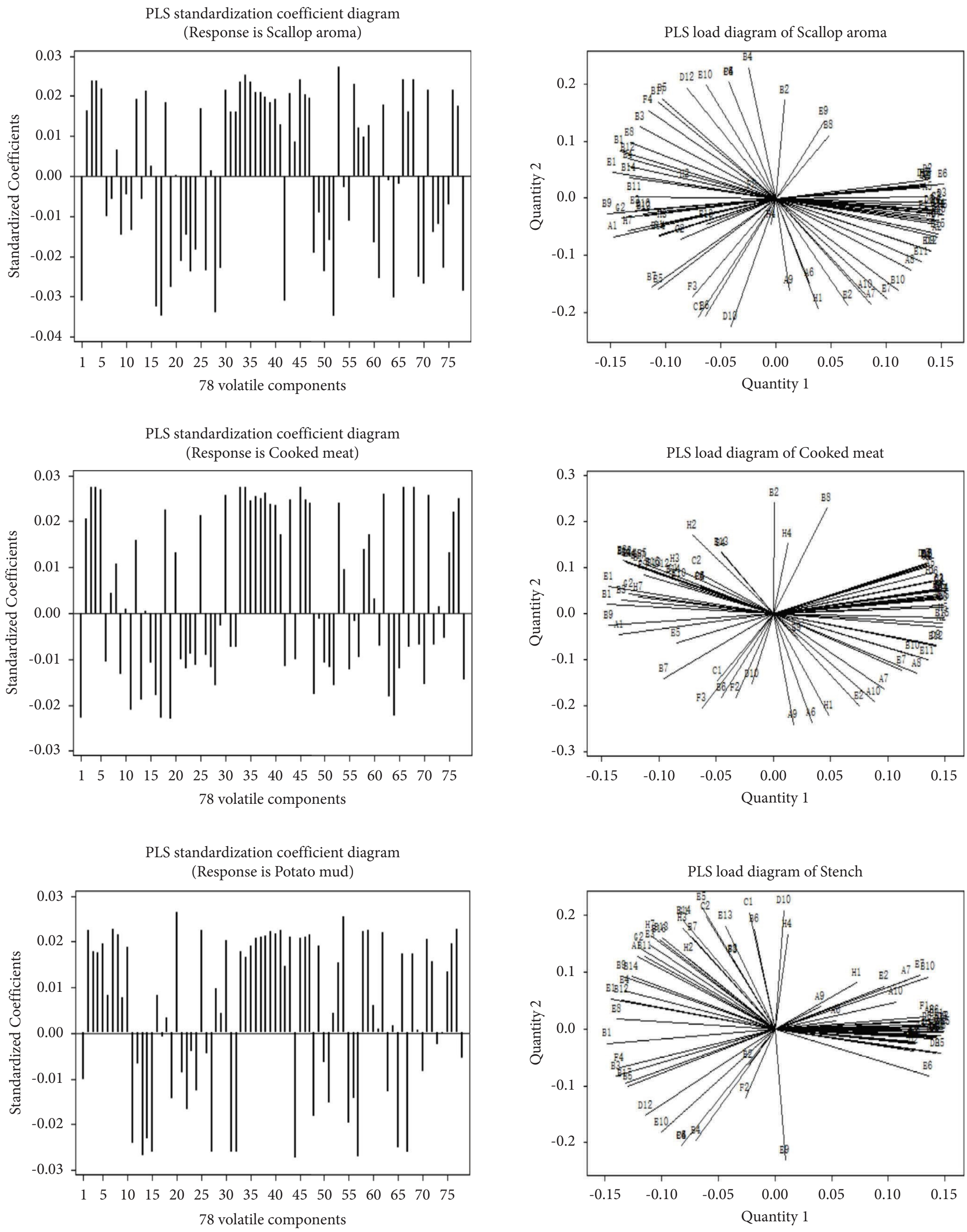


Figure 5: PLS between sensory evaluation of pleasant odor and volatile components.

basis for odor characteristic formation and change in scallops. Odor precursors in meat products generally include certain polypeptides, free amino acids, lipids, free fatty acids, reducing sugars, and thiamine [21]. Of these, there are a wide variety of free amino acids and free fatty acids, and these substances are a particular focus of meat flavor research.

HPLC chromatograms of the free amino acids are shown in Figure 6; GC-MS total ion current diagrams for the free fatty acids are shown in Figure 7. The results for odor precursors under different conditions are shown in Table 5. Generally, with the decline of scallop quality caused by environmental stress, the content of free amino acids for scallops in the poor fresh state is significantly higher than that of the excellent state, which indicates that proteins or polypeptides have been decomposed to a certain extent under the action of microorganisms and enzymes during environmental stress, leading to the content of free amino acids increasing. This provides numerous flavor precursors

Table 3: Evaluation of volatile components related to unpleasant odor by the star-mark method.

Volatile components related to Stench	Consistent with GC-O description (Stench: ** ; Other unpleasant odor: *)	Threshold size (threshold value≤1: ** ; 1< threshold value≤100: *)	Volatile components related to Earthy-musty	Consistent with GC-O description (Earthy-musty: ** ; Other unpleasant odor: *)	Threshold size (threshold value≤1: ** ; 1< threshold value≤100: *)	Volatile components related to Sulfur	Consistent with GC-O description (Sulfur: ** ; Other unpleasant odor: *)	Threshold size (threshold value≤1: ** ; 1< threshold value≤100: *)
Octyl aldehyde	**	**	Methyl mercaptan	**	**	Methyl mercaptan	**	**
Trimethylamine	*	**	Decanal	**	**	Methylallyl disulfide	**	*
2-Methylbutyraldehyde	*	**	2-Methylbutyraldehyde	**	**	2-Methylbutyraldehyde	*	**
Dimethyl sulfide	*	*	3-Octanone	**	*	N-propyl mercaptan	**	*
1-Hydroxy-2-acetone	*	*	Methylallyl disulfide	**	*	Octyl aldehyde	*	**
Nonanal	*	*	Octyl aldehyde	*	**	Toluene	**	/
3-Octanone	*	*	Nonanal	**	*	Carbonyl sulfide	*	*
2-Methylnaphthalene	/	*	N-propyl mercaptan	*	*	Dimethyl sulfoxide	*	/
Decane	*	/	Trimethylamine	*	*	Heptane	*	/
Heptane	/	/	Toluene	*	/	Butylbenzene	/	*
Cyclohexene	/	/	Carbonyl sulfide	/	/	Octane	/	/
1,3-Octadiene	/	/	Heptane	/	/	1,4-Diethyl benzene	/	/
Isopropylamine	/	/	Cyclohexene	/	/	Amyl benzene	/	/
2-Butylthiophene	/	/	2-Butylthiophene	/	/	Hexyl benzene	/	/
Styrene	/	/	N-amyl alcohol	/	/	N-amyl alcohol	/	/
Cyclohexanol	/	/	Cyclohexanol	/	/	Cyclohexanol	/	/

Note:/means not having or not reaching, 4-stars: [ ], 3-stars: [ ], 2-stars: [ ], 1-star: [ ], 0-star: [ ].

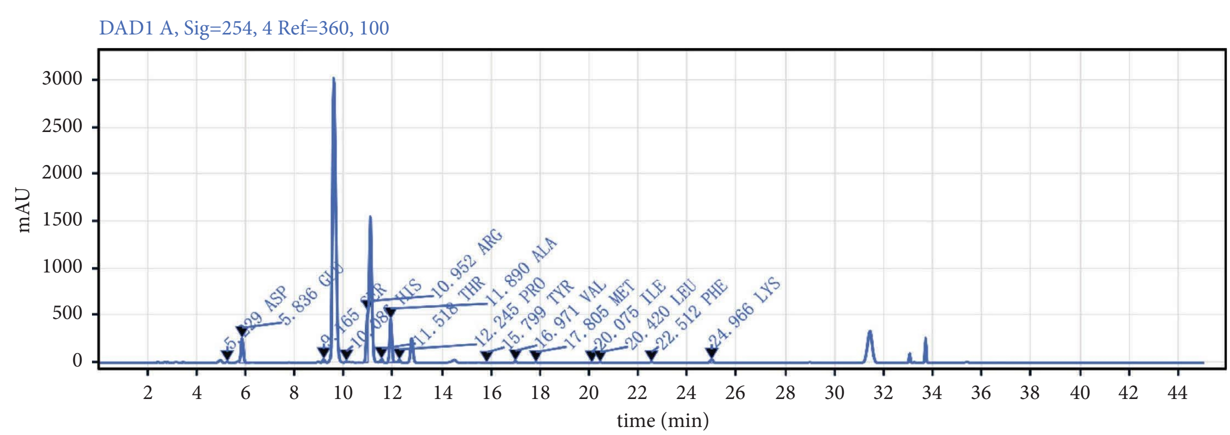
for the formation of many volatile components. The content of free amino acids in cooked scallop is significantly lower than that in live scallop meat, indicating that free amino acids react to form other small-molecular compounds during the cooking process, thus forming the odor characteristics of cooked scallop. Free fatty acids also play an important role in the formation of scallop odor characteristics. It can be seen from Table 5 that, on the whole, the content of free fatty acids in the meat of live scallops in poor condition is significantly lower than that in excellent condition, and some free fatty acids are not even detected, which is related to fatty acid oxidation by microbial and enzymatic action during environmental stress. The content of free fatty acids in cooked scallops increases as a whole, indicating that some of the fat is decomposed to a certain extent during the cooking process and more free fatty acids are produced.

3.4.1. Preliminary Analysis of the Formation and Change Mechanisms of the Unpleasant Odor Characteristics of Yesso Scallops. The reason for the formation of unpleasant odor characteristics in Yesso scallops is that some bad volatile components are produced directly during long periods of environmental stress, or the relevant odor precursors are produced and then further produce bad volatile components. Without considering the interaction between volatile components, the formation mechanism of unpleasant odor characteristics in scallops can be preliminarily obtained by analyzing the volatile components and flavor precursors with scores above 3-stars for these experimental conditions. The unpleasant odor characteristics are mainly related to trimethylamine, some small-molecule aldehydes and ketones, and sulfur compounds. Trimethylamine is an important source of the fishy smell of scallops, and its production mechanism has been thoroughly studied. It is formed by the reduction of trimethylamine oxide under the action of reductase or microorganisms under environmental stress [22]. The aldehydes octanal, nonanal, and sunflower aldehydes, as well as 3-octanone, are involved in the formation of unpleasant odor characteristics upon deterioration of the quality of scallops. These small-molecule aldehydes or ketones are generally considered to be the products of the oxidative decomposition of unsaturated fatty acids. For example, Wang et al. reported that the small-molecule aldehydes are related to linoleic acid and some of the volatile components of abalone ω-3. And the unpleasant odor characteristics are related to the oxidation of fatty acids, which is consistent with the detection of free fatty acids in this study [23]. 2-Methylbutyraldehyde is also an important aldehyde involved in the formation of bad odor characteristics in scallops, and some studies have indicated that 2-methylbutyraldehyde in meat is produced by Strecker degradation of free amino acids such as leucine and isoleucine [24]. Sulfur compounds are another source of the

Table 4: Evaluation of volatile components related to pleasant odor by the star-mark method.

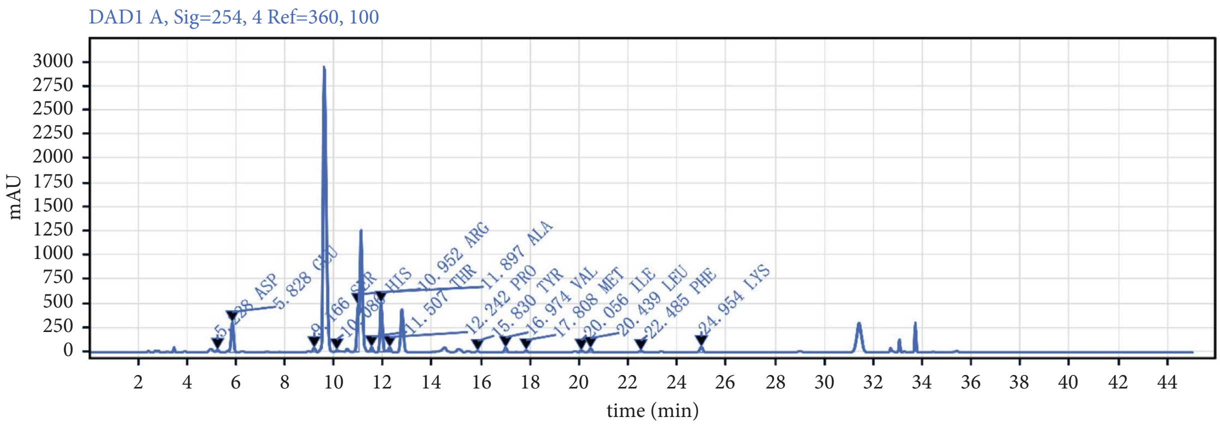
Volatile components related to Scallop aroma	Consistent with GC-O description (Scallop aroma: ** ; Other pleasant odor: *)	Threshold size (threshold value≤1: ** ; 1< threshold value≤100: *)	Volatile components related to Cooked meat	Consistent with GC-O description (Cooked meat: ** ; Other pleasant odor: *)	Threshold size (threshold value≤1: ** ; 1< threshold value≤100: *)	Volatile components related to Potato mud	Consistent with GC-O description (Potato mud: ** ; Other pleasant odor: *)	Threshold size (threshold value≤1: ** ; 1< threshold value≤100: *)
Diallyl sulfide	/	*	2-Ethylfuran	* *	*	Dimethyl trisulfide	* *	**
2-Ethylpyridine	*	/	2,3,5-Trimethylpyrazine	* *	*	2-Acetyl-2-thiazoline	* *	*
1,4-Dimethylbenzene	*	/	2-Amylfuran	* *	*	2-Methylpropanal	* *	/
1-Pentene-3-ol	*	/	2,5-Dimethylpyrazine	* *	/	2-Ethylpyridine	* *	/
Diallyl disulfide	/	*	2Heptanone	* *	/	1,4-Dimethylbenzene	* *	/
Trichloromethane	/	*	1-Octene-3-ol	* *		2,3,5-trimethylpyrazine	*	*
Thiophene	/	*	2-Acetylthiazole	/	*	1-Octene-3-ol	*	/
3-Methyl-pentane	/	/	2-Methylpropanal	*	/	2-Ethylthiophene	/	*
1,2-Dimethylhydrazine	/	/	Diallyl sulfide	/	*	2-Acetylthiazole	/	*
Urea	/	/	Diallyl disulfide	/	*	Butylbenzene	/	*
Methylcyclothioethane	/	/	Thiophene	/	*	Carbonyl sulfide	/	/
Pyridine	/	/	2-Ethylpyridine	*	/	Dimethyl sulfoxide	/	/
1,4-Diethyl benzene	/	/	Allyl methyl sulfide	/	/	Octane	/	/
2,2-oxodiethanol	/	/	Methylcyclothioethane	/	/	2-Methylpropene	/	/
2-Octyne-1-ol	/	/	2,2-Oxodiethanol	/	/	Amyl benzene	/	/
2,3-dimercaptopropanol	/	/	2,3-Dimercaptopropanol	/	/	Hexyl benzene	/	/

Note:/means not having or not reaching, 4-stars: , 3-stars: , 2-stars: , 1-star: , 0-star: .

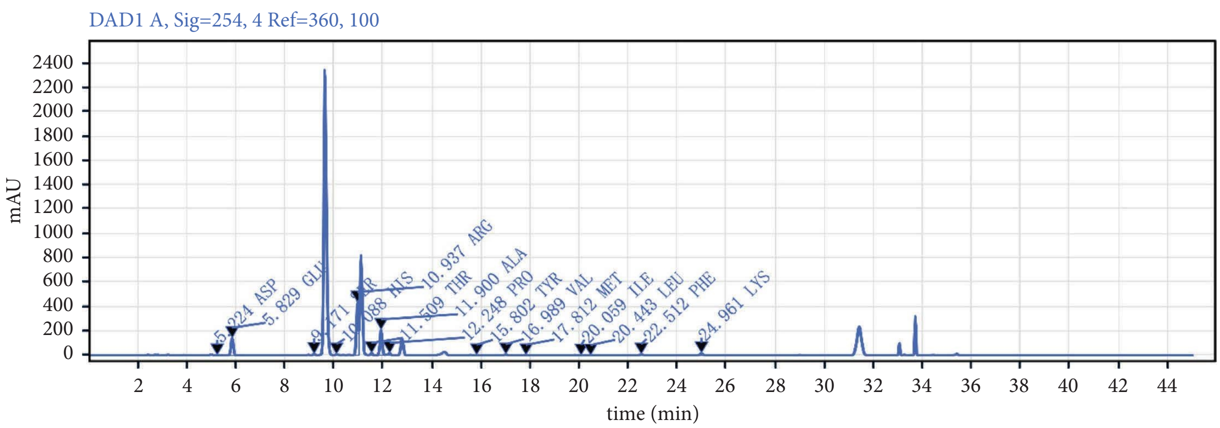


(a)

Figure 6: Continued.



(b)



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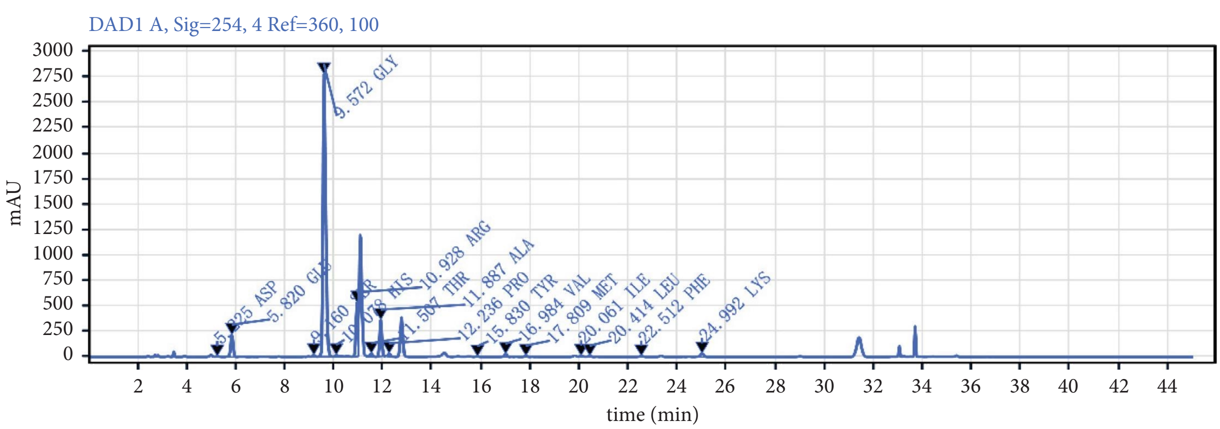

(d)

Figure 6: HPLC chromatogram of the free amino acids in Yesso scallop in different conditions: (a) alive in excellent condition, (b) alive in poor condition, (c) cooked in excellent condition, and (d) cooked in poor condition.

unpleasant odor characteristics of scallops. In this study, the sulfur compounds related to unpleasant odor characteristics include methylallyl disulfide, methyl mercaptan, and n-propylmercaptan. It is believed that these volatile sulfur compounds in refrigerated cod are the result of microbial degradation of free methionine and other sulfur-containing

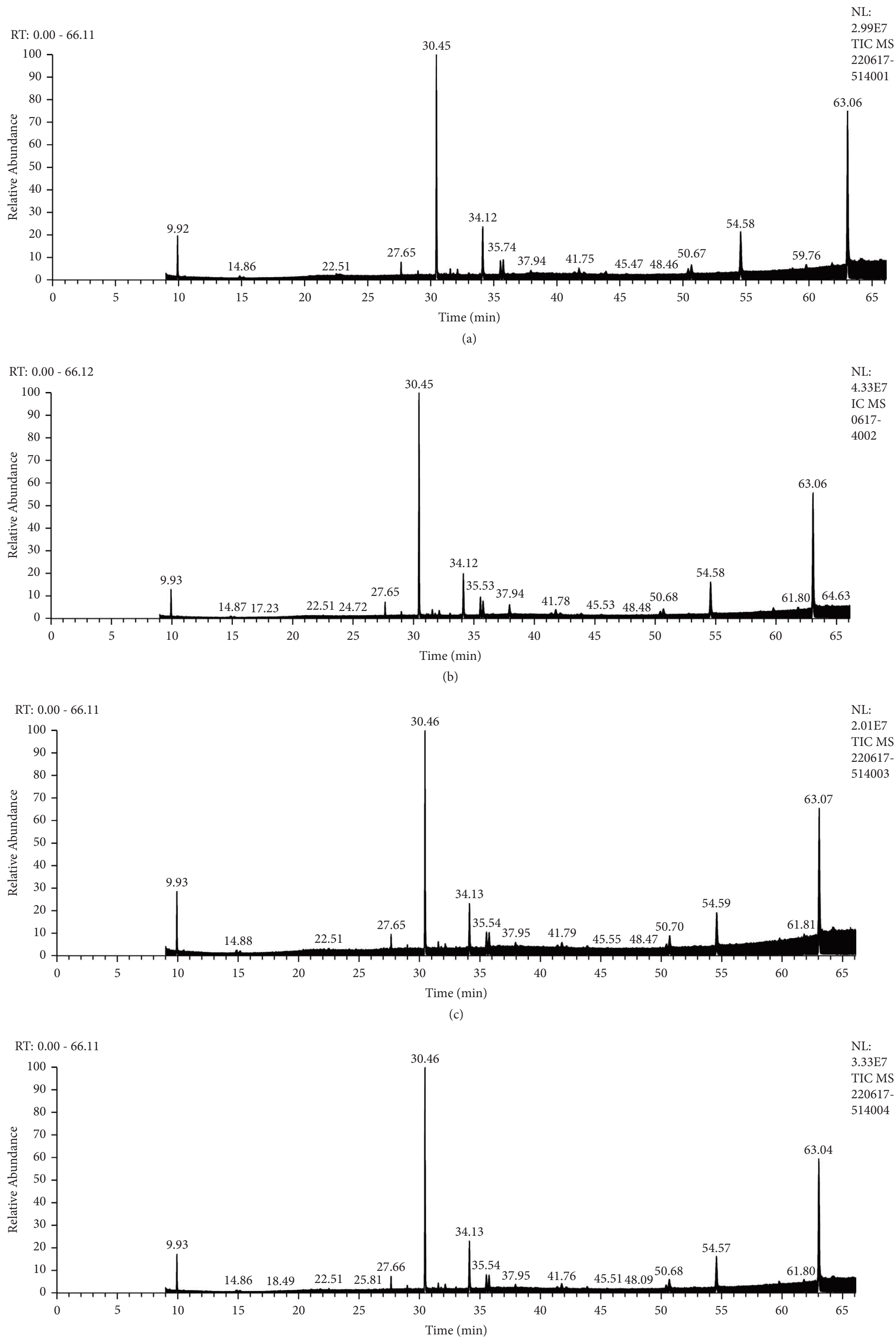

Figure 7: GC-MS total ion current diagram for the free fatty acids in Yesso scallops in different conditions: (a) alive in excellent condition, (b) alive in poor condition, (c) cooked in excellent condition, and (d) cooked in poor condition.

Table 5: Comparison of odor precursors of Yesso scallop in different conditions.

Odor precursors	Units	Alive		Cooked	
		Excellent	Poor	Excellent	Poor
Free Amino Acid					
Aspartic acid	Mg/kg	27.19 ± 1.21	72.53 ± 2.92	9.32 ± 0.43	28.82 ± 1.34
Glutamate	Mg/kg	1050.84 ± 19.41	1298.44 ± 23.12	880.12 ± 19.11	1076.25 ± 24.23
Serine	Mg/kg	107.16 ± 1.89	134.80 ± 8.91	56.53 ± 3.99	65.03 ± 2.18
Glycine	Mg/kg	9510.94 ± 95.15	9261.70 ± 18.64	8633.07 ± 75.32	8928.99 ± 69.43
Histidine	Mg/kg	50.49 ± 5.87	77.68 ± 5.54	46.87 ± 4.11	73.82 ± 4.31
Arginine	Mg/kg	1782.31 ± 45.32	1922.05 ± 31.72	2694.84 ± 34.91	2562.80 ± 51.34
Threonine	Mg/kg	117.08 ± 6.36	163.88 ± 8.15	78.99 ± 3.51	120.04 ± 5.11
Alanine	Mg/kg	1082.19 ± 21.52	1245.31 ± 22.45	753.48 ± 19.54	1017.75 ± 23.56
Proline	Mg/kg	75.34 ± 5.87	118.79 ± 5.29	69.43 ± 3.45	98.22 ± 3.79
Tyrosine	Mg/kg	14.68 ± 1.02	62.20 ± 2.45	19.86 ± 1.54	36.95 ± 2.93
Valine	Mg/kg	62.38 ± 4.37	141.05 ± 4.23	44.52 ± 2.49	102.06 ± 7.41
Methionine	Mg/kg	31.60 ± 2.14	86.06 ± 4.56	22.01 ± 3.14	58.14 ± 5.79
Isoleucine	Mg/kg	27.92 ± 2.16	91.37 ± 7.78	14.32 ± 1.65	76.95 ± 4.45
Leucine	Mg/kg	33.34 ± 3.33	163.38 ± 7.67	13.63 ± 1.99	63.70 ± 3.78
Phenylalanine	Mg/kg	62.09 ± 6.01	93.57 ± 6.16	88.99 ± 7.12	77.19 ± 5.16
Lysine	Mg/kg	102.73 ± 10.45	162.28 ± 9.98	77.91 ± 6.78	134.55 ± 10.13
Free Fatty Acid					
C14:0	Mg/100 g	5.7 ± 0.56	3.8 ± 0.87	8.6 ± 0.96	7.0 ± 0.75
C16:0	Mg/100 g	49.3 ± 4.66	27.8 ± 4.72	88.6 ± 6.43	67.0 ± 4.56
C16:1	Mg/100 g	3.6 ± 0.62	<0.0033	5.4 ± 0.86	4.4 ± 0.56
C18:0	Mg/100 g	18.1 ± 0.92	10.1 ± 0.49	27.3 ± 1.61	23.6 ± 2.83
C18:1n9c	Mg/100 g	7.4 ± 0.98	<0.0033	14.2 ± 2.54	9.3 ± 1.14
C18 :2n6c	Mg/100 g	3.4 ± 0.64	<0.0033	10.7 ± 1.45	4.0 ± 0.67
C20:1	Mg/100 g	5.2 ± 0.77	<0.0033	8.1 ± 0.85	6.2 ± 0.98
C22:1n9	Mg/100 g	7.7 ± 0.76	5.8 ± 0.78	9.9 ± 1.01	11.1 ± 0.86
C20:4n6	Mg/100 g	5.4 ± 0.58	<0.0033	7.1 ± 0.76	5.7 ± 0.63
C20:5n3	Mg/100 g	25.2 ± 2.56	11.9 ± 0.93	35.8 ± 4.32	26.0 ± 2.57
C22:6n3	Mg/100 g	92.4 ± 5.54	40.6 ± 3.84	125.9 ± 6.56	97.2 ± 5.71

amino acids in fish muscle, which is consistent with the detection of free amino acids in this study [25].

In addition, among the volatile components with scores below 3-stars, dimethyl sulfide is also considered to be an important source of unpleasant odor characteristics in aquatic products. Some studies have indicated that methionine is converted into dimethyl sulfide upon cooking through a series of reactions including Strecker degradation, thermal degradation, and oxidation [26].

3.4.2. Preliminary Analysis of the Formation and Change Mechanisms of the Pleasant Odor Characteristics of Yesso Scallops. There are relatively few volatile components for experimental conditions related to pleasant odor characteristics. Analysis of these volatile components and flavor precursors shows that some furans, pyrazines, and sulfur compounds participate in the formation of pleasant odor characteristics during the cooking process. Among them, 2-ethylfuran, 2-pentylfuran, and 2,3,5-trimethylpyrazine are considered to be derived from amino acids. Reducing sugar and other substances are produced by the Maillard reaction [3, 27]; Furans are found in cooked or sterilized crustacean meat and are thermal-degradation products of lipids or thiamine [28]. The sulfur compound dimethyl trisulfide is considered to be produced by thermal degradation of some sulfur-containing amino acids [21].

In addition, among the volatile components with scores below 3-stars, 2,5-dimethylpyrazine is also an important odor substance of cooked meat and a product of the Maillard reaction [3]; 1-Penten-3-ol is considered to make a certain contribution to meat flavor. Sun et al. found that 1-octen-3-ol can be produced by linoleic acid peroxide degradation and arachidonic acid degradation by lipoxygenase through GC-O-MS [29].

The formation and change mechanisms of odor characteristics of Yesso scallops discussed in detail above are shown in Figure 8.

3.4.3. Additional Analysis of the Sulfur Compounds in Scallops. According to the results of this study, sulfur compounds have a very important influence on the formation of odor characteristics in scallops. It is generally believed that the sulfur compounds in marine products have a very low odor threshold, and with the increase of concentration, the aroma will transition from "fresh sea water" to a "rotten stink" sulfur-like odor [25]. The sulfur compounds screened in this study mainly include mercaptans, thioethers, thiazoles, and other heterocyclic compounds. Similarly, the effects of these sulfur compounds on the formation of odor characteristics in scallops are complex.

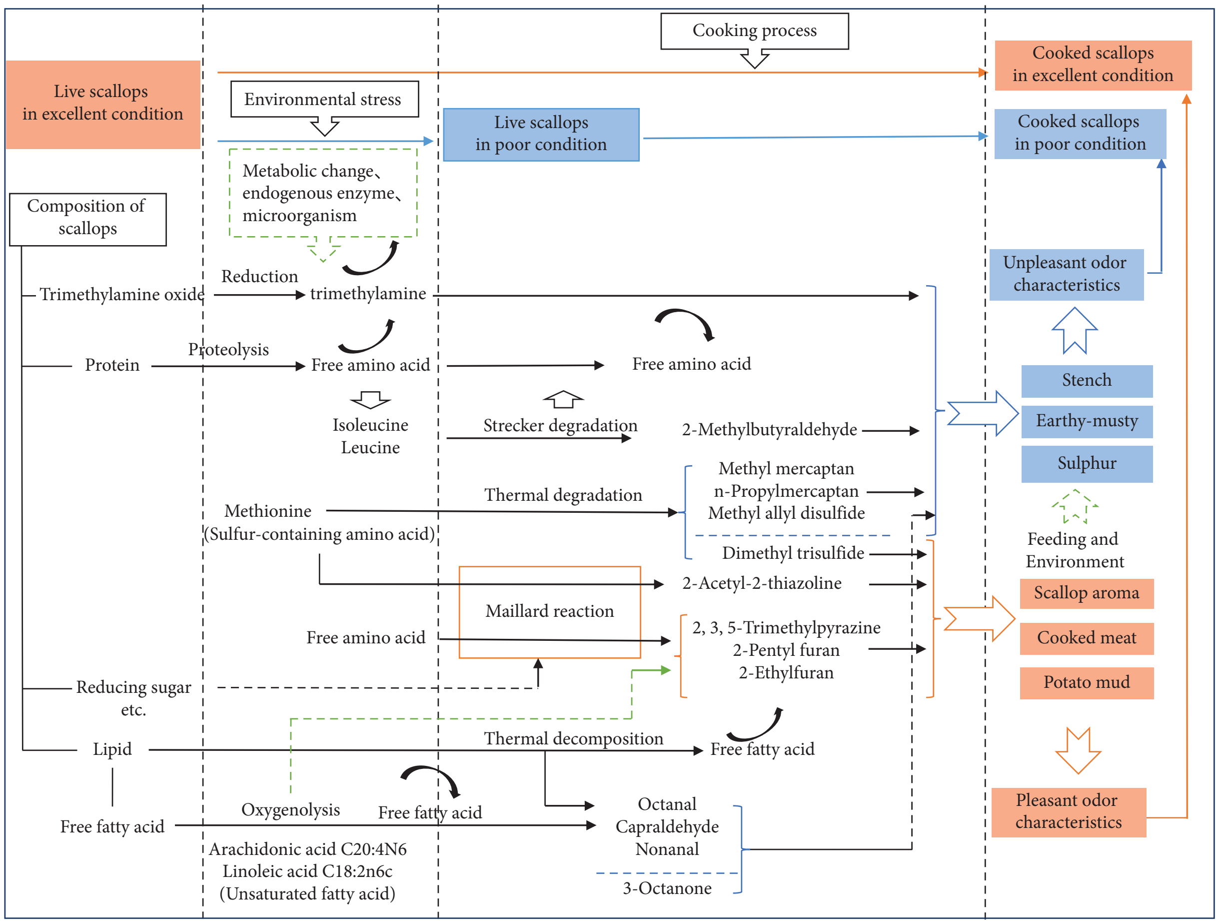

Figure 8: Formation and change mechanism of the odor characteristics of Yesso scallops.

With changing concentration, their odor characteristics will also change, and the conclusions mentioned above need to be verified with further research. In addition, scallops are filter feeders and feed on algae in the ocean. Sulfur compounds are important contributors to the characteristic odor of algae, and their feeding and growth environment may also be one of the sources of sulfur compounds in scallops [30]. Propyl dimethyl sulfonate is degraded to dimethyl sulfide under the action of microorganisms [31].

4. Conclusions

In this study, the pleasant and unpleasant odor characteristics of scallops were analyzed separately. Although their correlation was not taken into account, the quantification of sensory descriptors was found to improve the accuracy of the quantitative description analysis. The sensory results were used for regression analysis with the GC-MS measurement results, and the 16 most relevant volatile components for each odor characteristic were identified.

Considering the accuracy and difficulty of quantifying GC-O olfactory results, this study limited the GC-O olfactory range to six sensory descriptors and combined olfactory results with olfactory thresholds to establish a new standard star-mark grading method to further evaluate the role of the most relevant 16 volatile components in the formation of odor characteristics, dividing the volatile components into four grades.

On the basis of the abovementioned research, two types of possible flavor precursors were selected for analysis, and combined with the literature, the possible flavor precursors were identified, completing a preliminary analysis of the formation and change mechanisms of odor characteristics.

This study did not consider the synergistic effect between volatile components and only studied the formation of odor characteristics by individual volatile components. Therefore, in our further research, flavor loss and recombination tests will be further carried out on the basis of the results of this study. In addition, the determination range of flavor precursors will be expanded, including lipids, reducing sugars, and other possible flavor precursors, and removal analysis of flavor precursors will also be performed in order to better reveal the formation and change mechanisms of odor characteristics, and even provide a reference for the development of scallop flavor essence.

Data Availability

The data that supports the findings of this study are available in the tables of this article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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