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Creating added-value filet product from rainbow trout (*Oncorhynchus mykiss*) by salting and smoking method: physicochemical and textural attributes

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Rainbow trout (*Oncorhynchus mykiss*) are currently consumed as live fish, primarily for catering or consumers, as an alternative to salmon in sashimi or dishes. However, Covid-19 has hampered store and restaurant operations. Therefore, developing suitable processing conditions to extend its shelf life, such as online distribution specifications while enhancing the filets' commercial value, would raise its production value. In this study, we investigated the fish filets salted in a 5% salt solution for 2days and then smoked at 65°C for 4h under different storage conditions. As result, the higher rate of salt penetration and water loss in the resolved rigor mortis group was associated with tenderization of the meat compared to the rigor mortis group. Thermal-shrinkage and thermal-induced tissue destruction of the smoked fish filets during processing which affects the appearance, flavor, chewiness and overall acceptability. Nevertheless, according to the results of a consumer-type evaluation, the product characteristics of the fish filets from the resolution of rigor mortis group were consistent with those of the rigor mortis group, except for a weaker aroma. Thus, these results explain the relationship between frozen stored fish and the quality of processed products. The economic concept of regulating and distributing scheduling production between raw materials and finished products in the food industry conveys promising findings that will contribute to developing sustainable food processing systems.

KEYWORDS

rainbow trout, salted, smoked, circulation economy, sustainability

Highlights

- Flexibility in organizing stock and production schedules for bulk production.
- Maximizes the use of raw materials while reducing waste.
- Processing temperature and time must be strictly controlled.
- The smoked value of the fish remains even after storage at low temperatures.

1. Introduction

In 2020, international trade in world fisheries and aquaculture products yielded about $151 billion attributed to the COVID-19 explosion, below the record high of $165 billion in 2018 (FAO, 2022). Notably, aquaculture accounts for 91.6% of total production, and it is estimated that some 600 million people's livelihoods depend at least partly on fisheries and aquaculture (FAO, 2022). Fish is a significant contributor to macro- and micro-nutrient intake. Muscle foods, rich in valuable nutrients, such as high-quality protein, vitamins, and minerals, as well as n-3 polyunsaturated fatty acids (PUFAs), have long been appreciated by consumers (Sobral et al., 2018; Douny et al., 2021; Yemmen and Gargouri, 2022). It has been reported that about 60% of dietary protein requirements for adults are supplied by fish consumption (150 g) (Yemmen and Gargouri, 2022), and aquatic food provides about 17% of animal protein worldwide, reaching more than 50% in several countries in Asia and Africa (FAO, 2022).

Moreover, 80% of the total quality of fish meat is composed of water, which plays a crucial role in the texture and quality of the associated products (Sun et al., 2020). Consequently, it is essential to ensure the quality and safety of fish during processing while retaining the maximum quality of the original attributes, such as texture, flavor, and taste (Fomena Temgoua et al., 2022). Fisheries products (live, fresh, or frozen) account for 45% of global market consumption, while preserved products (dried, salted, brined, fermented, or smoked) account for 12% (Ekonomou et al., 2020; Gomes et al., 2021; Aksun Tümerkan, 2022). A significant increase in the production of rainbow trout (*Oncorhynchus mykiss*) has been realized, as this species has been widely cultured worldwide (Vásquez et al., 2022). The restaurant market favors sashimi as a rich source of PUFAs and the soft, delicate flavor (Zhao et al., 2022), which has the double benefit and provides sensory characteristics comparable to salmon at an affordable price for consumers with slightly more profitability for operators.

Smoking has been frequently used to store fish and meat. Smoking is an ancient food processing method that extends the shelf life of food by reducing moisture content and the antioxidant effects of phenols to minimize the microbial load (Iko Afé et al., 2021). It also improves sensory characteristics, including flavor, aroma, and appearance (Aksun Tümerkan, 2022; Praveen Kumar et al., 2022). The convenience of smoked fish products sold as ready-to-eat food has become popular (Bolívar et al., 2021). Nevertheless, these products have been recognized as high-risk in terms of potential contamination by foodborne pathogens, particularly *Listeria monocytogenes* (Iacumin et al., 2021), as the food requires no cooking before consumption. Thus, the initial microbial levels in food should be strictly controlled.

Smoking processes can be differentiated by temperature, and holding the temperature of the product at 30°C is called cold smoking. In comparison, hot smoking temperatures can reach 85°C at the center of the product to cook the food (Stołyhwo and Sikorski, 2005), but about 90% of the proteins are denatured at 60°C-65°C (Ünlüsayın et al., 2001). In addition, the smoke drying process involves hot smoking followed by a drying step in the equipment. Taken together, the food processing theory is that the smoke-drying process produces dried products with a water activity (AW) value≤0.75, thus, preserving the final product at room temperature and inhibiting microbial development (Iko Afé et al., 2021). Food products are smoked, dried, and heated *via* smoke obtained from the incomplete combustion of wood. Smoking causes more than 200 chemical compounds in the smoke to solidify, deposit on the product's surface, and infiltrate the inner layers. In particular, phenolic compounds contribute to the distinctive aroma and flavor of smoked products, while carbonyl groups yield sweet aromas and colors *via* the Maillard reaction (Bienkiewicz et al., 2022). The microbial growth and oxidation processes are delayed by the synergistic effects of salt, the smoke compounds, and dehydration, whether carried out using traditional or innovative smoking techniques, which facilitates preserving the smoked products (Ekonomou et al., 2020; Cunha et al., 2021; Gomes et al., 2021; Bienkiewicz et al., 2022). However, cooking and smoking (cold or hot) can reduce the risk of food hazards in raw fish; they may contribute to the formation of degradation products of unknown toxicity from existing pesticides or antibiotic residues (Mengden et al., 2015; Sobral et al., 2018). Therefore, processing time and temperature must be controlled during industrial production and home cooking. Hence, this study investigated the correlation between the degree of salinity, temperature, and smoking duration, which may help extend the shelf life of rainbow trout filets and increase the product's added value due to the smoke's unique flavor.

2. Materials and methods

2.1. Materials

The cultured rainbow trout (average weight 650 g) were purchased from a local market (Taichung, Taiwan). After removing the scales and viscera (average weight 500 g), the fish were rinsed in tap water, packed in polystyrene boxes covered with ice, and carried back to the laboratory within 30 min, where they were processed under different conditions for further analysis. All analytical grade reagents were purchased from Sigma-Aldrich® (Merck KGaA, Darmstadt, Germany).

2.2. Preparation for the smoking process

The smoking fish samples from each temperature (15 individuals) were transferred under a cold chain to the laboratory within 30 min. This study divided the rainbow trout filets (skinless) into groups according to the method described by Concollato et al. (2016), as detailed below. (1) Rigor mortis period (stored at 25°C for 2.5 h, 4°C and 0°C for 12 h). (2) Resolution of rigor mortis group (stored at 4°C and 0°C for 72 h), followed by the fish filets cut.

2.2.1. Evaluation of the smoked fresh rainbow trout processing conditions

The method followed that of Aksun Tümerkan (2022) with modifications. The rainbow trout filets stored under different conditions in section 2.2 were salted (5–20% NaCl, 5 days) and drained. The cured fish were washed with RO water, dried with tissue paper, and smoked (temperature 50°C- 80°C, 1–4 h) in a smokehouse ASR1297EL/WA (M&M Equipment Co., Skokie, IL, United States) until the filets reached an internal temperature of 72°C. Then, each group was packed separately under a vacuum and stored at 4°C to observe the filet quality changes. A sensory evaluation determined the optimal processing conditions for the final product.

2.2.2. Evaluation of the quality obtained with optimal salting and smoking

The rainbow trout filets stored for different times were salted (5% NaCl, 2 days) and smoked (temperature 65°C, 4 h) to evaluate the quality of the final product.

2.3. Determination of total viable count and psychrophilic bacteria

Microorganisms were detected based on the description of Lu et al. (2022) with modifications. Fish meat (10 g) was homogenized with 90 ml of sterile saline in the Stomacher® 400 Circulator Lab Blender (Seward Ltd., Worthington, United Kingdom) at low and high speeds for 2 min. Then 1 ml of the homogenate was added to 9 ml of sterile saline, followed by serial dilution, and 1 ml of the dilution was dispensed into culture dishes. The psychrophilic plate count agar (15 ml) was poured and then incubated at 37°C and 7°C for 2 and 10 days, respectively, and expressed as log CFU/g fish meat.

2.4. Determination of moisture content

Moisture was determined based on the method described in AOAC (2022) 930.15. The fish filets (3–5 g) were weighed in a flask (with constant weight) and dried in an oven at 105°C to constant weight. Moisture content was calculated using the following formula, expressed as moisture content (%).

$$Moisture\ content\,(\%) = {}^{W1}\!/_{W} \times 100$$

where W is the weight of the sample before baking (g) and W1 is the weight of the sample after drying (g).

2.5. Determination of salt content

A 5-g of salt-preserved sample was homogenized in 45 ml of distilled water, centrifuged at 1,000 × g for 5 min, and measured with a salinity meter (Atago Co., Ltd. Tokyo, Japan).

2.6. Determination of color

The color of the samples was measured as described by Huang et al. (2022). The samples' *L*, *a*, and *b* values were measured with a colorimeter (Nippon denshoku Co., Tokyo, Japan). The equipment was calibrated with a standard whiteboard (Y = 93.97, X = 91.96, and Z = 110.41) and measured by reflection, with three random measurements for each sample. The *L* value reflects the degree of lightness and darkness. A positive *a* value indicates a reddish color, while a negative value tends to be green. A positive *b* value indicates a yellowish color, while negative values tend to be blue.

2.7. Textural analysis

The textural analysis of the samples was performed using the methods described by Li et al. (2022) and Praveen Kumar et al. (2022), with some modifications. The samples were cut into about 1.5 cm^3 cubes, which were measured for hardness, elasticity, cohesion, and chewiness using the TA-XT2 Texture Analyzer (Stable Micro Systems Ltd., Godalming, U.K.) performed at 25°C room temperature. A P3 probe determined the conditions with 90% penetration of the measured sample at a 2 mm/s speed.

2.8. Sensory evaluation

The sensory evaluation was performed according to the method of Linhartová et al. (2019) and Lu et al. (2022), with modifications. In brief, the smoked fish filets were heated to a central temperature of 95°C in a microwave oven and then cooled for the hedonic scale test. A 7-point scale was used, including very much like = 7, neither like nor dislike = 4, and dislike = 1, for appearance, aroma, flavor, chewiness, and overall acceptability. The evaluation panel consisted of 60 experienced assessors, and the temperature was controlled at 25 ± 2°C. The panelists rinsed their mouths with drinking water after tasting each sample before proceeding to the next one.

2.9. Statistical analysis

All analyzes were performed in triplicate. The data were analyzed using SAS software (Version 9.0, SAS Institute, Cary, NC, United States) and the most minor square means (LS means). All data were statistically analyzed using one-way ANOVA, while as expressed as mean ± standard deviation. Duncan's multiple-range test was used to compare the differences between the means. A value of $p < 0.05$ was considered significant.

3. Results and discussion

3.1. Evaluation of rainbow trout smoking conditions

The smoking process was divided into fleshing, cutting, salting, seasoning, smoking, and storage. The salting process is important to enhance storage, flavor, and moisture for drying (Estévez et al., 2021). The functional role of salt in the texture of fish products is to solubilize the fish proteins, initiate protein extraction, and improve hydration and water-holding capacity. Additionally, the protein structural changes facilitate interaction with other components (e.g., water and lipids), which helps hold the product together while preventing water and fat loss (Gomes et al., 2021). Variations in the salt content of rainbow trout meat for the different salt formulations are shown in Table 1 and Figure 1A. In this study, the concentration of the salting solution was 5–10%, and the salt penetration rate slowed to 2.9 and 4.8%, respectively, within 2 days of dipping. It has been reported that filets dipped in 10% salt water for 4 h heighten the perception of the salty and smoky flavors, thus minimizing the fish taste (Ruiz-Alonso et al., 2021). However, the salt concentration was higher than 15%, thus showing an increasing trend in salt content with increased salting time, and did not reach the equilibrium concentration within 5 days. However, as the salinity of commercially available smoked products ranges from 2 to 6%, fish filets with a salt content >3% will be salty, and the salinity of fish filets that are salt dipped increases because of smoke drying. Therefore, this study selected 2 days of salt dipping in a 5% salt solution as the condition for salting the fish filets.

Moisture content changed during the salting of the rainbow trout filets in various concentrations of salt solution. The moisture content of the fresh fish filets (0 days) was 76.6%, and the moisture of the fish meat continuously trended downward with time at each salting concentration (Figure 1B). However, the moisture content of the fish filets decreased to about 75% within 2 days of dipping in the 5% salt solution. There was a greater tendency for moisture to decrease, as osmotic pressure increased with the higher salt content of the dipping solution (Delbarre-Ladrat et al., 2006). In addition, it has been reported that *Listeria monocytogenes* causes 11–60% of disease in cold-smoked fish and 4–12% of disease in heat-treated and cured seafood (Kołodziejska et al., 2002). Another investigation showed that the probability of *L. monocytogenes* in smoked fish is about 2.7% at the industrial level and 25% at the retail level (Mengden et al., 2015).

TABLE 1 Compositions of the brine pickling solution (%).

	Additives (%)			
NaCl	5.00	10.00	15.00	20.00
$NaNO_2$	0.16			
Water	94.57	89.57	84.57	79.57
Vitamin C	0.26			

The total viable count (TVC) (Figure 1C) of psychrophilic bacteria (Figure 1D) in the rainbow trout filets after dipping in the different salt concentrations showed that the TVC was lower, and the high salt content of the dipping solution had a pronounced inhibitory effect on bacteria beginning on the second day of storage. A significant difference was observed between the groups ($p < 0.05$; Figure 1C), indicating that the osmotic pressure caused by the salt solution significantly discouraged the propagation of microorganisms. At the same time, it was attributed to the ability of salt to reduce the AW of food and affect enzyme activity, which has been reported in the case of seafood products, where increasing salt concentration reduces bacterial growth (Gram and Huss, 1996; Mariutti and Bragagnolo, 2017; Abel et al., 2020; Giannakourou et al., 2023). Moreover, a significant case in point for the usefulness and necessity of salt is the inhibition of *Clostridium botulinum* development and toxin production in processed meats and cheeses (Taormina, 2010). The growth of psychrophilic bacteria was weakly inhibited by the dipping solutions with less than 10% salt content, but the inhibitory effect decreased on the second day of dipping, and the growth of the

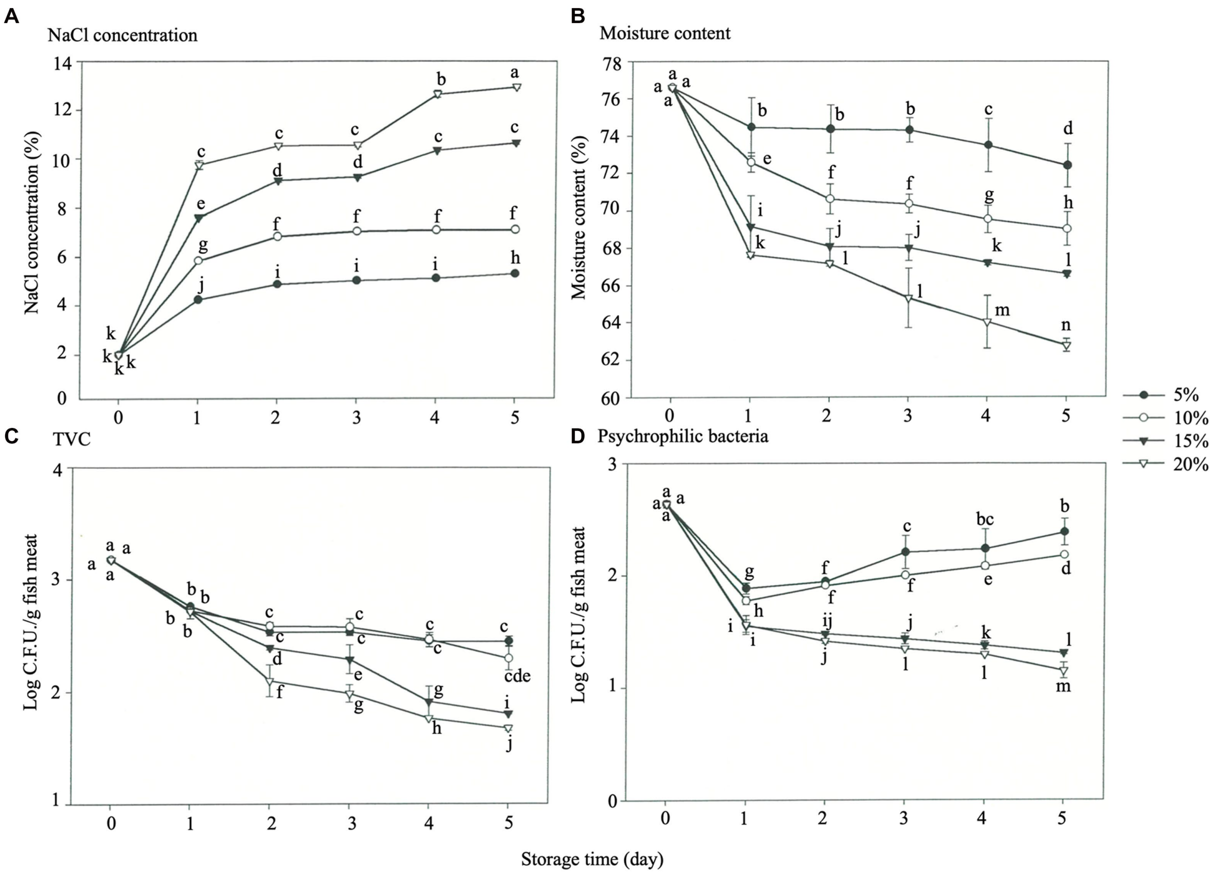

FIGURE 1
The evaluation of conditions suitable for smoking rainbow trout. **(A)** NaCl concentration; **(B)** Moisture content; **(C)** TVC; **(D)** Psychrophilic bacteria. Different lowercase letters indicate a significant difference (p<0.05).

psychrophilic bacteria increased with dipping time. However, the growth of psychrophilic bacteria was significantly inhibited in 15–20% salt content ($p < 0.05$; Figure 1D). However, it is worth mentioning that it indicates that seafood spoilage may be caused by lactic acid bacteria, *psychrotrophic Enterobacteriaceae,* and *Photobacterium phosphoreum* (Gram and Huss, 1996). Hence, NaCl will not ensure microbiological food safety (Kim et al., 2017).

The variations in the moisture content of rainbow trout during smoking showed that the moisture content decreased significantly at higher smoking temperatures ($p < 0.05$). However, the effect might also be related to the ability of NaCl, which increased the binding of water by causing swelling of proteins in the fish (Böcker et al., 2008; Abel et al., 2020). In addition, the moisture loss trend was consistent for 2 h at 65°C and 80°C (Figure 2A). We speculated that the high smoking temperatures probably caused the formation of a hard shell on the surface of the fish meat, which reduced drying efficiency during the subsequent stage.

Fresh fish products' apparent color and odor represent the two most important quality parameters for consumers (Linhartová et al., 2019). The chromatic changes in the *L*, *a*, and *b* values of rainbow trout during smoking indicated that the *L* value increased with increased smoking temperature and time, which was attributable to the denaturation of fish proteins at high temperatures. A similar trend was observed in the *a* and *b* values (Figures 2B–D). The variations in the *L* -value were attributed to moisture loss and protein degradation, but the product's surface underwent color changes after salting and smoking (Ruiz-Alonso et al., 2021). Furthermore, the formaldehyde, phenol, and cyclic hydrocarbon compounds in the smoke reacted with the Maillard reaction to the proteins on the fish surface, which could be the primary contributor to the color change (Bienkiewicz et al., 2022).

In contrast, given the delicate texture of rainbow trout meat, our goal was to maintain tenderness through smoking. Consequently, the salted rainbow trout filets were smoked at 50°C, 65°C, and 80°C for 1–4 h, respectively, followed by drying without post-heating, whereas the completed fresh rainbow trout filets were directly cooked in a microwave oven (900 W). The smoked rainbow trout filets were heated to a central temperature of 95°C and cooled to room temperature, followed by a consumer sensory evaluation. The sensory evaluation of the rainbow trout under different smoking conditions was conducted to assess the appearance, aroma, flavor, chewiness, and overall acceptability of the smoked filets (Table 2). The results revealed no significant difference in the chewiness or overall acceptability of the products smoked under different conditions. However, 4 h of smoking at 65°C provided the best appearance and flavor, and these parameters were used for smoking under different storage conditions.

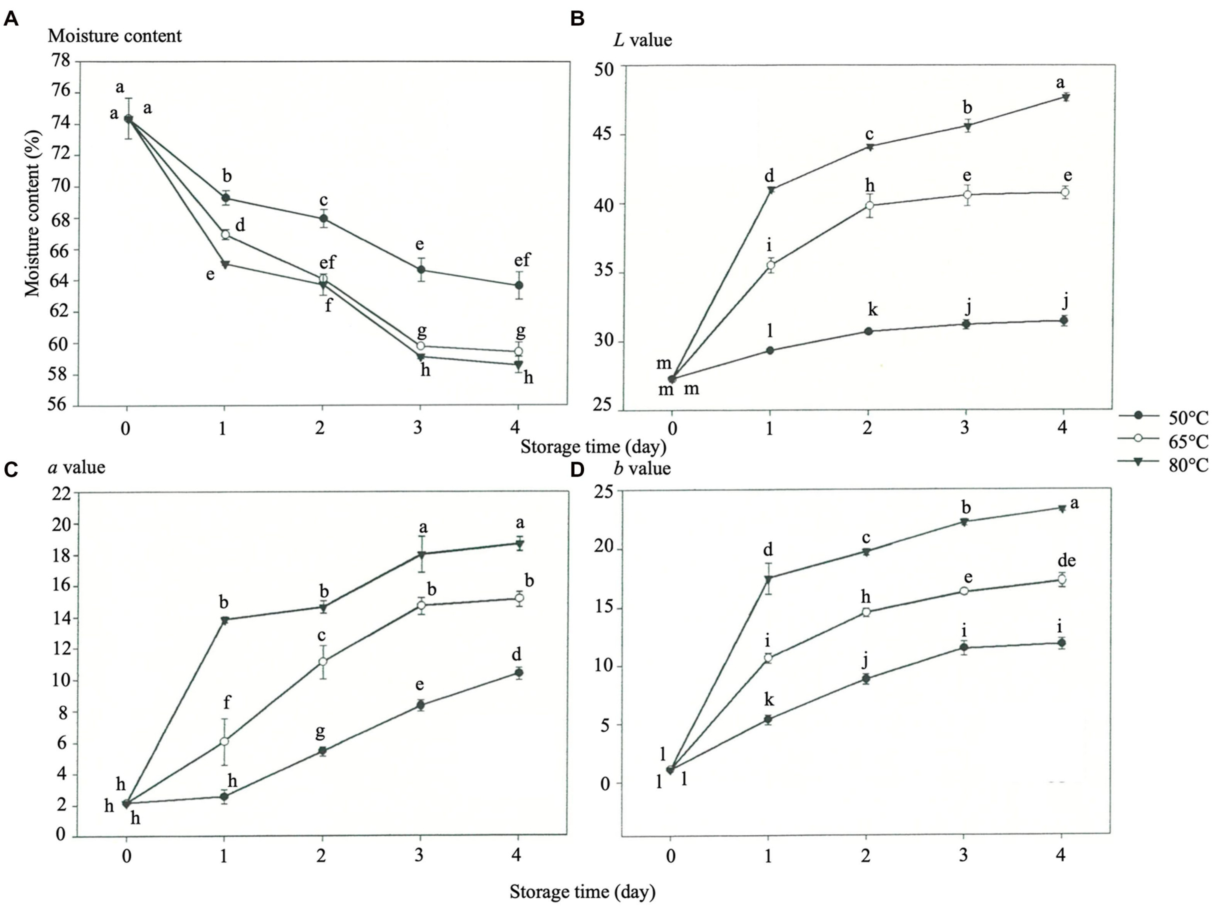

FIGURE 2
Effects of different smoking temperatures on the moisture content and color of smoked rainbow trout. **(A)** Mosture content; **(B)** *L* value; **(C)** *a* value; **(D)** *b* value. Different lowercase letters indicate a significant difference ($p<0.05$).

TABLE 2 Sensory evaluation of rainbow trout prepared with different smoking treatments.

Temperature (°C)	Time (h)	Appearance	Aroma	Flavor	Chewiness	Overall acceptability
50	1	4.7 ± 1.4c*	5.1 ± 1.1ab	5.2 ± 1.1ab	5.3 ± 1.0a	5.3 ± 0/9a
	2	4.9 ± 1.4bc	5.0 ± 1.1ab	5.2 ± 1.3ab	5.3 ± 1.1a	5.2 ± 1.1a
	3	5.2 ± 1.0abc	5.3 ± 1.1ab	5.2 ± 1.2ab	5.2 ± 1.3a	5.2 ± 1.1a
	4	5.4 ± 1.0ab	5.4 ± 1.1a	5.2 ± 1.2ab	5.4 ± 1.1a	5.4 ± 1.0a
65	1	5.2 ± 1.1abc	4.9 ± 1.2ab	4.9 ± 1.4ab	5.0 ± 1.4a	4.9 ± 1.5a
	2	5.2 ± 1.1abc	5.1 ± 1.0ab	5.3 ± 1.5ab	5.5 ± 1.0a	5.4 ± 0.9a
	3	5.1 ± 1.3abc	5.3 ± 1.3ab	5.7 ± 1.4ab	5.3 ± 1.4a	5.1 ± 1.3a
	4	5.5 ± 1.0a	5.0 ± 1.4ab	5.7 ± 0.9a	5.2 ± 1.6a	5.0 ± 1.5a
80	1	5.2 ± 1.0abc	4.7 ± 1.3b	5.0 ± 1.5ab	5.2 ± 1.4a	5.2 ± 1.3a
	2	5.1 ± 1.1abc	4.9 ± 1.3ab	5.1 ± 1.2ab	5.2 ± 1.4a	5.1 ± 1.1a
	3	5.0 ± 1.1abc	5.0 ± 2.0ab	5.0 ± 1.2ab	5.2 ± 1.1a	5.3 ± 1.1a
	4	4.9 ± 1.1abc	4.9 ± 1.1ab	4.9 ± 1.3b	5.0 ± 1.2a	5.0 ± 1.2a

*The lowercase letters mean in the same row with different subscripts are significantly different ($p < 0.05$).

3.2. Quality of rainbow trout products smoked under different conditions

The best way to assess the quality of a product is a sensory evaluation (Linhartová et al., 2019). Therefore, the sensory preference and overall acceptance of consumers regarding storage, aging, salting, and smoking conditions, with a positive effect on enhancing the quality of smoked products, is significant. In this study, the rainbow trout filets were cut during rigor mortis (2.5 h at 25°C, 12 h at 4°C, and 0°C), and the resolution of rigor mortis group (72 h at 4°C and 0°C), followed by salting and smoking to investigate the effects of the muscular state of the rainbow trout filets on the quality of the smoked product. In this study, variations in the salt content of rainbow trout were found in the resolution of rigor mortis (2.5 h at 25°C and 12 h at 4°C and 0°C) compared to the rigor mortis groups (72 h at 4°C and 0°C; Figure 3A). However, the salt content of the fresh fish was the lowest on the first day of dipping, whereas the salt concentration on the second day was approximately the same as that of the rigor mortis group, which may have been caused by the intact muscle structure of the fresh fish, as fish meat with intact cell membranes maintains a specific permeation pressure in response to different internal and external salt concentrations (Oliveira et al., 2017). Furthermore, endogenous enzymes damaged the fish tissue in the resolution of rigor mortis group, resulting in incomplete cell membranes and higher salt concentrations during the impregnation process.

Changes in the moisture content of rainbow trout under the different storage conditions in a 5% salt solution (Figure 3B) were detected for the rigor mortis and the resolution of rigor mortis groups. An increase in moisture content was associated with increased dipping time. However, the moisture content of the fish filets in the resolution of rigor mortis group was significantly higher than that of the rigor mortis group, which was attributed to the weakness of the muscle tissue after rigor mortis, which allowed the brine to enter gaps in the muscle tissue. As salt-soluble proteins dissolved, the degree of protein hydration increased, thus, increasing the moisture content of the fish. In contrast, fresh fish are continuously dehydrated, caused by intact muscle cells and the effect of osmotic pressure. Again, it was verified that NaCl serves preservation purposes rather than seasoning, which was attributed to the reduction of AW, and inhibited microbial growth, resulting in the extended shelf life (Abel et al., 2020; Ekonomou et al., 2020; Gomes et al., 2021; Giannakourou et al., 2023).

A food process must enhance the product's safety, reduce the formation of hazardous substances (chemical or microbial), and retain nutrients (Sobral et al., 2018; Praveen Kumar et al., 2022). Several studies have reported that lactic acid and yeast are most abundant in vacuum-packed hot-smoked fish stored at low temperatures, but appropriate storage maintains the organoleptic properties and inhibits microbial growth in products (Jemmi and Keusch, 1992; Mengden et al., 2015; Ekonomou et al., 2020). The most common species of psychrophilic bacteria are *Yersinia* pestis, *L. monocytogenes*, and *Pseudomonas* spp. The TVC (Figure 3C) and psychrophilic bacteria (Figure 3D) in rainbow trout under different storage conditions and a 5% salt dipping solution decreased during dipping in the rigor mortis and the resolution of rigor mortis groups. However, the TVC in the resolution of rigor mortis group was higher than that in the rigor mortis group, which was attributed to the higher bacterial count in the fish before dipping.

The psychrophilic bacteria increased during the dipping period in all groups. In particular, the resolution of rigor mortis groups (4°C and 72 h and 0°C and 72 h) showed a rapid rise in the number of psychrophilic bacteria on days 2 and 4 of dipping. It is well known that the combination of smoking, refrigeration, and reducing AW and antibacterial and antioxidant properties prolongs the shelf life of smoked fish, as similar results were observed in this study. Fortunately, regardless of the storage conditions, the microbes in the 5% salt-dipped rainbow trout for 2 days complied with the food hygiene standards. Although the levels of microorganisms are low after smoking and refrigeration, it is important to prevent contamination. Notably, *L. monocytogenes* can contaminate food during storage at refrigerated temperatures (Mengden et al., 2015). However, smoked fish can also become contaminated with microbes due to improper storage conditions and manufacturing practices before or after smoking (Douny et al., 2021). Thus, consumers may be at increased risk when storing smoked fish products for extended periods.

The changes in moisture content of the rainbow trout filets during smoking showed that the moisture content in the resolution of rigor

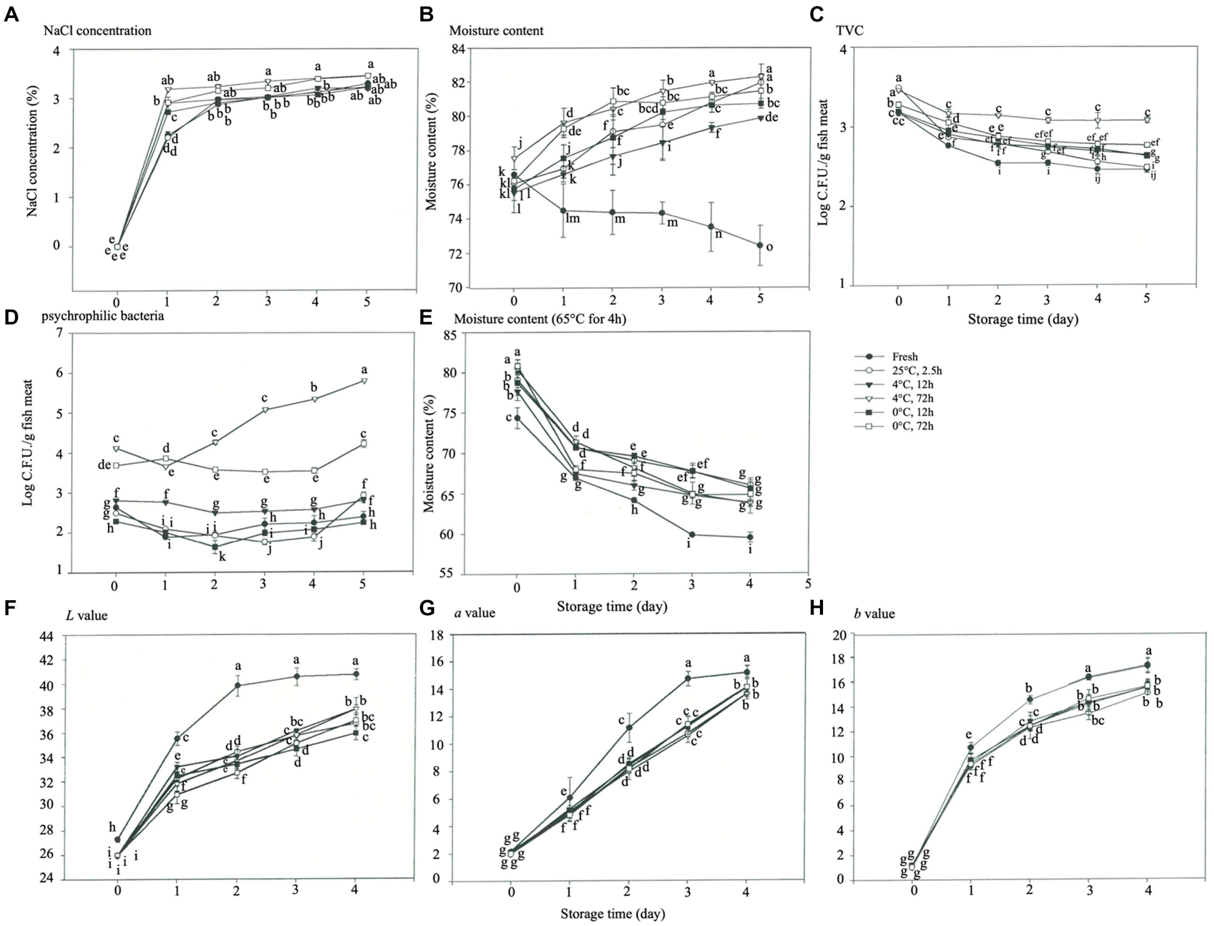

FIGURE 3
The physicochemical properties of smoked rainbow trout under different storage conditions. **(A)** NaCl concentration; **(B)** Moistue content; **(C)** TVC; **(D)** Psychrophilic bacterias; **(E)** Moisture content; **(F)** *L* value; **(G)** *a* value; **(H)** *b* value. Different lowercase letters indicate a significant difference ($p<0.05$).

mortis groups decreased faster than in the rigor mortis groups (Figure 3E). We hypothesized that the fish tissue in the rigor mortis group weakened due to forming more muscle fiber interstices, thereby releasing more moisture from the muscle. In contrast, moisture content decreased significantly in the fresh fish (control group) due to the lower moisture content post-salting. The *L*, *a*, and *b* values increased during the smoking of the rainbow trout filets under different storage conditions (Figures 3F–H). The muscle filet conditions have no significant effect on the chromatic changes during the smoking process.

The textural analysis included variations in the hardness, elasticity, cohesiveness, and chewiness of the rainbow trout filets during smoking (Table 3). As a result, hardness increased continuously in all groups during the smoking process, which was attributable to the constant denaturation of muscle protein. Contraction of beef during cooking is caused by the thermal denaturation ascribed to myofibrillar and connective tissue proteins (Vaskoska et al., 2021). The myofibrillar fraction or the structural proteins accounted for 64% of the total protein in rainbow trout white muscle, while soluble myoplasmic proteins accounted for 30% of the total protein (Delbarre-Ladrat et al., 2006). Moreover, the elasticity, cohesiveness, and chewiness of the fresh and rigor mortis groups increased during smoking, while these characteristics appeared to increase and then decrease in the resolution of rigor mortis groups. According to these results, the weakening of muscle tissues was more evident in the resolution of rigor mortis group than in the rigor mortis groups. Remarkably, the hardness of the filets increased by smoking and heating. It was hypothesized to be associated with sustained thermal exposure, which damages the muscle tissue, thereby altering the texture of the filets. Praveen Kumar et al. (2022) reported that fish meat texture softens during storage, which is caused by protein- degradation or hydrolysis, resulting in slightly reduced chewiness and gumminess.

Furthermore, protein is a key component in food that interacts with various functional components to form the sensory properties of the food (Tahergorabi et al., 2011). The sensory evaluation results revealed no differences in appearance, flavor, chewiness, or overall acceptability scores for the rainbow trout filets (Table 4) smoked at 65°C for 4 h and cooked in microwave heat. However, the rigor mortis group had higher aroma scores than the resolution of rigor mortis groups, except for the 25°C/2.5 h condition. In theory, there should be a significant difference in the taste of the smoked product resulting from rigor mortis, resolution of rigor mortis, and fresh material. However, the results showed that the resolution of rigor mortis groups had the same properties, except fewer aromas after smoking in the resolution of rigor mortis groups, indicating that rainbow trout stored at 4°C and 0°C for 3 days can be processed for smoking.

TABLE 3 Changes in hardness, elasticity, cohesiveness, and chewiness of rainbow trout stored under different conditions.

	Conditions	0	1	2	3	4
Hardness	Fresh	156.30 ± 10.30c	170.20 ± 10.00bc	184.00 ± 12.80b	225.70 ± 5.10a	242.70 ± 11.20a
	25°C, 2.5 h*	108.80 ± 4.70c	116.80 ± 6.80c	128.50 ± 5.50b	138.00 ± 5.60b	155.00 ± 13.20a
	4°C, 12 h	109.30 ± 13.20b	118.00 ± 8.50b	123.80 ± 6.80b	140.30 ± 7.80a	154.00 ± 7.90a
	4°C, 72 h	51.30 ± 11.90c	66.70 ± 4.20b	70.00 ± 2.70b	77.30 ± 2.50b	89.00 ± 3.60a
	0°C, 12 h	108.80 ± 12.50c	116.00 ± 4.80c	122.30 ± 8.70bc	131.50 ± 7.40b	159.70 ± 6.10a
	0°C, 72 h	52.70 ± 3.20c	63.70 ± 1.20b	65.00 ± 3.60b	78.30 ± 5.50a	82.30 ± 6.70a
Elasticity	Fresh	0.95 ± 0.00d	0.96 ± 0.00c	0.97 ± 0.01b	0.98 ± 0.00a	0.98 ± 0.00a
	25°C, 2.5 h	0.92 ± 0.01b	0.94 ± 0.01a	0.95 ± 0.02a	0.95 ± 0.01a	0.94 ± 0.01a
	4°C, 12 h	0.92 ± 0.01c	0.93 ± 0.00b	0.95 ± 0.01ab	0.96 ± 0.00a	0.96 ± 0.00a
	4°C, 72 h	0.91 ± 0.07bc	0.93 ± 0.01a	0.92 ± 0.00b	0.91 ± 0.00c	0.88 ± 0.01d
	0°C, 12 h	0.92 ± 0.01bc	0.93 ± 0.01bc	0.95 ± 0.01a	0.95 ± 0.01a	0.94 ± 0.01ab
	0°C, 72 h	0.92 ± 0.00b	0.93 ± 0.01a	0.92 ± 0.00b	0.91 ± 0.01c	0.88 ± 0.01d
Cohesiveness	Fresh	0.36 ± 0.00d	0.37 ± 0.01 cd	0.38 ± 0.00bc	0.40 ± 0.01a	0.40 ± 0.01a
	25°C, 2.5 h	0.35 ± 0.01b	0.37 ± 0.01a	0.38 ± 0.01a	0.38 ± 0.01a	0.37 ± 0.01a
	4°C, 12 h	0.35 ± 0.01b	0.36 ± 0.01b	0.38 ± 0.01a	0.38 ± 0.01a	0.37 ± 0.01a
	4°C, 72 h	0.32 ± 0.01b	0.34 ± 0.00a	0.34 ± 0.01a	0.32 ± 0.00b	0.31 ± 0.01b
	0°C, 12 h	0.34 ± 0.01c	0.35 ± 0.01bc	0.36 ± 0.01b	0.38 ± 0.01a	0.36 ± 0.01b
	0°C, 72 h	0.34 ± 0.02abc	0.34 ± 0.01ab	0.30 ± 0.00a	0.33 ± 0.01bc	0.32 ± 0.01c
Chewiness	Fresh	52.87 ± 4.09c	58.74 ± 3.74c	68.72 ± 5.47b	86.06 ± 4.00a	91.22 ± 3.62a
	25°C, 2.5 h	33.99 ± 1.41d	41.05 ± 4.04c	45.94 ± 2.56bc	49.81 ± 2.82ab	52.73 ± 4.56a
	4°C, 12 h	35.18 ± 3.45c	39.73 ± 3.54c	45.20 ± 2.86b	50.11 ± 2.85ab	54.17 ± 2.09a
	4°C, 72 h	15.30 ± 3.86c	20.23 ± 0.70b	22.06 ± 0.43a	22.52 ± 0.54a	21.30 ± 1.20ab
	0°C, 12 h	32.43 ± 1.97d	39.68 ± 1.40c	41.55 ± 1.98c	45.73 ± 2.03b	52.94 ± 2.74a
	0°C, 72 h	16.28 ± 0.76c	20.05 ± 0.99b	23.48 ± 1.73a	21.90 ± 1.49ab	20.81 ± 1.25ab

*The lowercase letters mean in the same row with different subscripts are significantly different ($p < 0.05$).

TABLE 4 Sensory evaluation of smoked fish meat of rainbow trout in different storage conditions.

Conditions	Appearance	Among	Flavor	Chewiness	Overall acceptability
25°C, 2.5 h	4.9 ± 1.1a*	4.9 ± 1.1a	5.0 ± 1.4a	5.1 ± 1.2a	5.1 ± 1.1a
4°C, 12 h	5.0 ± 1.1a	5.0 ± 1.0a	5.1 ± 1.2a	5.3 ± 1.2a	5.2 ± 1.1a
4°C, 72 h	5.1 ± 1.1a	4.8 ± 1.0ab	5.1 ± 1.2a	5.0 ± 1.3a	5.0 ± 1.1a
0°C, 12 h	4.9 ± 1.1a	5.0 ± 1.0a	4.9 ± 1.4a	5.0 ± 1.1a	5.1 ± 1.2a
0°C, 72 h	4.9 ± 1.2a	4.7 ± 1.1ab	4.7 ± 1.4a	5.0 ± 1.3a	4.8 ± 1.3a

*The lowercase letters mean in the same row with different subscripts are significantly different ($p < 0.05$).

4. Conclusion

This study found that the characteristics of rainbow trout filets with rigor mortis or resolution of rigor mortis were processed by salting and smoking at different storage temperatures were similar, except for less aroma in the resolution of rigor mortis groups. Therefore, rainbow trout stored at 4°C and 0°C for 3 days could be smoked, resulting in a good quality smoked product and a potential home application for the general public. It will be necessary to develop a process to extend the shelf life of rainbow trout to minimize the physical, chemical, and biological reactions that cause the deterioration of freshly harvested seafood. In cases of a lack of availability of fresh fish, a refrigerated stock (4°C and 0°C for 3 days) could be considered for production by smoking to relieve the inventory pressure. A risk assessment should be conducted on heat-induced toxic compounds in food (nitrosamines and polycyclic aromatic hydrocarbons) in the future.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

P-HH and P-HL: conceptualization. P-MW and P-HL: formal analysis. Y-TC and W-CK: funding acquisition and resources. Y-TC, S-CC, P-MW, and W-CK: investigation. P-HH, W-CL, S-CC, and P-HL: methodology. Y-TC: project administration. Y-TC, S-CC, P-MW, and P-HL: software. S-CC: supervision. Y-TC, W-CL, P-MW, and P-HL: validation. P-HH and W-CL: visualization. P-HH, W-CL, and P-HL: writing–original draft and writing–review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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