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Research Paper

Effects Of Ultra-High Pressure and Thermal Treatment on Quality Characteristics of Prepared Mackerel Fish Balls

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Abstract: Safe and high-quality prepared foods are increasingly preferred by consumers. This study investigates how ultra-high pressure (UHP) and thermal treatment affect the quality characteristics of prepared mackerel fish balls for surimi product manufacturing. Prepared mackerel fish balls were subjected to UHP treatment at 250 or 350 MPa (10 min) and thermal processing (121°C for 13 or 15 min) to establish comparative preservation protocols. Comprehensive evaluation was conducted on microbiological parameters (total bacterial count), chemical indicators (total volatile basic nitrogen [TVB-N] and malondialdehyde [MDA] levels), organoleptic properties (sensory evaluation), chromatic measurements, and texture analysis. Results demonstrated that both thermal and ultra-high pressure treatments reduced total bacterial count, TVB-N content, and MDA content in prepared mackerel fish balls. UHP treatment did not significantly affect color and texture of fish balls, with pressure-induced color changes remaining within acceptable bounds. However, thermal treatment adversely affected these properties and compromised sensory characteristics. UHP processing (350 MPa/10 min) demonstrated excellent microbial inactivation at 0 and 7 days while maintaining superior sensory properties in mackerel fish balls. Compared with thermal treatment, 10-minute UHP treatment at 350 MPa is recommended for producing prepared mackerel fish balls with optimal quality characteristics.

Keywords: Ultra-High Pressure Processing, Thermal Processing, Mackerel, Surimi Products, Fish Balls, Food Preservation, Microbial Inactivation, Sensory Quality

Introduction

Scomberomorus, belonging to the *Perciformes* order, *Scombroidei* suborder, *Scombridae* family, is a significant marine commercial fish species in China (Yang *et al*., 2024). It has a delicious taste, abundant fish meat with few bones, and is rich in various proteins and vitamins (Zhang *et al*., 2022). Mackerel cannot only be directly cooked and consumed, but also be processed into various seafood products such as surimi-based products, dried fish, and fish intestines (Wu, 2016; Yang *et al*., 2025; Mkadem & Kaanane, 2024). Due to pandemic and other reasons, prepared meals (or prepared foods) are becoming increasingly popular, ad various fish-based prepared foods provide significant convenience for daily life (Jia *et al*., 2024; Liu *et al*., 2025).

Fish balls are fish surmi-based products that have high moisture content and rich nutrition. They are widely welcomed due to low cost and high nutrition. However, they are also prone to microbial contamination and spoilage. Thermal treatment technology, as a traditional sterilization method, uses high temperature to inactivate microorganisms and enzymes for food preservation (Yu *et al*., 2024a). Thermal treatment is essential for most prepared meat products (such as fish balls), as it can improve their texture, color, taste, and smell. Long-time thermal treatment will kill microorganisms in fish balls, thereby lowering the textural quality. There have been some explorations on the preservation effect of fish balls such as treating fish balls with extracts of peppermint leaves, cowpea leaves, and grape seeds that have natural antioxidant and antibacterial properties (Guan *et al*., 2019), preparing composite chitosan coatings to improve the preservation of fish balls (Wei *et al*., 2018), and adding sodium alginate to reduce the quality loss of frozen fish balls after thawing (Li *et al*., 2024). However, these treatments are difficult to achieve good sterilization and preservation while improving the quality of fish balls.

Therefore, to prevent quality degradation caused by high-temperature treatment and improve product safety and quality, alternative methods such as non-thermal processing should be adopted.

Ultra-high pressure (UHP) technology, as an emerging non-thermal sterilization technology, is a promising environmental protection technology for various food applications. It can effectively reduce microbial contamination while maintaining product quality attributes (Huang *et al*., 2024; Liu *et al*., 2022). Food treated with UHP has also been demonstrated to have an extended shelf-life (Enchangan *et al*., 2025). Recent studies have shown that UHP treatment is effective in seafood processing, particularly in extending shelf-life, ensuring microbial safety of raw products, altering protein functionality, and enhancing textural properties (Luo *et al*., 2021). However, pressures exceeding 400 MPa may cause adverse effects, including permanent protein denaturation, accelerated lipid oxidation, structural degradation and color alterations (Aubourg, 2018). Therefore, in practical applications, optimal UHP treatment parameters (pressure levels and duration) should be determined based on specific samples.

There are no studies on UHP-treated prepared mackerel fish balls, and the use of UHP technology in developing prepared surimi-based products is limited. It is needed to verify whether UHP treatment is better than thermal processing in improving the quality of fish balls. This study aims to systematically evaluate the quality characteristics (microbiological, chemical, physical, textural and sensory characteristics) of prepared mackerel fish balls, so as to assess the feasibility of UHP treatment in the production of prepared fish balls.

Materials and Methods

Material and Reagents

Fresh mackerel (each weighing approximately 1kg) were acquired at the fish market in Zhanjiang. Eggs, salt, sweet potato flour, chicken essence, edible oil, scallions and ginger are commercially available in food grade.

Agar medium, sterile phosphate buffer/sterile physiological saline, malondialdehyde (purity ≥97%), methyl red indicator, bromocresol green indicator, 95% ethanol, thiobarbituric acid, trichloroacetic acid, magnesium oxide, boric acid, and hydrochloric acid/sulfuric acid are all analytical grade.

Main Instruments and Equipment

Ultra-high pressure equipment: HPP.W1-400/1 Tianjin Huatai Senmiao Biotechnology Co., Ltd; Vacuum packaging machine: DZ400-2SB, Zhejiang Dingye Machinery Equipment Co., Ltd; Texture analyzer: TMS-PRO, FTC Corporation in the United States; Fully automatic colorimeter: SC-80C, Dalong Xingchuang Experimental Instrument (Beijing) Co., Ltd; Autoclave: LDZX-50KB, Shanghai Shen'an Medical Equipment Factory; Tapping homogenizer: JZ-1B, Shanghai Keqi Instrument Equipment Co., Ltd; analytical balance: FA2204B Shanghai Jingke Tianmei Scientific Instrument Co., Ltd; Biochemical incubator: LRH-250F, Shanghai Yiheng Scientific Instrument Co., Ltd; fridge: BCD-480WBPT, Qingdao Haier Co., Ltd; UV-Vis Spectrophotometer: TU-1810DASPC, Beijing Puxi General Instrument Co., Ltd; Digital constant temperature water bath: HH-4, Changzhou Guohua Co., Ltd.

Sample Preparation

Referring to the experimental methods of Yuan *et al*. (2022), Tang *et al*. (2024) and Li *et al*. (2018), after cleaning, a piece was cut at the tail of the fresh mackerel, and then the fillets were carefully separated from both sides along the central backbone. The surface was sprinkled with an appropriate amount of salt and marinated for 15 min. The white meat was carefully separated from the marinated fish by scraping with a clean spoon and then weighed. After that, a blender was used to stir the white meat until the fish paste was gelatinous, and then the prepared scallion ginger water (the ratio of fish meat to scallion ginger water was about 10:1) was added in multiple portions, and stirred evenly in the same direction until the scallion ginger water was completely absorbed. After that, an appropriate amount of sweet potato flour and egg white was added to stir well (the ratio of fish meat to sweet potato flour is about 125:2). Fish paste was squeezed through the thumb-web space to form smooth balls, and then spooned into an ice water-filled stainless steel basin. If the fish balls float, it indicates that the paste has been sufficiently whipped; on the contrary, it should be continued to whip the paste until the fish balls can float in the ice water. The prepared fish balls were boiled until cooked, then removed and cooled to room temperature. Afterward, a vacuum sealer was used to package them for later use. Figure 1 shows the general process of preparation of mackerel fish balls. Then these balls were processed at pressures of 250 and 350 MPa for 10 min (Water was used as the pressure transfer medium at room temperature, and the temperature increase caused by adiabatic heating was about 2-3 ℃/100 MPa.) and 121 ℃ for 13 min and 15 min, respectively. Untreated fish balls were used as the control group, and the processed samples were maintained at 4°C under refrigeration prior to analysis.

Determination of Total Bacteria

The total bacteria shall be determined in accordance with Chinese National Standard GB 4789.2-2022 for

Food Safety Standard for Enumeration of Total Bacteria in Food. 90 mL of sterile saline solution (0.85% w/v) was used to homogenize a 10 g aliquot of minced fish balls that had been aseptically transferred into a sterile plastic bag. The supernatant was diluted to a suitable concentration according to 10 times series. One milliliter of the dilution was transferred to sterile plate count agar plates, followed by incubation at 30 ± 1 °C for a period of 72 hours. The standard CFU/g metric was applied to express bacterial counts in the fish ball sample.

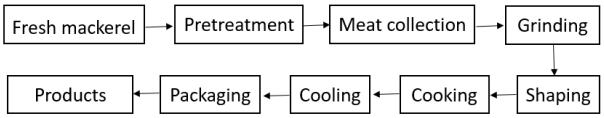

Fig. 1. Flowchart of preparation of mackerel fish balls

Determination of Color Value

Prior to color measurement, the colorimeter should be calibrated using a standard white tile. Fish balls were cut into a 1.5-centimeter cube, and then the lens were placed vertically on the fish balls to ensure a tight fit and avoid light leakage. The shooting button was pressed to record the corresponding values after the data displayed on the screen stabilized (Luo *et al*., 2021). A color difference measuring instrument was used to determine the L* value (brightness, L*=0 denotes black, and L*=100 denotes white), a* value (red green degree, positive a* indicates sample reddish color, negative a* indicates sample greenish color), and b* value (yellow blue degree, positive b* indicates sample yellowish color, negative b* indicates sample bluish color). Each experiment was conducted in triplicate. The whiteness (WH) is calculated according to the Hunter whiteness formula.

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

Determination of Texture Characteristics

The fish balls were sliced into 1.5 cm × 1.5 cm × 1.5 cm cubes and put on a texture analyzer, following, with minor adjustments, the procedure of Cui *et al*. (2018). The textural properties of prepared mackerel fish balls were assessed using the textural Profile Analysis (TPA) model. The experimental conditions are as follows: using a P5 metal cylindrical probe at 2 mm/s pre-compression, 5 mm/s compression, 5 mm/s retraction, and 50% target deformation, a dwell time between two compressions of 5 s; the triggering type is automatic, and the triggering force is 5 g. The evaluation metrics selected are hardness, elasticity, adhesiveness, and chewiness. Each group will conduct three repeated experiments to ensure the reliability and reproducibility of the results.

Determination of thiobarbituric acid reactants (TBAR values)

The spectrophotometric method described in "Chinese Food Safety Standard for Determination of Malondialdehyde (MDA) in Food" (GB 5009.181-2016) is used to make the deduction. The calculation formula is as follow:

$$X = \frac{C \times V \times 1000}{m \times 1000} \quad (2)$$

where V is the sample solution's final volume, m is the sample's mass, g, C is the MDA concentration derived from the standard curve, μ g/mL, and X is the MDA content, mg/kg, and 1000 is the conversion factor.

Determination the Content of Total Volatile Basic Nitrogen (TVB-N)

The spectrophotometric method outlined in GB 5009.181-2016 (Chinese Food Safety Standard for Determination of TVB-N in Food) Sheng and Wang (2024) was used to determine TVB-N. The calculation formula is as follow:

$$X = \frac{c \times (V_1 - V_2) \times 14}{m \times \left(\frac{V}{V_0}\right)} \times 100 \quad (3)$$

where X is the content of sample's TVB-N, mg/100g; c is the standardized HCl concentration, mol/L; V_1 is the standardized HCl solution's volume for sample, mL; V_2 is the standardized HCl solution's volume for blank, mL; m is the sample's mass,, g; V is the accurately filtrate aliquot volume, mL; V0 is the sample solution's total volume, mL; 14 is the nitrogen molar mass, g/mol, and 100 is the conversion factor.

Sensory Evaluation

Based on Li's (2011) approach with some modifications, eight students were selected and received relevant training. According to certain evaluation criteria (Table 1), scores were given based on the color, smell, elasticity, tissue state, texture, and taste of the prepared mackerel fish balls.

Statistical Analysis

In this study, for each experimental group, triplicate samples were analyzed, and in terms of outcomes, mean ± standard deviation was used. All data were analyzed for significant differences using SPSS data processing software.

Table 1. Sensory evaluation standard of prepared mackerel fish balls

Color (25 points)	Smell (25 points)	Elasticity (25 points)	Texture (25 points)	Taste (25 points)
Gloomy (0-5)	a strong fishy smell and a strong odor (0-5)	Ruptured when lightly pressed with the middle finger, loose tissue (0-5)	Rough surface, loose structure, and a paste cut surface (0-5)	Rough taste, with a strong fishy smell (0-5)
Grayish yellow (5-10)	Almost no fresh fish flavor, with a certain fishy smell (5-10)	Ruptured after pressing hard with the middle finger (5-10)	With a small amount of uneven small holes on the surface, and relatively soft cut surface (5-10)	Rough taste, with slight fishy odor (5-10)
Pale to yellowish (10-15)	Relatively mild freshness of fish meat (10-15)	Indented but not break when pressing the fish ball firmly with the middle finger, cannot fully restore its original state after releasing (10-15)	Smooth surface, almost dense cut surface, no large pores, and with a small amount of small pores (10-15)	Light and fresh flavor of fish meat (10-15)
White with a hint of red (15-20)	A fresh fish flavor (15-20)	Indented but not break when pressing firmly with the middle finger, can restore its original state after releasing (15-20)	Smooth surface, dense cut surface, no large pores, and with a small amount of small pores (15-20)	Delicate taste, with a fresh and delicious fish flavor (15-20)
Light white (20-25)	Unique freshness and rich flavor of mackerel meat (20-25)	Indented but not break when pressing firmly with the middle finger, can restore its original state after releasing (20-25)	Smooth surface, dense cut surface, no large pores, and with many small and uniform pores (20-25)	Delicate taste, with the unique fresh aroma of mackerel, delicious, and a rich and long-lasting aftertaste (20-25)

Results and Discussion

Effect of UHP and Thermal Treatment on the Total Bacterial Count of Prepared Mackerel Fish Balls

Given their inherent high protein and high moisture levels, the prepared mackerel balls require processing methods to ensure microbial stability. The development and multiplication of bacteria are the primary causes for the spoilage and deterioration of prepared mackerel fish balls. The total bacterial count of samples treated with ultra-high pressure and thermal treatments were immediately measured. Then the changes in their total bacterial count after being refrigerated at low temperature for 7d were measured. As shown in Figure 2, after ultra-high pressure and thermal treatments, the total bacterial count of mackerel fish balls significantly decreased (p<0.05). There were 2.18 lg(CFU/g) of colonies overall in the control group sample on the 0th day, while that after ultra-high pressure treatment of 250 and 350 MPa was less than 1 lg(CFU/g). After heat treatment at 121℃ for 13min and 15 min, the total number of colonies decreased to 1.74 and 1.77 lg (CFU/g), respectively. After 7 days of low-temperature refrigeration storage of the samples, the control group's overall bacterial colony count rose to 3.62 lg(CFU/g). After 7 days of storage, the total number of bacterial colonies in the heat-treated and ultra-high pressure-treated samples, as well as the control group, differed significantly (p<0.05). Both ultra-high pressure and thermal treatments can effectively improve the food safety of prepared mackerel fish balls, which is in line with Jin *et al*.'s (2023) findings about scallop columns under the ultra-high pressure treatment. In the ultra-high pressure group, which was kept at 4 °C for 0 days, the total number of bacterial colonies was significantly (p<0.05) fewer than in the high-pressure treatment group, which was kept at 4 °C for 7 days, as Figure 2 illustrates. As a result, UHP treatment is more effective than thermal treatment to regulate the development and reproduction of microorganisms. Ultra-high-pressure treatment belongs to non-thermal sterilization and mainly achieves sterilization effect by destroying microbial cell membranes. As shown in Figure 2, the colonies of prepared mackerel fish balls treated with two different treatment methods demonstrated differential microbial proliferation profiles after being stored at 4 ℃ for 7d. It was noteworthy that even after UHP and thermal treatments, some germs were still present in the prepared mackerel fish balls. These could include pressure-resistant Gram-positive bacteria, such *S. aureus* and *L. monocytogenes*, which need at least 500 MPa to be rendered inactive. Prepared mackerel fish balls might also contain bacterial spores, known for their remarkable ability to survive pressures greater than 1000 MPa (Olaonipekun *et al*., 2025). To completely kill the microorganisms in prepared mackerel fish balls, it is necessary to increase the treatment intensity (higher pressure and more pressure holding time), which is in line with the findings of Luo *et al*. (2021) on the UHP sterilization treatment of hairtail fish balls and Wu *et al*. (2021) on the UHP sterilization treatment of fruit juice.

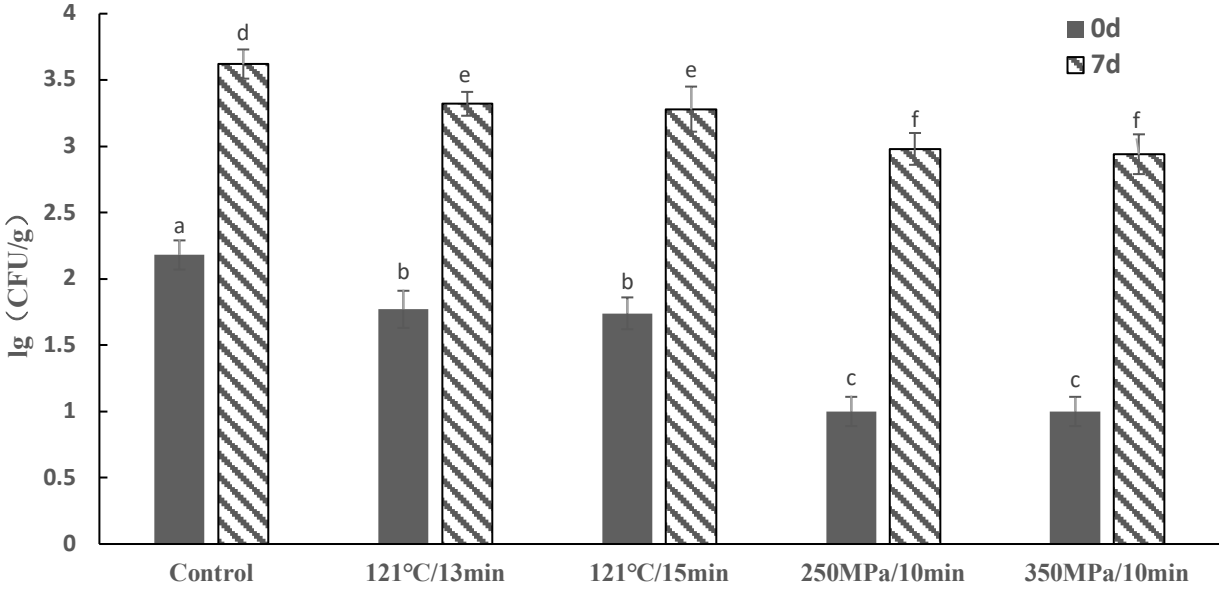

Fig. 2. Effect of UHP and thermal treatment on the total bacterial count of prepared mackerel fish balls

Effect Of UHP And Thermal Treatment on the Color Value of Prepared Mackerel Fish Balls

Food's visual appeal and consumer acceptance are greatly influenced by color. The impact of UHP processing on the color of meat products varies depending on processing parameters, inherent muscle pigmentation of different species, and specific food matrix composition (Luo *et al*., 2021). Table 2 shows that the color value L* of the prepared mackerel fish balls was not significantly affected by the ultra-high pressure of 250 MPa/10 min or the thermal treatment of 121 °C/13 min when compared to the control group (p>0.05). Compared with the control group stored at 4 ℃ for 7 days, a significant decrease (p>0.05) in L values was observed in mackerel balls across all treatment groups. After storage at 4 ℃ for 0 days, the effects of heat treatment at 121 ℃/15 min and 350 MPa/10 min on L* values were significantly decreased (p<0.05). L* represents the depth of black and white, an increase in L* indicates that the fish ball is whiter (brighter), while a decrease indicates that the fish ball is darker (darker). Table 2 shows that the values of the heated, pressured, and control samples do not differ significantly (p>0.05). The pre-cooking qualities of the fish balls used in the study are responsible for this phenomena. During pre-cooking, myoglobin is converted into nitrosyl - haemochromogen pigment, a compound that remains stable under pressure and heat variations. This is in line with what Luo *et al*. (2021) found when they treated hairtail fish balls with UHP treatment. As shown in Table 2, the heat treatments of 121 °C for 15 minutes and 350 MPa for 10 minutes did not significantly (p>0.05) affect the a* stored at 4 °C for 0 days when compared to the control group. After being refrigerated at 4 ℃ for 7 days, the a* values of prepared mackerel balls in all treatment groups were significantly reduced (p>0.05) compared with the control group. The b* of mackerel fish balls was significantly affected (p<0.05) by heat treatment, but b* was not significantly affected (p>0.05) by ultra-high pressure treatment. Ultra-high pressure treatment causes a decrease in b* of fish balls, while thermal treatment actually increases b*. A positive b * value indicates that the fish balls are yellowish, and mackerel fish balls have a brighter yellowish hue the higher the positive value. It can be seen that the smaller b* of the high-pressure treatment group, the more yellow the fish balls than the control group, with the yellowing degree being increased. This is in line with the findings of Yu *et al*. (2024b) on heat sterilization treatment of shrimp. When compared to the control group, fish balls treated with ultra-high pressure processing exhibited a significant (p>0.05) decrease in yellowing, improving their visual appeal (Table 2). This is mainly due to the fact that ultra-high pressure belongs to non-thermal sterilization, which inhibits fat oxidation and reduces yellowing. After ultra-high pressure and thermal treatments, the whiteness of fish balls significantly decreased (p<0.05), except that of 250 MPa/10 min, which may be related to the treatment intensity. Compared with the control group stored at 4 ℃ for 7 days, the whiteness of mackerel balls prepared in all treatment groups was significantly reduced (p>0.05). The color of the sample after ultra-high pressure non- thermal treatment is better than that after thermal treatment, which is in line with the findings of Chen *et al*. (2023).

Table 2. Effect of UHP and thermal treatment on the color value of prepared mackerel fish balls

Treatment groups	4 ℃ storage time (d)	L*	a*	b*	Whiteness
Control	0	54.90±0.39^{a}	-4.47±1.10^{a}	12.23±0.34^{b}	53.01^{a}
	7	54.67±0.21^{a}	-3.62±0.17^{a}	12.21±0.25^{b}	52.92^{a}
250 MPa/10 min	0	54.42±0.04^{a}	-3.50±0.20^{a}	11.47±0.36^{bc}	52.85^{a}
	7	53.15±0.22^{b}	-4.41±0.34^{a}	11.43±0.21^{bc}	51.58^{b}
350 MPa/10 min	0	51.46±0.13^{c}	-4.56±1.23^{a}	10.98±0.79^{c}	50.02^{c}
	7	50.74±0.11^{c}	-4.71±0.34^{a}	10.89±0.54^{c}	49.33^{c}
121 ℃/13 min	0	54.22±0.06^{a}	-3.75±0.40^{a}	14.99±0.02^{a}	51.68^{b}
	7	53.13±0.24^{b}	-4.39±0.31^{a}	14.96±0.11^{a}	50.61^{bc}
121 ℃/15 min	0	53.45±0.55^{b}	-4.30±0.59^{a}	15.85±0.29^{a}	50.62^{bc}
	7	52.99±0.18^{b}	-4.62±0.32^{a}	15.73±0.26^{a}	50.21^{c}

Note: Significant differences ($p< 0.05$) are indicated by different letters in the same column.

Effect of UHP and Thermal Treatment on the Texture Characteristics of Prepared Mackerel Fish Balls

The texture characteristics of processed mackerel fish balls were evaluated based on three key parameters: hardness, elasticity, and chewiness. Table 3 shows that the ultra-high pressure treatment had a substantial ($p<0.05$) impact on the hardness of mackerel balls when compared to the control group. Mackerel balls' hardness can be greatly ($p<0.05$) reduced and their flavor enhanced by ultra-high pressure treatment; samples treated at 250 MPa for 10 minutes had the lowest values. This result is in line with the findings of Luo *et al*. (2021), who reported that the increase with pressure levels resulted in greater gel hardness in pressurized minced tuna samples. Following a 13-minute, 121°C heat treatment, the fish balls' hardness dramatically dropped ($p<0.05$) in comparison to the control group. In terms of elasticity, ultra-high pressure treatment of 350 MPa/10 min significantly ($p<0.05$) improved the elasticity of fish balls, while mackerel balls were not significantly affected by thermal treatment or ultra-high pressure treatment of 250 MPa/10 min ($p>0.05$). The main factors causing the change in the elasticity of fish balls are the degradation of endogenous proteins and the loss of bound water. To a certain degree, UHP treatment can suppress protein denaturation and oxidative reactions, slow down the degradation of proteins, and maintain the activity of endogenous proteases. In addition, it can enhance the water retention capacity of mackerel balls, leading to improved elasticity, reduced firmness, and better overall quality preservation (Zeng *et al*., 2022). However, as compared to the control group, the chewiness of mackerel fish balls was significantly affected ($p<0.05$) by the UHP with 250 MPa/10 min and thermal treatment, but the ultra-high pressure treatment with 350 MPa/10 min had no discernible effect. The chewiness of fish balls is less affected by ultra-high pressure treatment than by heat treatment, and heat treatment significantly reduces their chewiness ($p<0.05$). This result is in line with the observations of Tong *et al*. (2023). From the above analysis, UHP treatment can effectively maintain the elasticity and chewiness of prepared mackerel fish balls, reduce hardness, and improve taste. Fish balls that have undergone thermal treatment may still be firm, although their chewiness may be reduced.

Table 3: Effect of UHP and thermal treatment on the texture characteristics of prepared mackerel fish balls

Treatment groups	Hardness/ (N)	Elasticity /(mm)	Chewiness / (mj)
Control	10.81±0.86^{a}	4.87±0.38^{b}	26.74±0.70^{a}
250 MPa/10 min	6.00±0.76^{b}	5.52±0.03^{ab}	20.33±0.53^{b}
350 MPa/10 min	6.95±1.72^{b}	5.99±0.42^{a}	24.69±4.65^{a}
121 ℃/13 min	8.26±1.54^{c}	5.37±0.24^{b}	19.67±4.72^{b}
121 ℃/15 min	10.27±2.19^{a}	5.04±0.56^{b}	19.63±3.95^{b}

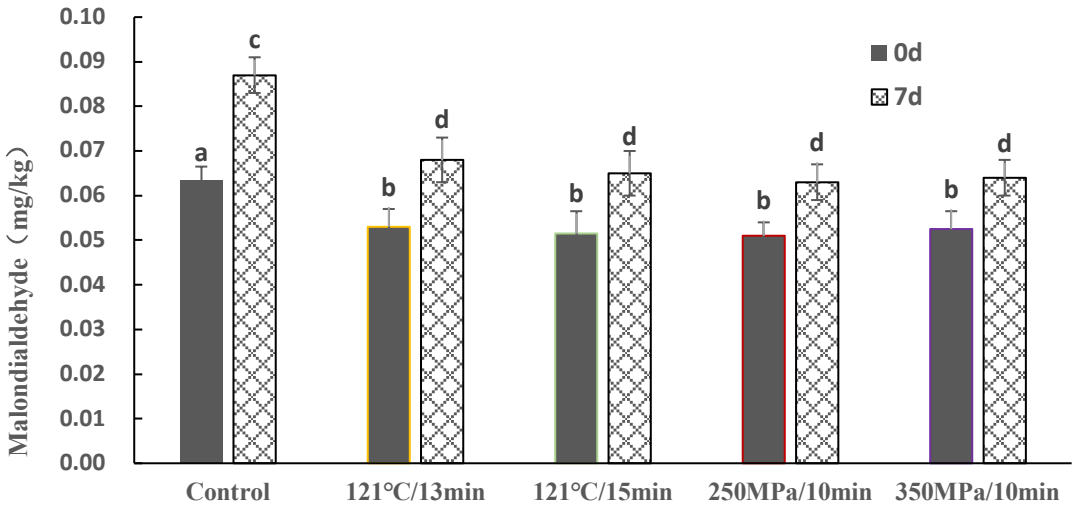

Fig. 3. Effect of UHP and thermal treatment on MDA content of prepared mackerel fish balls

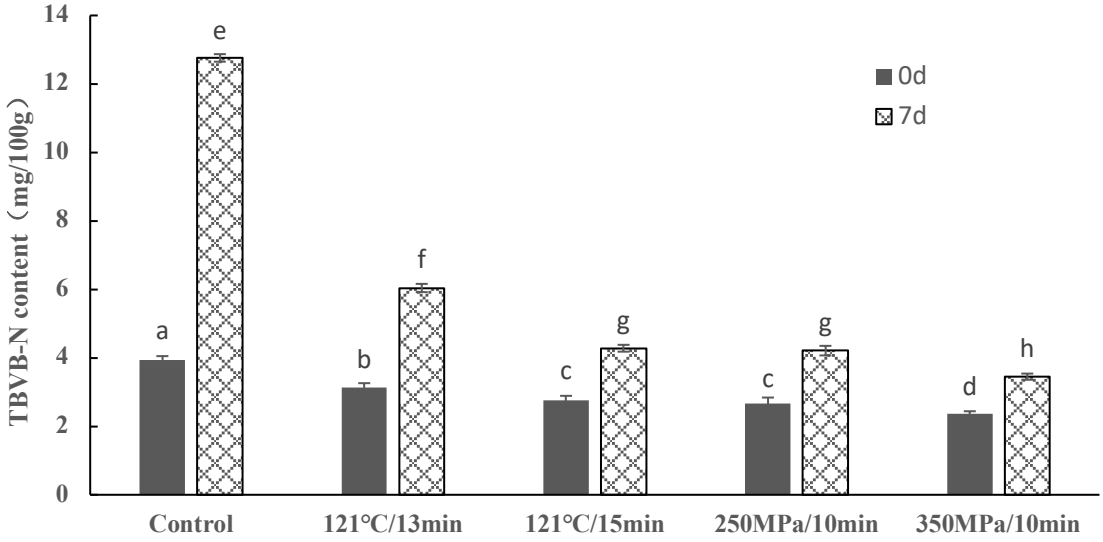

Fig. 4. Effect of UHP and thermal treatments on the TVB-N content of prepared mackerel fish balls

Effect of UHP and Thermal Treatment on TBARS of Prepared Mackerel Fish Balls

TBARS (Thiobarbituric Acid Reactive Substances) is a key biomarker for assessing lipid peroxidation in food products. In fish muscle tissue, the oxidation of unsaturated fatty acids produces malondialdehyde (MDA) as a secondary breakdown product. This MDA subsequently reacts with thiobarbituric acid (TBA) to form a characteristic pink-colored chromogen, whose intensity is quantitatively measured to determine the degree of lipid oxidation. The TBARs value can be used to estimate the level of lipid rancidity (Piranavatharsan *et al*., 2023). The effects of UHP treatment and thermal treatment on the content of MDA are shown in Figure 3. Compared with the control group, the MDA content in mackerel balls was dramatically (p<0.05) reduced by UHP and thermal treatments, although there was no significant difference (p>0.05) between the two treatment methods. Similar results were observed after 7 days of low-temperature (4 ℃) storage. This indicates that both treatment methods can reduce fat oxidation in fish balls. The determination of TBARS value is related to fat oxidation, showing the level of lipid oxidation in the sample. The degree of lipid oxidation increases with the increasing TBARS value, that is, the more severe the degree of fish ball rancidity (Dong *et al*., 2024). Based on the above analysis, both ultra-high pressure and thermal

treatments can reduce the content of MDA in prepared mackerel fish balls, inhibit fat oxidation and improve the quality of fish balls. According to similar results, hairtail fish balls' lipid oxidation was inhibited during cold storage by applying extracts of grape seeds, sage, and oregano (Guan *et al*., 2019).

Effect of UHP and thermal treatment on the TVB-N content of prepared mackerel fish balls

The value of TVB-N in animal based foods refers to the degradation of proteins by bacteria and enzymes into alkaline nitrogen-containing compounds such amines and ammonia. An increase in TVB-N levels indicates more extensive protein degradation, resulting in a more significant reduction in food's nutritional value (Ni, 2023). The amount of ammonia and amines that microorganisms in the sample produce through the breakdown of endogenous proteins and other materials is represented by the TVB-N content, which serves as an indication for tracking the freshness of seafood (Zhang *et al*., 2024). The TVB-N content in fish balls treated with UHP and thermal treatments is similar with Dong *et al*. (2021) and Luo *et al*. (2021) when compared to the control group, as shown in Figure 4. Storage at 4 °C for 0 day and treatment at 350 MPa/10 min resulted in the maximum reduction of TVB-N content in prepared mackerel fish balls. Similar results were observed after 7 days of storage at low-temperature (4 °C). The decrease in TVB-N levels is correlated with the reduction in microbial populations and decay activity after UHP and thermal treatment, leading to a decrease in ammonia nitrogen production (Luo *et al*., 2021). From the above analysis, it can be seen that ultra-high pressure treatment is more effective than thermal treatment in maintaining the freshness of prepared mackerel fish balls and extending the shelf life of the product.

Effect of UHP and Thermal Treatment on the Sensory Analysis of Prepared Mackerel Fish Balls

As shown in Figure 5, the sensory characteristics (such as color, smell, texture, taste, and elasticity) of the prepared mackerel balls were minimally affected by UHP treatment at 350 MPa for 10 minutes, and the comprehensive sensory score was the highest. UHP treatment at 250 MPa/10 min and thermal treatment at 121°C for 13 min were carried out sequentially for 13 min. The most pronounced adverse effects on sensory attributes were observed during the thermal treatment at 121°C/15 min. According to feedback from sensory evaluators, after being sterilized by thermal treatment, the internal moisture of fish balls was lost, with yellowed color, decreased elasticity, larger and uneven pores, and heavier fishy smell. During thermal processing, these changes showed more time-dependent effects, which ultimately resulted in a drop in sensory scores. There is minimal impact of UHP treatment on the prepared mackerel fish balls' sensory qualities. Following UHP treatment, the prepared mackerel balls' color and flavor did not differ substantially from the control group (p>0.05), and their elasticity was greater. This may be that UHP treatment can improve the interaction between macromolecules in fish balls and better maintain the tissue characteristics of fish balls. Similarly, Luo *et al*. (2021) demonstrated that UHP processing effectively maintained the sensory integrity of hairtail fish balls, with no detectable deterioration in organoleptic characteristics. Therefore, UHP treatment maintains the sensory characteristics of prepared mackerel fish balls. Due to the improvement of sensory properties, it is recommended that the processing conditions for the fish balls be 350 MPa for 10 minutes.

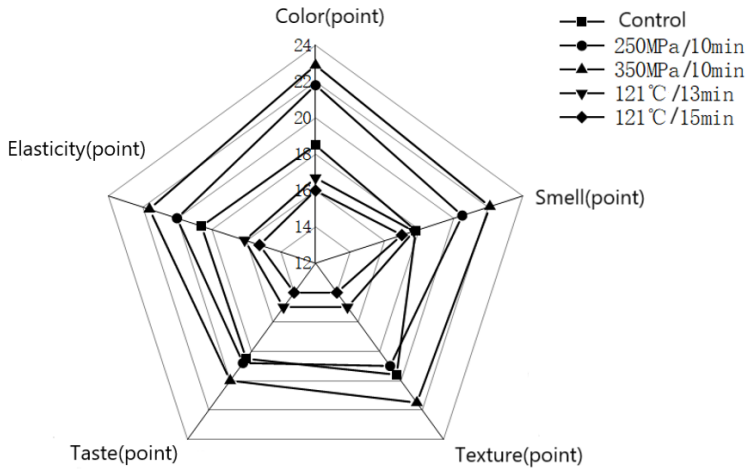

Fig. 5: Effect of UHP and thermal treatment on the sensory characteristics of prepared mackerel fish balls

Conclusion

Both UHP and thermal treatment can lower the total bacterial count of fish balls. Ultra-high pressure treatment is superior to thermal sterilization in terms of lowering the overall bacterial count of fish balls and preventing their microbial growth. Both treatment methods can significantly reduce TVB-N and MDA content, improving the preservation quality of fish balls. The mackerel balls treated with ultra-high pressure sterilization have better appearance, texture, and sensory characteristics than those treated with thermal treatment. UHP treatment can improve the preservation effect and sensory quality of prepared mackerel fish balls and 350 MPa/10 min was recommended for processing fish balls because of improved safety and high-quality maintenance. Ultra-high pressure treatment is a sterilization method that maintains good quality of fish balls and has good application prospects. The process conditions of ultra-high pressure treatment can be further optimized for better sensory attributes, and the possibility of UHP practical application can be explored in combination with low-temperature preservation in the future.

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Author Contributions

Biaoshi Wang: Participated in the experimental design, written the draft and revised the manuscript.

Xiaojun Hu: Completed some experiments, written the draft manuscript.

Jingqiu Ma: Participated in the process of gathering experiment-related supplies and did some experiments.

Ying Xu: Did some experiments, analyzed the experimental data.

All authors read and approved the final manuscript.

Ethics

None of the authors of this article have conducted any animal studies. The authors assume full responsibility for any ethical dilemmas that may emerge following the manuscript's publication.

Conflict of Interest

The authors assert that they do not have conflicting agendas. The co-author certifies that every author has perused and given their approval to the manuscript.

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