

Application of *Rosa roxburghii* Tratt. extraction in improving gel properties and flavour of hairtail (*Trichiurus lepturus*) surimi

Jixiang Zhang^{1,§}, Lin Yu^{1,§}, Xinyang Li¹, Feifan Wu¹, Taiyu Li¹, Chenyang Zhao¹, Islam Shafiul¹, Xiaoguo Ying¹ ✉, Shanggui Deng¹, Charles Brennan², Soottawat Benjakul³, Zhengxuan Qin⁴, Lukai Ma⁵ ✉

¹Key Laboratory of Health Risk Factors for Seafood of Zhejiang Province, Food and Pharmacy College, Zhejiang Ocean University, Zhoushan 316022, China

²School of Science, Royal Melbourne Institute of Technology University, Melbourne 2474, Australia

³International Center of Excellence in Seafood Science and Innovation, Faculty of Agro-industry, Prince of Songkla University, Songkhla 90110, Thailand

⁴Oceanside (Zhoushan) Premium Products Co., Zhoushan 316022, China

⁵Key Laboratory of Green Processing and Intelligent Manufacturing of Lingnan Specialty Food, Ministry of Agriculture and Rural Affairs, Guangdong Provincial Key Laboratory of Lingnan Specialty Food Science and Technology, College of Food Science and Technology, Zhongkai University of Agriculture and Engineering, Guangzhou 510225 China

[§]These authors contributed equally to this article.

✉ Address correspondence to Xiaoguo Ying, yingxiaoguo@zjou.edu.cn; Lukai Ma, m1991lk@163.com

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Abstract: The aim of this experiment was to investigate the effect of a natural additive *Rosa roxburghii* Tratt. extraction (RRTE) on the gel properties and flavour of hairtail (*Trichiurus lepturus*) surimi gels. The effects of different additive concentrations of RRTE on the flavour improvement of hairtail surimi gels were systematically investigated by combining the electronic nose and sensory evaluation techniques. The results showed that the addition of RRTE, especially 2% (m/m) RRTE, could effectively improve the odour score; enhanced the gel strength, water-holding capacity and rheological properties; improved the elasticity, hardness and viscoelasticity of the hairtail surimi gels. The results of water migration and protein secondary structure analysis showed that RRTE could effectively stabilise the internal water distribution of hairtail surimi gels and inhibit protein denaturation. Microstructural observation showed that the gel structure of hairtail surimi in the RRTE added group was more uniform and dense, and the fractal dimension was reduced. The comprehensive results showed that RRTE, as a natural additive, could significantly improve the gel properties and flavour of hairtail surimi gels, providing a scientific basis for the high value-added processing of hairtail surimi products.

Keywords: hairtail surimi; *Rosa roxburghii* Tratt. extraction; surimi gel properties; surimi flavour

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1 Introduction

The hairtail (*Trichiurus lepturus*) is a significant marine resource in Chinese fisheries, valued for its high nutritional content, which includes proteins, vitamins, minerals, and fats^[1]. Most hairtails are sold chilled, while smaller and damaged ones are often processed into frozen surimi. The surimi industry, which has expanded rapidly in recent years, is poised for further growth^[2]. The market is currently dominated by marine fish such as cod and lower-value fish, with relatively limited research on hairtail-derived surimi products. Surimi products are easy to process and are in great demand in the market, so the development of hairtail surimi products is extremely necessary, and the processing of hairtail surimi needs to be further studied^[3].

Although hairtail is highly nutritious, fat and protein oxidation can promote the generation of undesirable flavours, which greatly affects the quality and flavour of hairtail surimi gel^[4]. Proteins and lipids undergo oxidation, degradation, denaturation, and aggregation during the production and storage of hairtail surimi. This can easily lead to oxidation, intramolecular or intermolecular cross-linking, and protein degradation, resulting in a weaker gel

network and reduced elasticity, water-holding capacity, and gel properties^[5]. This has implications for the flavour of hairtail surimi during processing. Flavour is a crucial determinant of the quality and overall sensory properties of food and its enjoyment. Therefore, improving the flavour of surimi products is important to improve consumer experience. Efforts toward improving the quality and flavour of surimi gels have mainly focused on the development of new processing technologies and desirable additives^[6]. Since the development and reproduction of new processing techniques often requires expensive equipment, their industrial applications are limited^[7]. The development of additives is the more economical and practical approach that usually involves the addition of exogenous substances to improve the quality and flavour of surimi gels^[8].

Natural plant extracts are a rich source of active substances, including polysaccharides and polyphenols, which are widely employed as preservatives and antioxidants^[9]. Plant extracts have been shown to improve the quality and storage stability of surimi gels^[10]. However, few studies have reported effective generalizable approaches for improving the quality and flavour of hairtail surimi gels. Natural additives are extensively employed in surimi products, primarily as gelling agents, antifreeze agents, antioxidants, and

emulsifiers^[11]. *Rosa roxburghii* Tratt. is naturally distributed in the Chinese Yunnan-Guizhou Plateau, among other regions, and widely planted in Guizhou Province. *R. roxburghii* Tratt. is rich in vitamins, polysaccharides, flavonoids, polyphenols, and other active ingredients, with nutritional and health care functions that ameliorate antioxidant, hypoglycemic, and immune dysregulations^[12]. The active ingredients of *R. roxburghii* Tratt. extraction (RRTE) exhibit a certain inhibitory effect on protein and lipid oxidation. This high-quality natural additive has been employed in functional foods, dietary supplements, and pharmaceutical preparations, among other applications^[13]. However, the use of RRTE in the processing of surimi products has been rarely reported.

Surimi products are usually processed into fish balls, fish intestines, fish tofu, imitation crab meat and so on. As the basis of green food, surimi products can be adjusted and changed according to different groups of people and market demand, and are popular among consumers for their unique taste and excellent nutritional value. The study investigated the effects of different concentrations of RRTE on the gel quality and flavour of hairtail surimi gels by investigating the color, water-holding capacity, odor characteristics, sensory quality, gel properties, texture profile analysis (TPA) parameters, and rheological properties, and systematically evaluated the mechanism of improving the quality of hairtail surimi gels, to provide theoretical support for the application of the natural additive, RRTE, in surimi gel products.

2 Materials and methods

2.1 Materials and reagents

Frozen hairtail surimi was supplied by Zhejiang Xingye Group Co., Ltd. (Zhoushan, China), which was stored at -20°C . RRTE was brownish-yellow fine powder (polysaccharides $(93.30 \pm 2.68)\%$, polyphenols $(1.16 \pm 0.16)\%$, vitamins $(1.09 \pm 0.04)\%$, flavonoids $(0.05 \pm 0.01)\%$, m/m), purchased from Ningshan Guosheng Biological Technology Co. (Ankang, China), and enteric casings (diameter 40 mm) were purchased from the local market. All the reagents used in this experiment were of analytical pure grade and were purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China).

2.2 Preparation of hairtail surimi gel

The frozen hairtail surimi, weighing 200 g, was thawed at 4°C for 5 h to reach a half-thawed state, cut into cylinders about 2 cm high, and then chopped with a food chopper (FP3010, Braun, Frankfurt, Germany) at 2 000 r/min for 2 min. This was followed by the addition of 3% (m/m) NaCl and further chopping at 2 000 r/min for 3 min. Subsequently, 6% (12 g) of tapioca starch and 4% (8 g) of soybean isolate protein were added. No RRTE was added to the control group, 1%, 2%, 3%, and 4% (m/m) RRTE were added to the experimental groups by dissolving TTRE in 91 g of ice water. The temperature of the whole process was controlled below 10°C , and the water mass fraction was adjusted to 78%. The resulting solution was vacuumed for 30 s to expel the air. The resulting sample was then injected into the enteric coating and heated in two stages: first at 40°C for 30 min and then at 90°C for 30 min. Cooling, for measurement.

2.3 Determination of whiteness, water-holding capacity, and cooking loss

Morphological analysis of food by sensory instrumentation has the advantages of objectivity, accuracy, high sensitivity, good reproducibility, and quantifiable results.

The whiteness was determined by referring to the method of Zhang et al.^[14] with a slight modifications. The hairtail surimi gel was cut into cylinders with a length of 1 cm and allowed to equilibrate at room temperature for 30 min. The raw chromaticity (brightness value (L^*), redness value (a^*), and yellowness value (b^*)) of the hairtail surimi gel was recorded using a hand-held precision colourimeter (DS-200, Hangzhou Colour Spectrum Technology Co., Hangzhou, China) in six parallel passes. The whiteness was calculated according to the formula (1):

$$\text{Whiteness} = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad (1)$$

The hairtail surimi gel samples were sliced into thin pieces, each 5 mm thick, with the mass recorded as m_1 . The samples were then wrapped in three layers of filter paper and placed in a 50 mL centrifuge tube and centrifuged at 8 000 r/min for 10 min at 4°C , after which the samples were removed, weighed and recorded as m_2 . The water-holding capacity was calculated according to the formula (2):

$$\text{Water-holding capacity (\%)} = \frac{m_2}{m_1} \times 100 \quad (2)$$

The hairtail surimi gel samples were cut into thin slices of 5 mm thickness recorded as m_3 , sealed into a cooking bag, bathed in water at 90°C for 20 min, after cooling, the surface water of the sample was removed and absorbed, and recorded its mass as m_4 . The cooking loss was calculated according to the formula (3):

$$\text{Cooking loss (\%)} = \frac{m_3 - m_4}{m_3} \times 100 \quad (3)$$

2.4 Electronic nose measurement

Refer to the method of Zhang et al.^[15] with appropriate modifications. The electronic nose comprises three main components: a sensor sensing part, a signal transmission part, and an information processing part. Three grams of minced hairtail surimi gel samples were accurately weighed and placed in a 30 mL headspace injection vial. The samples were left to equilibrate for 30 min before being measured. Tests were conducted using a PEN-3 electronic nose (Airsense Analytics, Schwerin, Germany) system equipped with 10 metal oxide semiconductor sensors. The self-cleaning and detection times were 180 and 60 s, respectively. Sensor signal values obtained between 56 and 58 s were selected for data analysis.

2.5 Sensory evaluation

Traditional sensory evaluation is a direct method for judging food quality, relying on human sensory organs to evaluate the color, flavour, shape, and texture of food. Referring to NY/T 1327–2018 *Green food-Surimi products and making certain adjustments*, a tasting panel was formed by personnel trained in sensory evaluation, and participation was completely voluntary. Our study did not require further ethics committee approval as it did not involve animal or human clinical trials and was not unethical. In accordance with the ethical principles outlined in the *Declaration of Helsinki*, all participants provided informed consent before participating in the study. The panel evaluated 5 aspects: organization and morphology, colour and lustre, taste, texture, and odour. The evaluation criteria are shown in Table 1. According to the weighted method, the overall rating was calculated by odour $\times 0.25$ + colour $\times 0.25$ + texture $\times 0.25$ + taste $\times 0.25$, and the average value of each index was taken.

Table 1 Sensory evaluation and scoring criteria for hairtail surimi gel.

Norm	Weighting factor	Sensory score		
		1–3	4–7	8–10
Odour	0.25	Excessive fishy taste and odour	The fishy flavour is moderate in intensity, with a light fish aroma and no discernible off-flavour	The product does not exhibit any fishy flavour or aroma
Colour	0.25	Yellowish colour, uneven, with stray colours	The colour is lighter and more uniform	Full colour, very white, even and free of variegation
Texture	0.25	Coarse and superb texture, loosely cut, porosity and heterogeneity	The material in question exhibits a more delicate texture, with densely cut fibres and small pores, as well as an uneven distribution of surfaces	The fabric has a fine texture, a dense cut, and no air holes
Taste	0.25	Poor elasticity, the surface cracks when pressed a little hard	General elasticity, slightly hard to press the surface does not crack, and can not quickly return to its original state	The material exhibits good elasticity, with the surface remaining intact even when subjected to considerable force. Furthermore, it can be rapidly restored to its original state

2.6 Determination of gel properties

Referring to the method of Duan et al.^[16] with slight modifications, hairtail surimi gel was cut into 2 cm high cylinders and equilibrated at room temperature for 0.5 h. The P/0.5 spherical probe was selected (iTexture, Zhejiang Zheke Instrument Equipment Co., Ltd., Hangzhou, China), and the parameters were set as follows: a trigger force of 5 g, a pre-measurement speed of 5 mm/s, a mid-measurement speed of 1 mm/s, and a post-measurement speed of 10 mm/s, with a compression distance is 10 mm. Six parallel experiments were conducted. The gel strength was calculated using the formula (4):

$$\text{Gel strength (g} \cdot \text{cm)} = \text{Breaking distance (cm)} \times \text{Breaking force (g)} \quad (4)$$

2.7 Determination of TPA parameters

TPA parameters was determined using the method of Zhang et al.^[17] with slight modifications. Hairtail surimi gel was cut into 20 mm cylinders and equilibrated at room temperature for 0.5 h. TPA parameters were determined by a texture analyzer (iTexture, Zhejiang Zheke Instrument Equipment Co., Ltd., Hangzhou, China) with probe P/50, and the parameters were set as follows: pre-measurement speed of 2 mm/s, mid-measurement speed of 1 mm/s, and post-measurement speed of 10 mm/s, with a compressive deformation of 50%. Six experiments were conducted, and the resulting numerical changes in hardness, springiness, chewiness, gumminess, and cohesiveness were recorded.

2.8 Determination of rheological properties

The rheological properties of hairtail surimi gel were determined by rotational rheometer (HR-20, TA Instruments, Newcastle, USA) using the method of Zhao et al.^[18] with slight modifications. The surimi sol was placed between two plates spaced 1 mm apart and sealed with silicone oil to prevent moisture loss. The scanning temperature was maintained within a range of 20 to 90 °C, with a heating rate of 2 °C/min and a cooling rate of 2 °C/min. The scanning frequency was set at 1 Hz. The rheological properties of the different sample sets were determined by measuring the elastic modulus (G') and the viscous modulus (G''). The loss tangent ($\tan\delta$) was calculated according to the formula (5):

$$\tan\delta = \frac{G''}{G'} \quad (5)$$

2.9 Determination of water distribution

The reference method^[19] was employed with minor adjustments for the determination. The spin-spin relaxation time (T_2) of the hairtail surimi gel was quantified using an low-field nuclear magnetic resonance (NMR) analyser (PQ001, Shanghai Newmax Electronic Technology Co., Shanghai, China). A 5 g hairtail surimi gel sample was placed in a 15 cm NMR tube and inserted into the NMR probe. Instrument parameters were as follows: 3 000 for the number of sampling points, 0.2 ms for the time waiting, 10 000 for the time echo, and 4 for the number of collected echoes, as well as the number of scans was set to 4. The images of the T_2 were obtained using NMR relaxation time inversion fitting software. NMR image processing software v3.0 was used to perform false-color processing on the obtained image files.

2.10 Determination of Fourier transform infrared (FTIR) spectra

The hairtail surimi gel was cut into 0.5 cm square pieces, freeze-dried, ground, and pulverised. A quantity of 1–2 mg of the lyophilised powder sample was ground with 200 mg of potassium bromide, placed in a mould and pressed. The sample was subsequently tested on the Fourier infrared light spectrometer (Tensor II, Bruker, MA, Germany) in the wavenumber range of 400–4 000 cm^{-1} , scanning number of 32, and resolution of 4 cm^{-1} . The resulting data were used for fitting calculations of the protein secondary structure using PeakFit software.

2.11 Determination of microstructure and fractal dimension (D_f)

The reference method of Yu et al.^[20] was employed with minor modifications. Hairtail surimi gel samples spiked with RRTE were cut into 5 mm × 5 mm × 1 mm slices, fixed with 3% (V/V) glutaraldehyde for 4 h, rinsed three times with 0.1 mol/L phosphate buffer for 10 min each time, dehydrated in a gradient of 30%, 50%, 70%, 90% and 100% (V/V) ethanol for 10 min each time, and dehydrated twice with 100% (V/V) ethanol. The replacement of isobutyl acetate was conducted in two stages, with 50% replacement on the first occasion and 100% replacement on the second. Following this, the microstructure was observed by scanning

electron microscope (JSM-840, JEOL Ltd., Akishima, Japan) and 10 000× images were recorded. The scanning electron microscope images were then processed using ImageJ software and its Fractal Box Count plug-in to measure the D_f . Prior to analysis, the scanning electron microscope images were thresholded and binarised. The D_f was calculated according to the formula (6). The D_f analysed through the image was performed based on a two-dimensional space and required an additional dimension to be added to the calculated value as a way to represent the three-dimensional properties of the protein gel system.

$$D_f = \frac{\ln N_\epsilon}{\ln \epsilon} + 1 \quad (6)$$

Where N_ϵ represents the number of boxes in the image at a certain scale (ϵ).

2.12 Data analysis

Origin 2021 was used to plot the data and SPSS 20.0 statistical software was used to perform one-way analysis of variance. All experiments were performed at least three times. In order to statistically analyse the results of the experiments, the mean and standard deviation were calculated based on the results of three independent experiments. Differences in means were assessed using Duncan's multiple-range test, and differences were considered significant at $P < 0.05$.

3 Results and discussion

3.1 Analysis of whiteness, water-holding capacity, and cooking loss

Whiteness is a crucial factor for evaluating surimi gel quality since it directly affects consumer acceptance^[21]. Hairtail surimi gel products with high whiteness, L^* , and low b^* are popular among consumers. As shown in Figures 1A and B, an increase in RRTE concentration resulted in a significant decrease in whiteness and L^* ($P < 0.05$), which was due to the inherent light-green color of the RRTE powder, which was retained in the solution after dissolution in water, thus leading to an increase in the a^* of the surimi gel and corresponding decrease in L^* . There was no obvious change in the b^* which was relatively stable with the increase of RRTE concentration, indicating that RRTE significantly reduced the whiteness of the hairtail surimi gel by influencing the a^* and L^* .

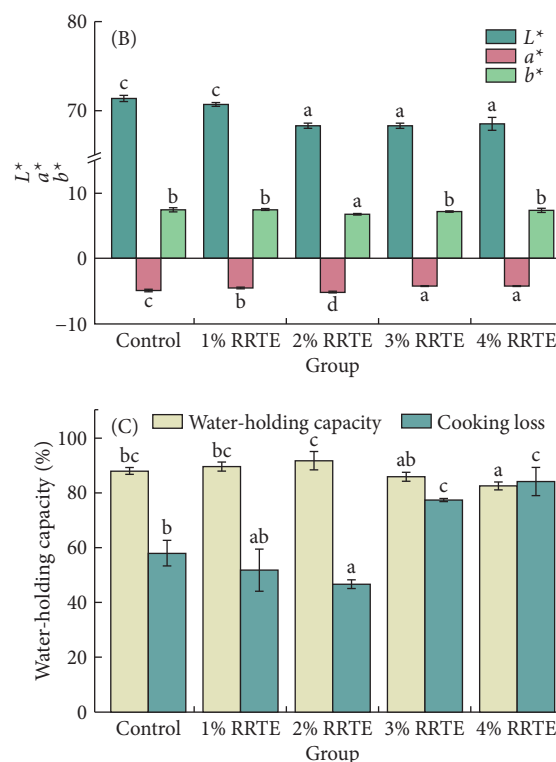
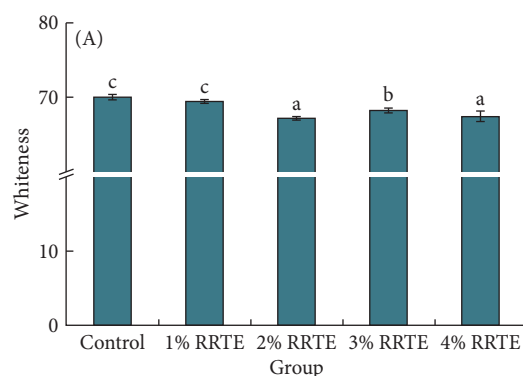


Figure 1 (A) Whiteness, (B) color difference values, and (C) water-holding capacity and cooking loss of hairtail surimi gel with different concentrations of RRTE. Different lowercase letters for the same indicator indicate significant differences ($P < 0.05$).

Water-holding capacity is an important index for evaluating the quality of surimi gel products^[22]. Figure 1C illustrates the effect of adding different concentrations of RRTE on water-holding capacity and cooking loss of hairtail surimi gel. The water-holding capacity tended to increase and then decrease as the RRTE concentration increased. The water-holding capacity of surimi gels with 1% and 2% RRTE increased to 89.54% and 91.70%, respectively, compared to the control group. In contrast, surimi gels with 3% and 4% RRTE decreased to 85.88% and 82.42% in water-holding capacity, respectively. In contrast, the cooking loss fluctuated, initially decreasing and then increasing ($P < 0.05$). The addition of 1% RRTE reduced cooking loss to 3.76%, while the addition of 2% RRTE reduced cooking loss to 3.39% ($P < 0.05$). Conversely, the addition of 3% and 4% RRTE increased the cooking loss to 5.62% and 6.11% ($P < 0.05$), respectively. The water-holding capacity are closely related to the gel network structure of surimi. The denser the three-dimensional network structure of the gel, the greater its water-holding capacity and lower its cooking loss^[23]. The greater the density, homogeneity, and order of the gel network, the more effective the water-holding properties^[24].

3.2 Electronic nose result analysis

Electronic nose has been widely used in the food industry for flavour analysis and quality control owing to its comprehensive characterization of food flavour^[25]. The electronic nose response values exhibited notable discrepancies between sensors W3C and W6S, suggesting that the observed differences in odor between the groups were primarily attributed to the aromatic and hydride components (Figure 2A). The response values of the W3C and W6S sensors exhibited a pronounced increase as the concentration

of RRTE increased, indicating that RRTE imparted aromatic and hydride components to the surimi gels. This phenomenon suggested that the addition of RRTE could significantly affect the volatile flavour components of surimi gel products and enhance the aromatic properties of the products. The accumulative variance contributions of the PC1 (95.15%) and PC2 (2.96%) of the principal component analysis (PCA) was 98.11% (Figure 2B), which demonstrated that the PCA was capable of representing the entirety of the volatile flavour components present in the samples. Through the PCA, the volatile components between the groups with RRTE had a certain overlap, and the degree of separation was low. There was no overlap between the gels of the Control group and the 4% RRTE group, which indicated that the volatile components differed greatly between the two groups, suggesting that the addition of a moderate amount of RRTE could improve the flavour of the surimi gels, but too much may mask the original odour characteristics of the surimi. Figure 2C shows the linear discriminant analysis (LDA) plot, which categorizes the samples and analyzes the distances between sample clusters. The analysis focuses specifically on low intragroup and high intergroup differences. The distribution of samples in the LDA plot is consistent with that in the PCA plot. It can be concluded that the addition of RRTE can change the flavour of surimi gel.

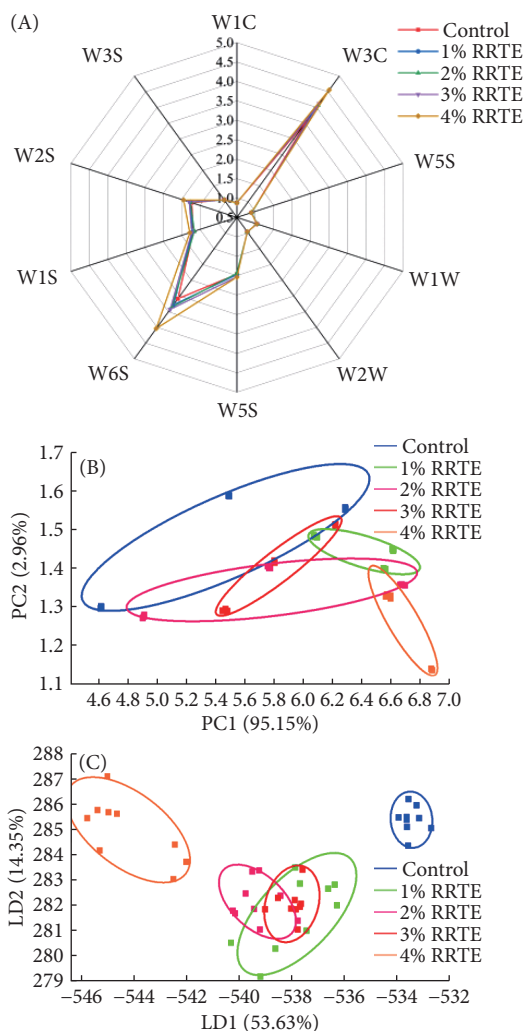


Figure 2 (A) Radar plots, (B) PCA and (C) LDA plots of electronic nose test results for hairtail surimi gel with different concentrations of RRTE.

3.3 Sensory evaluation result analysis

The sensory quality of food can be comprehensively evaluated using mathematical and statistical methods based on objective and authentic data obtained through sensory evaluations^[26]. A composite score was calculated from the weight of each indicator in the sensory evaluation (Figure 3). As the RRTE concentration increased, the colour scores decreased slightly, which was attributed to a reduction in the whiteness of the hairtail surimi gel owing to the color of the RRTE itself. As the concentration of RRTE increased, the odour scores gradually increased, indicating that the higher the concentration of RRTE, the better the effect of flavour improvement, which was consistent with the conclusion of the electronic nose PCA. However, as the concentration of RRTE increased, the taste scores decreased considerably due to the presence of organic acids such as tannins also present in RRTE, which could lead to an unpleasant taste sensation in the mouth, thus leading to a decrease in the taste scores of the consumers when chewing the surimi gel. What is noteworthy is that high concentrations of polyphenols and other active ingredients in RRTE can interact excessively with surimi proteins, leading to structural denaturation of the proteins, which reduces the stability and elasticity of the gel. In addition, high concentrations of RRTE may release excessive amounts of bitter components or off-flavour compounds, and excessive accumulation of these flavour and taste substances may affect the overall sensory quality of surimi products. In conclusion, a concentration of 2% RRTE is an ideal level of addition to enhance the quality of surimi gels, which can significantly improve the overall sensory quality while maintaining the stability of the gel structure.

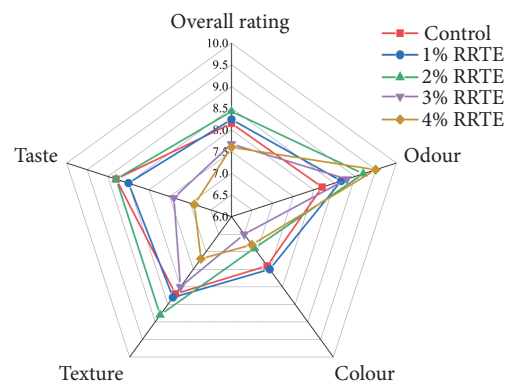


Figure 3 Sensory scores of hairtail surimi gels with different concentrations of RRTE.

3.4 Gel property analysis

Gel property is an important index for assessing the quality of surimi products, and the magnitude of gel properties is the product of the breaking force and distance^[27], with breaking force characterizing the hardness and breaking distance representing viscosity. With increasing RRTE, the breaking distance initially increased slightly and then decreased ($P > 0.05$) (Figure 4A), whereas breaking force decreased greatly ($P < 0.05$), indicating that the addition of RRTE affected the gel properties of surimi. The gel strength of the hairtail surimi first increased and then decreased ($P < 0.05$) (Figure 4B), with the maximum gel strength observed at 2% RRTE. The addition of polysaccharides to the hairtail surimi could promote cross-linking and aggregation of surimi gel proteins by water absorption and swelling, thus facilitating the formation of

a denser and more homogeneous three-dimensional network structure, which improves the properties of the surimi gel. However, the addition of excessive polysaccharides hindered the cross-linking and aggregation of surimi gel proteins, resulting in the three-dimensional network structure of the gel becoming relatively loose from ordered, thereby reducing the properties of the surimi gel. In this experimental study, the 2% RRTE had the best effect on the properties of surimi gels.

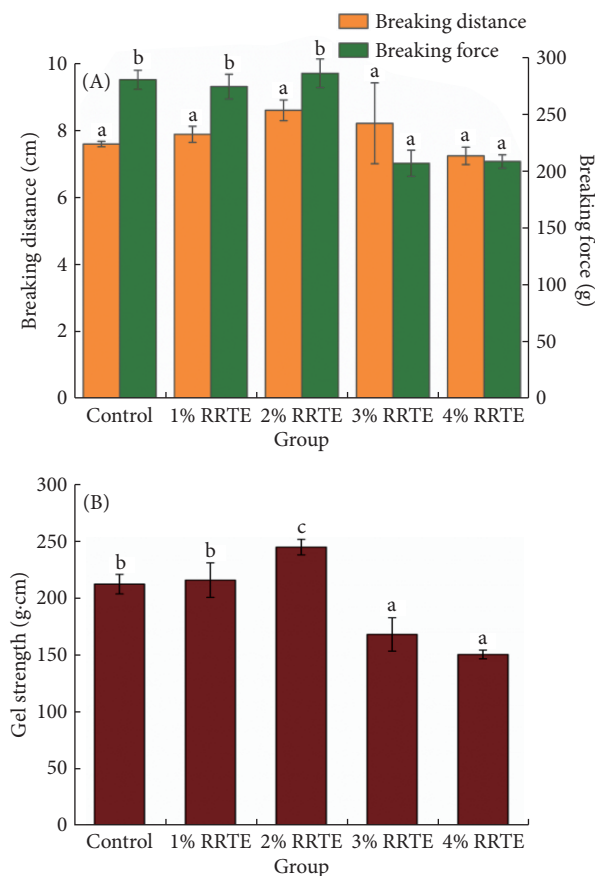


Figure 4 (A) Breaking force and breaking distance and (B) gel strength of hairtail surimi with different concentrations of RRTE. Different lowercase letters for the same indicator indicate significant differences ($P < 0.05$).

3.5 TPA parameters analysis

TPA characterizes the physical properties of food through simulating human tactile parameters (springiness, hardness, adhesiveness, stickiness, and chewiness). As shown in Table 2, the hardness of hairtail surimi gel was 7.49% and 16.21% higher than that of the control group at 1% and 2% RRTE, respectively, consistent with the trends in gel breaking force. The interaction

between polyphenols and polysaccharides is inevitable during the processing of hairtail surimi, which will result in the formation of different microstructures within the mixed system, altering the physicochemical properties of the food system, and thus affecting the organoleptic quality and nutritional properties of the hairtail surimi^[28]. The interaction between polysaccharides and proteins promoted the formation of a dense and uniform three-dimensional network structure, which enhanced the hardness of the hairtail surimi gel. Compared to control group, the hardness of the hairtail surimi gels decreased significantly by 11.59% and 22.88% with the addition of 3% and 4% RRTE, respectively. High polysaccharide levels inhibit the cross-linking and aggregation of proteins, resulting in a loose and disordered gel three-dimensional network structure^[29]. The springiness of the surimi gels decreased significantly with the addition of RRTE ($P < 0.05$), which could be attributed to the viscous behavior of the polysaccharide fractions within the gel matrix, leading to a decrease in springiness. In contrast, optimal chewiness was achieved with 2% RRTE and decreased significantly with 3% and 4% RRTE ($P < 0.05$). A similar pattern was observed regarding cohesiveness. This indicated that 2% RRTE could improve the mouthfeel of hairtail surimi gel. Gumminess demonstrated an inverse trend to springiness, indicating that the RRTE components promoted the viscosity of the gel matrix. The polyphenols in the extracts interacted with proteins to improve the density of the gel matrix and ultimately enhance texture and hardness^[30].

3.6 Rheological characterization

Rheological characteristic analysis is widely used to simulate human occlusion capacity, including viscosity, viscoelasticity, G' , and G'' ^[31]. Dynamic rheology is employed to investigate the viscoelastic changes in hairtail surimi gel during gelation at 20–90 °C. The G' and G'' are used to characterise the build-up and change of the three-dimensional network structure^[32]. All samples showed three phases during thermal induction at 20–90 °C, with gelation occurring at 20–35 °C, deterioration at 35–55 °C, and strengthening at 55–90 °C (Figure 5A). During gelation, a low peak appeared at 27 °C, indicating that protein interactions occurred at low temperatures and a relatively loose gel network structure was initially formed in the weakened stage of the gel^[14]. The G' decreased rapidly at temperatures between 40 and 60 °C, reaching its lowest level at 55 °C. The gel reinforcement stage, which G' increased steadily after 55 °C, was attributed to the thermally induced formation of an irreversible three-dimensional network structure, which stabilized the spatial structure of the hairtail surimi gel. At 20 °C, the control group exhibited the highest G' , which gradually decreased with increasing RRTE concentration. The addition of RRTE accelerated gel deterioration. The greatest improvement was observed in the 2% RRTE sample, which exhibited the highest G' at 90 °C, which indicated that RRTE induced the defolding of myosin molecules and increased the exposure of reactive ends to the

Table 2 TPA parameters of hairtail surimi gel with different concentrations of RRTE.

Group	Hardness (N)	Springiness (mm)	Chewiness (mJ)	Gumminess (N)	Cohesiveness
Control	2 428.84 ± 56.72 ^c	0.78 ± 0.00 ^b	423.22 ± 15.40 ^{b,c}	537.86 ± 13.64 ^{b,c}	56.66 ± 2.86 ^a
1% RRTE	2 610.79 ± 21.51 ^c	0.76 ± 0.02 ^b	386.53 ± 27.05 ^b	505.39 ± 26.15 ^b	65.66 ± 4.49 ^a
2% RRTE	2 822.57 ± 117.10 ^d	0.78 ± 0.00 ^b	551.05 ± 28.83 ^c	633.76 ± 34.17 ^c	58.66 ± 0.47 ^a
3% RRTE	2 147.39 ± 155.41 ^b	0.72 ± 0.01 ^a	289.53 ± 54.44 ^a	398.21 ± 71.11 ^a	80.66 ± 8.17 ^b
4% RRTE	1 873.04 ± 37.03 ^a	0.71 ± 0.02 ^a	217.19 ± 41.35 ^a	302.93 ± 48.84 ^a	88.33 ± 11.44 ^b

Note: Different superscript lowercase letters in the same column indicate significant differences ($P < 0.05$).

protein surface, leading to enhanced molecular interactions within the gel and, ultimately, to the formation of a stable gel network. The trends in G' and G'' were nearly identical within each group, with G' exhibiting a greater magnitude than G'' (Figure 5B). The $\tan\delta$ was consistently less than that during thermal induction, indicating that the G' predominated over the G'' (Figure 5C), which meant that surimi gels consistently exhibited firmness, higher elasticity, and stability during processing, which were key factors in their formation of a solid gel structure^[33].

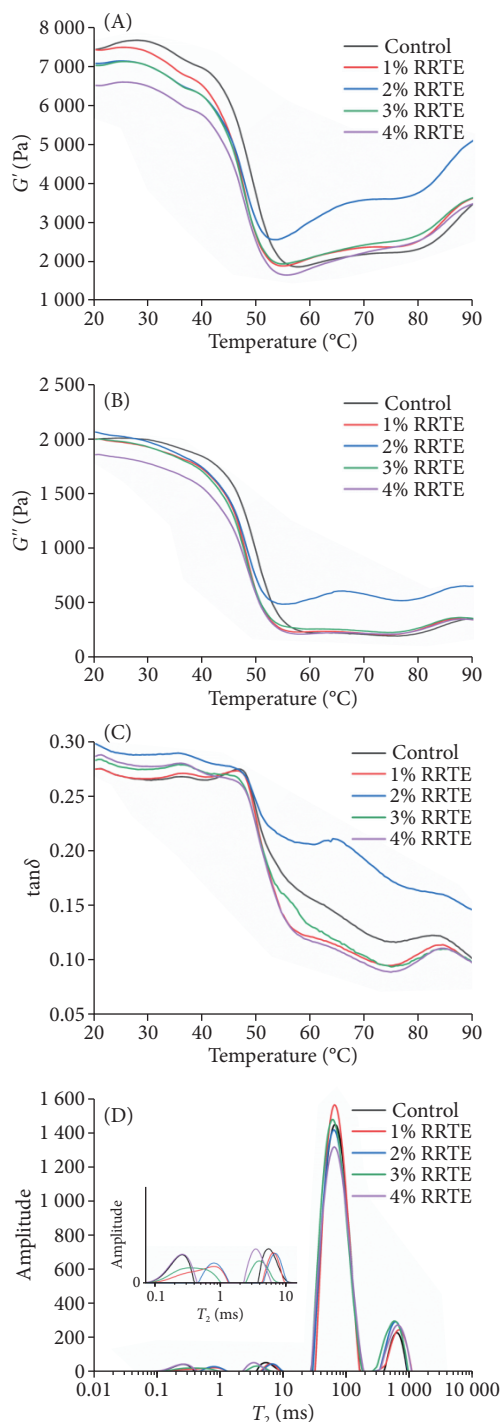


Figure 5 (A) G' , (B) G'' , (C) $\tan\delta$, and (D) T_2 relaxation spectra of hairtail surimi gels with different concentrations of RRTE.

3.7 Water distribution analysis

The low-field NMR T_2 can be used to assess the mobility of water molecules in surimi^[34]. When the mobility of water is restricted, the T_2 decreases accordingly, corresponding to a leftward shift in the T_2 plot. Figure 5D illustrates the T_2 of surimi derived from hairtail, with varying concentrations of RRTE supplementation. Four peaks of hydrogen protons are evident, representing the three states of moisture distribution. The first two peaks indicate bound water (T_{21} , 0–10 ms), the third one indicates fixed water (T_{22} , 10–300 ms), and the fourth peak indicates free water (T_{23} , 300–1 000 ms). The water migration distribution in hairtail surimi gel was revealed by comparing the T_2 and peaks of water in surimi samples between control group and different concentrations of RRTE supplemental groups. During the relaxation time, four typical peaks were observed in the T_2 relaxation spectra of each group, among which there were two distinct peaks in T_{21} . At both T_{22} and T_{23} , the hairtail surimi gel samples with different concentrations of RRTE exhibited a significant shift to the left relative to the control group. The addition of RRTE decreased the relaxation time and ability of water to migrate in the gel, which indicated that RRTE could enhance the ability of hairtail surimi gels to bind water by interacting with the proteins and forming a denser gel network^[35]. Further addition of RRTE increased the water relaxation time of hairtail surimi gels and increased the amount of free water, and excess RRTE inhibited protein aggregation and cross-linking, thereby reducing the binding of water in hairtail surimi gels, which was similar to the trends observed for indicators such as gel properties and water-holding capacity.

3.8 FTIR spectrum analysis

FTIR spectroscopy is a commonly employed technique for detecting molecular interactions based on changes in the intensity or position of absorption bands. Figure 6A shows the FTIR spectra of various surimi gel samples, which exhibit comparable absorption peak positions and sizes across all groups. The amide I band (C=O) stretching vibration was observed at 1 680–1 630 cm^{-1} , whereas the amide II (N–H vibration, 1 560–1 530 cm^{-1}) and amide III bands (C–N stretching and N–H bending vibration) appeared at 1 560–1 530 cm^{-1} and 1 630–1 600 cm^{-1} , respectively^[36]. Regarding protein secondary structures, considerable variability was observed in the spectra around 1 600–1 700 cm^{-1} , with peak intensity increasing with the incorporation of RRTE. The secondary structures of the proteins were analyzed using PeakFit software. Figure 6B illustrates the relative content of each protein secondary structure in the control group and different concentrations of RRTE groups. The protein secondary structures mainly included α -helix (1 600–1 640 cm^{-1}) and β -sheet. The relative content of the secondary structures exhibited considerable variation between groups, with peaks observed at 1 650–1 660 cm^{-1} , 1 660–1 700 cm^{-1} , and 1 640–1 650 cm^{-1} . These findings align with previous observations of four types of irregularly curled secondary structures at 1 640–1 650 cm^{-1} ^[37]. The α -helix and β -sheet secondary structures are important determinants of hairtail surimi gel strength. In the analysis of the secondary structures of proteins, the reduction of the α -helix structure is usually accompanied by the unfolding of the protein molecule and the exposure of hydrophobic groups, which in turn enhances the hydrophobic interaction forces between the molecules, thus swelling the gel network structure and increasing its stability. On the contrary, an increase in β -sheet structures suggests enhanced aggregation of protein molecules, which contributes to gel formation. In this study, the 2% RRTE group had the highest

relative content of β -sheet and random coil, while the lowest relative content of β -turn and comparatively low relative content of α -helix. This structural feature suggested that with the addition of RRTE, protein molecules unfolded more easily and increased hydrophobic interactions, whereas the formation of β -sheet promoted the aggregation of protein molecules, which ultimately constructed a robust gel network structure. This pattern of secondary structure changes explained the optimal gel performance of the 2% RRTE group.

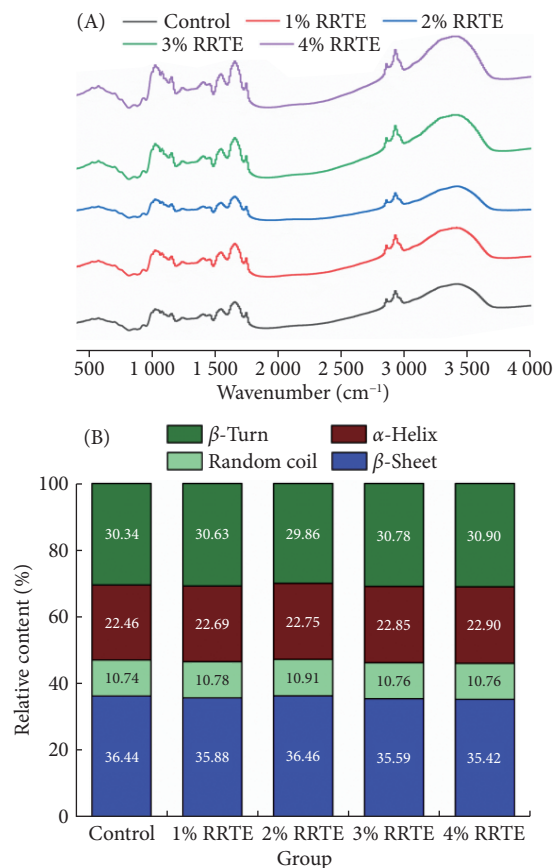


Figure 6 (A) FTIR spectra and (B) relative content of protein secondary structure of hairtail surimi gels with different concentrations of RRTE.

3.9 Microstructure and D_f analysis

The microstructure of the surimi is a crucial determinant of gel quality since it influences its water-holding capacity, appearance, and morphology^[38]. Figure 7 shows scanning electron microscope images of the microstructures of hairtail surimi gels in the control group and different concentrations of RRTE groups. The control group exhibited a poor microstructure, whereas RRTE improved the microstructure of the hairtail surimi gel. This was consistent with the trends in gel strength, water-holding capacity, and other indicators, thus proving that the moderate addition of RRTE could promote the cross-linking and aggregation of hairtail surimi proteins. Furthermore, by acting as a filler for gel pores while absorbing water to extrude the surimi matrix, RRTE improved the three-dimensional network structures of hairtail surimi gels.

The D_f is a physical quantity that describes the complexity of an irregular gel network. It reveals the compactness, denseness, and homogeneity of the three-dimensional network structure of the gel, as well as the size, number, and distribution of the pores in the gel network of surimi^[39]. A higher D_f indicates a denser and more homogeneous three-dimensional gel network, which in turn leads to enhanced surimi gel properties, including improved strength, water-holding capacity, and textural parameters, which collectively contribute to a superior quality surimi gel. The black portion of a dichotomization plot indicates the pores, while the white portion indicates the hairtail surimi matrix. In hairtail surimi gel, a greater D_f is associated with a denser and more homogeneous three-dimensional gel network, with superior properties and gel properties. The 2% RRTE samples exhibited the most favorable gel properties, including small and uniformly distributed pores. The addition of polysaccharides promoted protein network formation and enhanced gel properties. The variation rule for the different RRTE concentrations was found to increase and then decrease. The network structure of the surimi gel with 2% RRTE was the most complex, dense, and homogeneous, exhibiting optimal hairtail surimi gel properties.

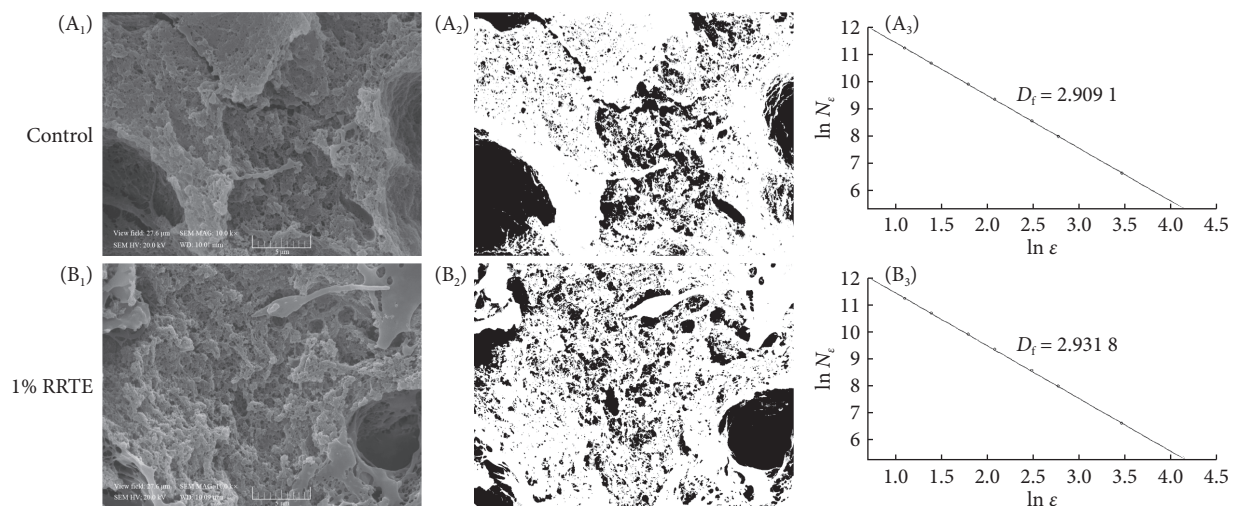


Figure 7 (A₁–E₁) Scanning electron microscope images and its (A₂–E₂) dichotomisation and (A₃–E₃) classification dimension diagrams of hairtail surimi gels with different concentrations of RRTE (10 000× magnification).

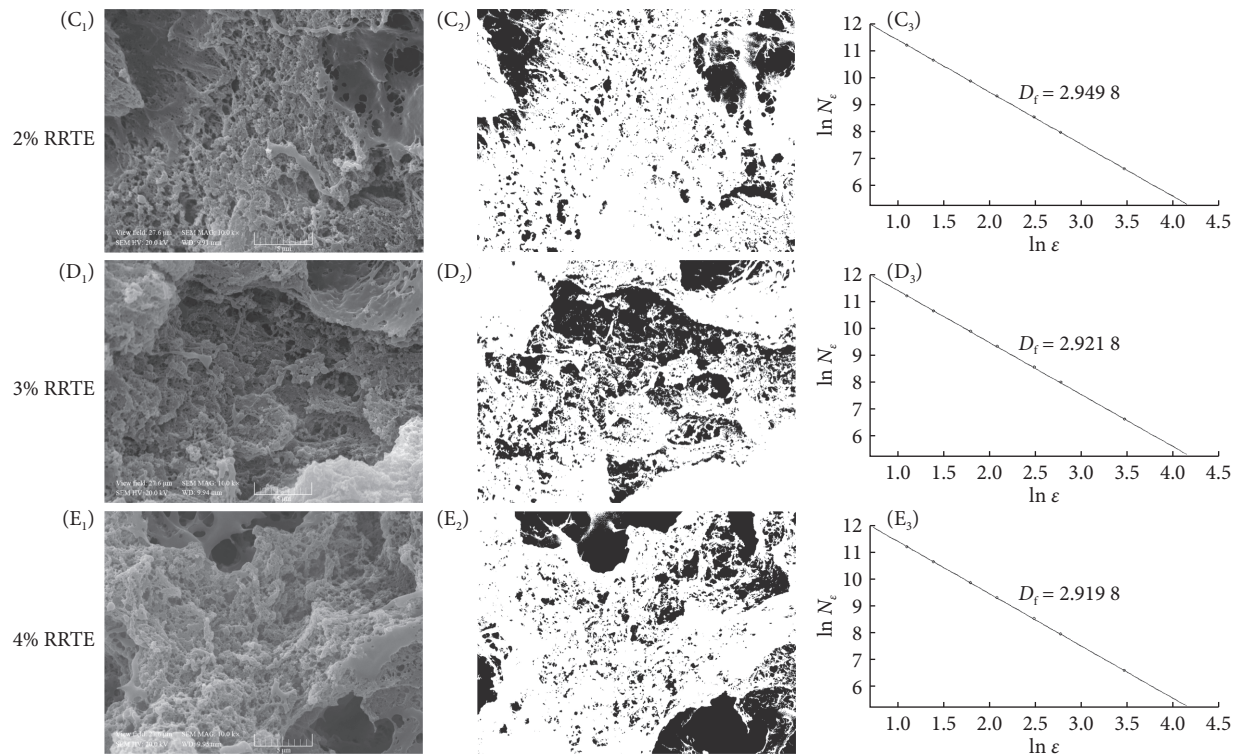


Figure 7 (Continued)

4 Conclusion

The sensory evaluation demonstrated that as the concentration of RRTE increased, the colour score exhibited a slight decline. This was attributed to the reduction in the whiteness value of surimi gel resulting from the light green colour of RRTE itself. Conversely, the odour score displayed an increase, which was in accordance with the findings of the electronic nose PCA. A comparison of the overall scores revealed that the 2% RRTE group exhibited the highest gel score, indicating that the addition of 2% RRTE concentration had the most beneficial effect on the quality and flavour of surimi gel. The addition of RRTE accelerated the deterioration phase in the gel formation of hairtail surimi sol, which improved heat-induced gel formation; altered the water relaxation time; and enhanced water fixation in the gel. The incorporation of RRTE into hairtail surimi gels enhanced their thermal stability, which was advantageous for maintaining stability during high-temperature sterilization. The addition of RRTE had a minimal impact on protein secondary structures in hairtail surimi gels. The 2% RRTE group exhibited the highest relative contents β -sheet and random coil, demonstrating the optimal surimi gel properties. This group also exhibited the best microstructure and highest D_f , indicating that 2% RRTE effectively maintained the optimal surimi gel properties. This study provides a useful reference for applying natural extraction additives in the production of high-quality surimi gels.

Conflict of interest

The authors have no conflicts of interest to declare.

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