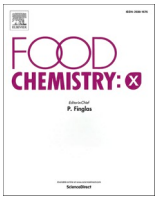
Food Chemistry: X 24 (2024) 101995

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x



Influence of starch on freeze-thaw stability of *Hypophthalmichthys molitrix* surimi gel observed via ice crystal distribution and gel properties

Xin Jiang, Qianqian Liang, Wenzheng Shi *

College of Food Sciences & Technology, Shanghai Ocean University, Shanghai 201306, China

ARTICLE INFO

Keywords:
Surimi gel
Starch gelatinization
Freeze-thaw
Tissue microstructure
Texture

ABSTRACT

Starch has been recognized as a vital ingredient in surimi products due to its ability to absorb water, which reduces the deterioration of gels and water loss during freezing and thawing. However, it is essential to ascertain the role of starch in the formation of ice crystals and the texture of surimi gels. The impact of freeze-thaw cycles on the morphology and distribution of ice crystals, as well as the textural characteristics of gelatinized and ungelatinized starch-surimi gels was investigated. The results of light microscopy revealed that the presence of starch, irrespective of whether it was gelatinized, resulted in a reduction in the size of ice crystals within the surimi gel network during the freeze-thaw process. In addition, starch in surimi gels was subjected to freeze-thaw cycles, resulting in the emergence of two distinct states of bound water (0.1–1 ms and 1–10 ms). The higher relative content of immobile water indicated that the gelatinized starch had improved water holding properties. Furthermore, the incorporation of gelatinized starch into surimi enhanced its freeze-thaw stability and retarded the loss of gel strength, hardness, and whiteness. The addition of starch had a synergistic impact, enhancing the gel properties by affecting the formation of ice crystals and water absorption.

1. Introduction

Surimi is a myofibrillar protein concentrate derived from fish flesh through a process of deboning, mincing, washing, and dewatering (Wang et al., 2024). Following thermal processing facilitates the cross-linking of dispersed myosin and actin in the surimi, thereby forming a network that endows surimi products with their distinctive gel texture (Yasui et al., 1982; Zhang, Mao, et al., 2023; Zhang, Xie, et al., 2023). The wholesome and nutritious attributes have contributed to the increased worldwide consumption of the surimi products such as crab-sticks, kamaboko, and fish balls (Jiang et al., 2022). The freezing of surimi products is a standard procedure that maintains quality and prolongs shelf life during the transportation and distribution process (Cao et al., 2022). However, it is unavoidable that temperature fluctuations occur in surimi products, resulting in repeated freeze-thaw cycles and the formation and growth of ice crystals. The ice crystal puts significant strain on the unfrozen matrix and may have an impact on the microstructural recovery following thawing (Jiang et al., 2019). According to Fan et al. (2022), the water holding capacity decreased significantly as well as the ice crystal sizes and water mobility increased with repeated freezing-thawing. Furthermore, surimi gel quality deteriorated with slower freezing rate, the drop in temperature was advantageous for storing (Jia et al., 2019). Thus, it is imperative to better maintain product quality and avoid the negative impacts of frozen storage on surimi products.

Starch is used primarily in surimi products on account of its water-holding capacity and its ability to maintain the desired gelation properties (Hunt et al., 2009; Park, 2005; Tee & Siow, 2017). The incorporation of starch into surimi gels serves to augment their freeze-thaw stability, a consequence of the swelling and gelatinization that ensue when the starch absorbs water (Jia, Hiraoka, et al., 2018; Jia, Katano, et al., 2018). The addition of starch was found to have a beneficial effect on the water exchange between free and bound water, resulting in the formation of a more compact and cohesive gel (Luo et al., 2020). In addition, Tee and Siow (2017) discovered that the gel strength increased upon increasing starch addition for both fish balls made with tapioca or potato starch. It was established that water absorption by starch was of vital importance in the surimi production. In addition, it has been found that starches with small granules contributed to lesser ice crystal formation and reduced structural damage following frozen storage (Jia et al., 2020). This indicated that alterations in starch morphology were also associated with changes in freeze-thaw stability of surimi gels.

* Corresponding author at: Shanghai Ocean University, P.R.China.
E-mail address: wzshi@shou.edu.cn (W. Shi).

https://doi.org/10.1016/j.fochx.2024.101995
Received 27 August 2024; Received in revised form 2 November 2024; Accepted 11 November 2024
Available online 12 November 2024

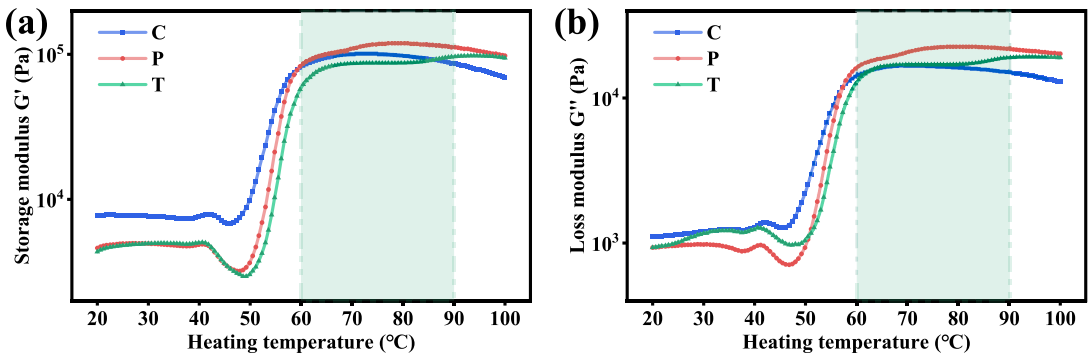


Fig. 1. Storage modulus G' (a) and loss modulus G" (b) of surimi gels. C, P, and T represent surimi matrix, potato starch-surimi matrix, and tapioca starch-surimi matrix, respectively.

Given the morphological alterations that occur during the starch gelatinization, it was imperative to undertake a study examining the impact of starch morphology on the gel freeze-thaw stability subjected to heat treatment.

Potato and tapioca starch are two common commercial native starches, which exhibit different particle size and gelatinization properties in surimi gels (Han et al., 2019). The selection of these two starches was made in order to gain a more representative understanding of the changes that occur in surimi gels. According to the previous study (Jiang et al., 2024), the starch in surimi gels after low-temperature heating (60 °C) and high-temperature heating (90 °C) showed non-gelatinized and gelatinized states, respectively. Therefore, the objective of this investigation was to examine the impact of starch on ice crystal size in surimi gels and the alterations in gelation properties following freeze-thaw cycles.

2. Materials and methods

2.1. Materials

Frozen silver carp surimi (AAA-grade) with 6 % sucrose and 0.25 % polyphosphate was purchased from Jingli Fishery Food Co., Ltd. (Honghu, China), and used within 6 months. The moisture and crude protein content of surimi were determined to be 75.13 % and 14.13 %, respectively. The potato starch and tapioca starch (food grade) were procured from Shanghai Fengwei Shiye Co., Ltd. (Shanghai, China), with a carbohydrate content of 79.00 % and 87.50 %, respectively. The chemicals (analytical grade) were obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China).

2.2. Preparation of surimi gels

The frozen surimi was thawed at 4 °C until the center temperature reached −2 °C. The surimi was chopped for 2 min in a blender (AM-CG108–1, ACA ELECTRICS Co. Ltd., Zhuhai, China) below 10 °C, followed by adding 2.5 % (*w*/w) NaCl for 4 min. 0 % starch (C), 6.00 % potato starch (P, w/w), and 6.00 % tapioca starch (T, w/w) were added to chop for 9 min immediately. The moisture content should be adjusted to 80 % by the addition of ice water during the chopping process. The starch-surimi mixture was packed into 25 mm plastic casings, then heated in bath water at 60 °C or 90 °C for 30 min before being quickly chilled with ice water.

2.3. Determination of rheological properties

Storage modulus (G') and loss modulus (G") were performed using MCR301 rheometer (Anton Paar GmbH, Austria), following the method of Gao et al. (2018) with a slight modification. Briefly, the temperature range was between 20 °C and 100 °C, the heating rate was 2 °C/min, the oscillation frequency was 0.1 Hz, and 2 % strain was used for the analysis.

2.4. Freeze-thaw cycles

The surimi gels were frozen at −18 °C for 60 h and thawed at 4 °C for 12 h to complete each freeze-thaw cycle. And the surimi gels underwent five freeze-thaw cycles according to the method of Zhou and Wang (2021), with minor modifications.

2.5. Light microscopy observation

The ice crystals of surimi gels were observed by light microscopy (MS500W, Shanghai Meizs Precision Instrument Co., Ltd., Shanghai, China) according to the method of Jiang et al. (2023). The frozen surimi gels were fixed with Carnoy's fixative at −18 °C for 28 d. Following dehydration of the paraffin samples with a gradient alcohol (75 %–100 %, v/v), the samples were then cut into 4-μm slices. The surimi gels were stained with hematoxylin-eosin (HE) in order to observe the distribution of the surimi matrix and the ice crystals. The gels were also stained using periodic acid-Schiff (PAS) in order to distinguish the starch granules. The size of the ice crystals was determined by analyzing the HE-stained light microscopy images using the ImageJ software (Fiji, National Institutes of Health, Bethesda, USA).

2.6. Determination of water holding capacity (WHC)

The moisture content and centrifugal loss were used to compute the WHC of surimi gels according to the method of Jiang et al. (2024). The centrifugal loss was measured by the weights of the gels (5 mm in thickness) before and after centrifugation (5000 ×*g*, 15 min).

2.7. T_2 relaxation time and water distribution analysis

Surimi gels were cut into cylinders with a height of 20 mm and then determined using a MesoMR23-060H-I pulsed NMR analyzer (Niumag Electric Co., Shanghai, China). The relaxation time (T_2) was examined by the Carr-Purcell-Meiboom-Gill pulse sequence, following the method of Jiang et al. (2022).

2.8. Breaking test

The texture analyzer (TA-XT Plus, Stable Micro Systems Ltd., Godalming, UK) was utilized to measure the breaking force and deformation according to the ISO 23855:2021 standard (International Organization for Standardization, Frozen surimi - Specification, 2021). A P/5S spherical probe was used to measure the breaking force (g) and deformation (mm) at a trigger force of 10 g. The gels were cut into cylinders with a height of 25 mm, and the compression distance was 15 mm.

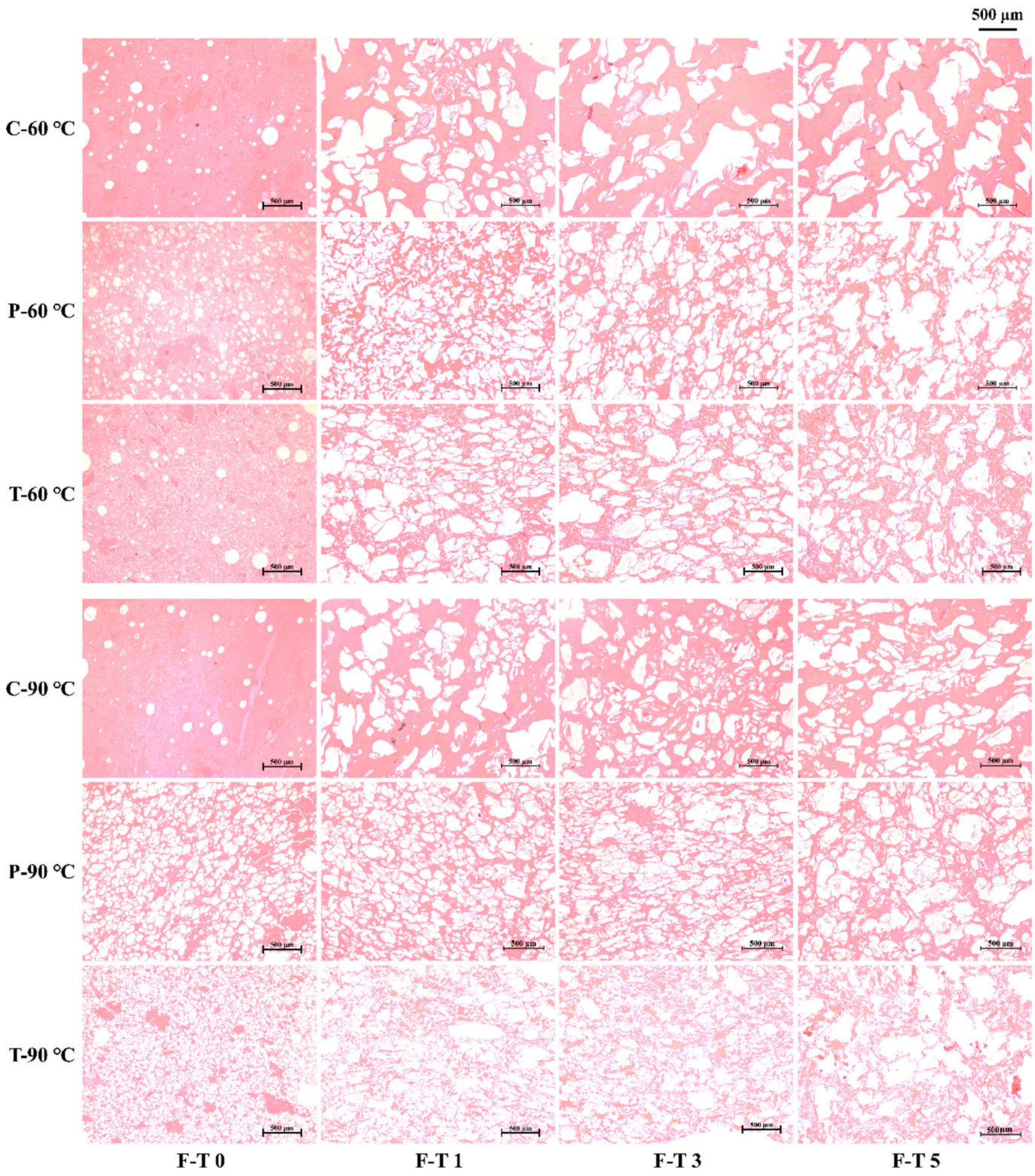


Fig. 2. Effect of freeze-thawing cycles on the ice crystal distribution of surimi gels. C, P, and T represent surimi gel, potato starch-surimi gel, and tapioca starch-surimi gel, respectively.

2.9. Texture profile analysis (TPA)

The textural properties of surimi gels were analyzed at a height of 20 mm using a texture analyzer with a P/50 cylindrical probe, following the method described by Sun et al. (2024). The trigger value was 5 g, and the test speed was 1.0 mm/s with a compression ratio of 40 %.

2.10. Microstructure observation

Samples of gel with dimensions of 0.5 × 0.5 × 0.2 cm were fixed in 2.5 % glutaraldehyde, subsequently dried with ethanol, and then observed using a scanning electron microscope (SEM, Hitachi High-Tech Co., Ltd., Shanghai, China) in accordance with the previously described

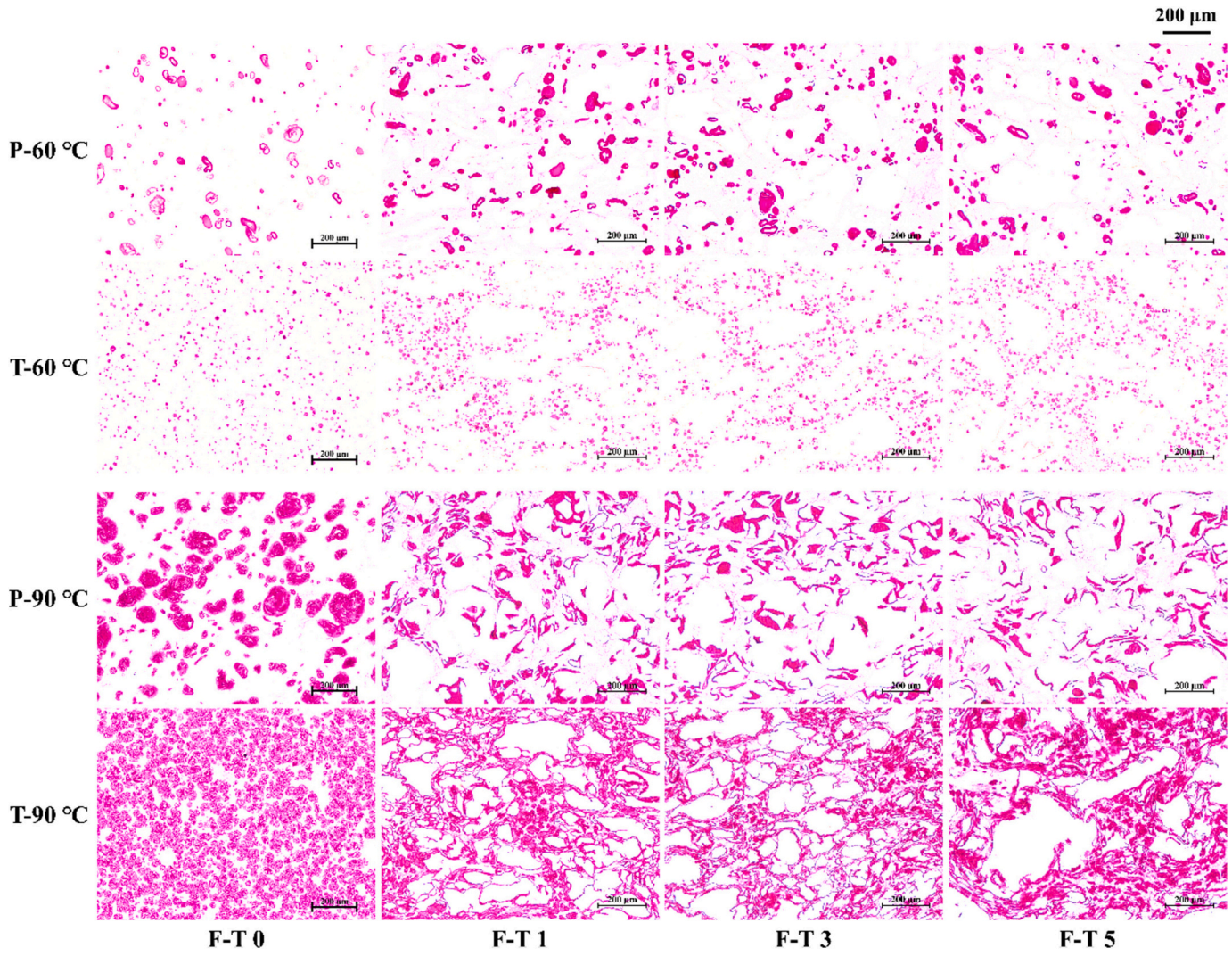


Fig. 3. Effect of freeze-thawing cycles on the starch morphology of surimi gels.

method (Zhang, Mao, et al., 2023; Zhang, Xie, et al., 2023).

2.11. Determination of whiteness

A colorimeter (CR-400, Konica Minolta, Tokyo, Japan) was used to assess the L^* (lightness), a^* (redness/greenness), and b^* (yellowness/blueness) values of the starch-surimi gels. The whiteness was subsequently assessed using the equation that followed (He et al., 2023):

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

2.12. Statistical analysis

The data were analyzed using SPSS Statistics 26 (SPSS Inc., Chicago, IL, USA), and significant differences were determined by ANOVA and Duncan's multiple range tests. The results were expressed as mean ± standard deviation, and differences were considered significant at $P < 0.05$. OriginPro 2023b (OriginLab Corp., Northampton, MA, USA) was used for plotting figures.

3. Results and discussion

3.1. Rheological properties

The rheological properties gain insight into the conversion of surimi sol to gel, as illustrated in Fig. 1. The storage modulus (G') indicates the elastic behavior of a sample, while the loss modulus (G") demonstrates its viscous qualities (Zhou et al., 2020). Fig. 1 illustrated that G' was considerably larger than G", indicating that the elastic component was more pronounced in surimi gels. The G' and G" of surimi gels exhibited a decline at 46–50 °C, when endogenous enzymes were active and the myosin tail unfolded, thereby increasing the mobility of the semi-gel (Benjakul et al., 2001). Myosin heavy chains and actin denatured at 50 °C, forming a dense gel network that enhanced rigidity and strength (Park, 2014). Furthermore, an increase in temperature from 50 °C to 60 °C resulted in a significant increase in G' and G" values, followed by an increase and then a decrease between 60 °C and 90 °C. In the unheated state, the starch-surimi matrix exhibited high moisture content and a low relative G'. As temperature rose, the starch underwent gelatinization and water absorption, leading to a rise in the G' of starch-surimi gels. The gelatinization temperatures of potato starch and tapioca starch were 65.05 ± 0.07 °C and 72.33 ± 0.11 °C, respectively (Jiang et al., 2024). Thus, the starch-surimi gels exhibited the properties of ungelatinized and gelatinized states at temperatures of 60 and 90 °C, respectively. In order to gain further insights into the influence of starch

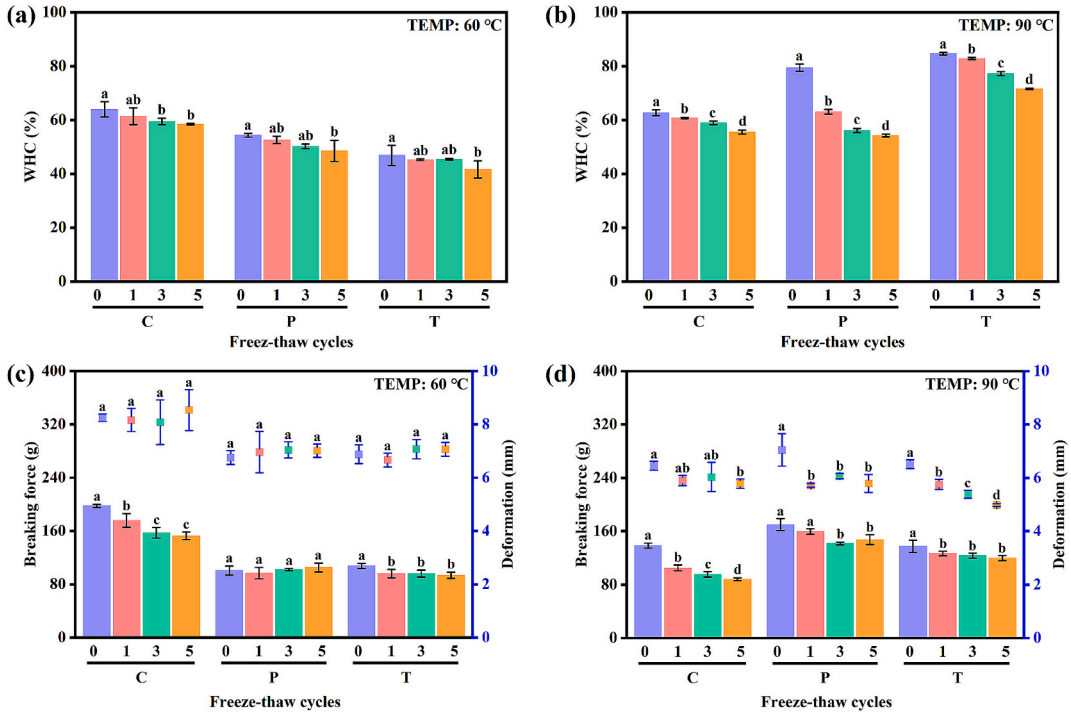


Fig. 4. Changes in the WHC (a, b), breaking force, and deformation (c, d) of surimi gels heated at different temperatures of 60 °C and 90 °C. Lowercase letters indicate the difference in a gel subjected to freeze-thaw cycles ($P < 0.05$), and the values are expressed as mean ± SD.

on the freeze-thaw stability of surimi gel, two distinct heating procedures were established at temperatures of 60 °C and 90 °C.

3.2. Ice crystal distribution and starch morphology

The network structure of surimi gels under freezing conditions is presented in Fig. 2 for the purpose of visualizing the distribution and morphology of ice crystals. The network of surimi gel was observed to become increasingly loosened with repeated freeze-thaw cycles, accompanied by an increase in the size of ice crystals (Li et al., 2024). This process resulted in the formation of a porous spongy network. The C gels obtained by low-temperature heating exhibited a coarser gel network structure but produced larger ice crystals. In contrast, the C gels heated at high temperatures had a small ice crystal area but formed significantly higher quantities than gels heated at low temperatures. This difference was attributed to the degree of thermal denaturation of proteins in surimi gels, where high-temperature heating promoted the formation of disulfide bonds (Jiang et al., 2024).

The pore area distribution of the gel structure was determined using Image J on the light microscopy images, as shown in Fig. S1. A reduction in pore size was observed for the gel network in starch-surimi gels, yet the number of pores increased, regardless of whether the starch had been subjected to high temperatures. It was noteworthy that the starch in surimi gel exhibited no discernible water absorption or swelling when subjected to low temperatures (P-60 °C and T-60 °C). Nevertheless, in this type of surimi gels, the formation of ice crystals was more dispersed, and it was hypothesized that the presence of starch affected the distribution of ice crystals. Additionally, the application of elevated temperatures to P gel and T gel resulted in the absorption of water by the starch, which led to a reduction in moisture content within the surimi matrix. This, consequently, resulted in the formation of a dense gel network (Hunt et al., 2009). A comparative analysis of two kinds of starch-surimi gels revealed that tapioca starch with smaller particles produced ice crystals of a smaller size but a greater number. This finding provided indirect evidence that the distribution of ice crystals was associated with the presence of starch. Furthermore, both starch-surimi gels exhibited identical characteristics following high-temperature treatment, namely an increase in the number of ice crystals.

The morphology and distribution of starch in surimi gels are shown in Fig. 3. The starch morphology in gels heated at a low temperature (60 °C) remained unchanged following multiple freeze-thaw treatment. It was observed that the temperature of 90 °C induced a transformation in the starch shape from an active filling state to a squeezing state during the freeze-thaw process, particularly notable in P gels. The PAS-stained images demonstrated that ice crystals were distributed around the starch, thereby forming the surimi gel pores. It was postulated that ice crystals would form more readily in areas in proximity to the starch. Therefore, the role of starch added to surimi was speculated to be: (1) The water absorption served to mitigate the damage caused by ice crystals during the freeze-thaw cycles; (2) Starch directed the distribution of ice crystals, leading to a reduction in the number of large ice crystals.

3.3. WHC

The WHC of starch-surimi gels that were heated at 60 °C and 90 °C and subsequently subjected to freeze-thaw cycles is shown in Fig. 4(a, b). The significant reduction in WHC ($P < 0.05$) during the freeze-thaw treatment was attributed to the deterioration of the gel network, in addition to the formation and expansion of ice crystals (Qin et al., 2022). The WHC of P and T gels heated at 90 °C was found to be higher than that of gels heated at 60 °C following freeze-thaw cycles, particularly in the case of T gels. This result corroborated the previous finding that the water-absorbing swelling of starch at high temperatures was an effective method of improving gel WHC (Jia, Hiraoka, et al., 2018; Jia, Katano, et al., 2018). Moreover, the WHC of T gels heated at 90 °C was higher than that of P gels, indicating tapioca starch exhibits superior freeze-thaw stability. Additionally, additional research was required to elucidate the mechanisms underlying water loss, including investigations into water distribution and relative content, which could be conducted using LF-NMR.

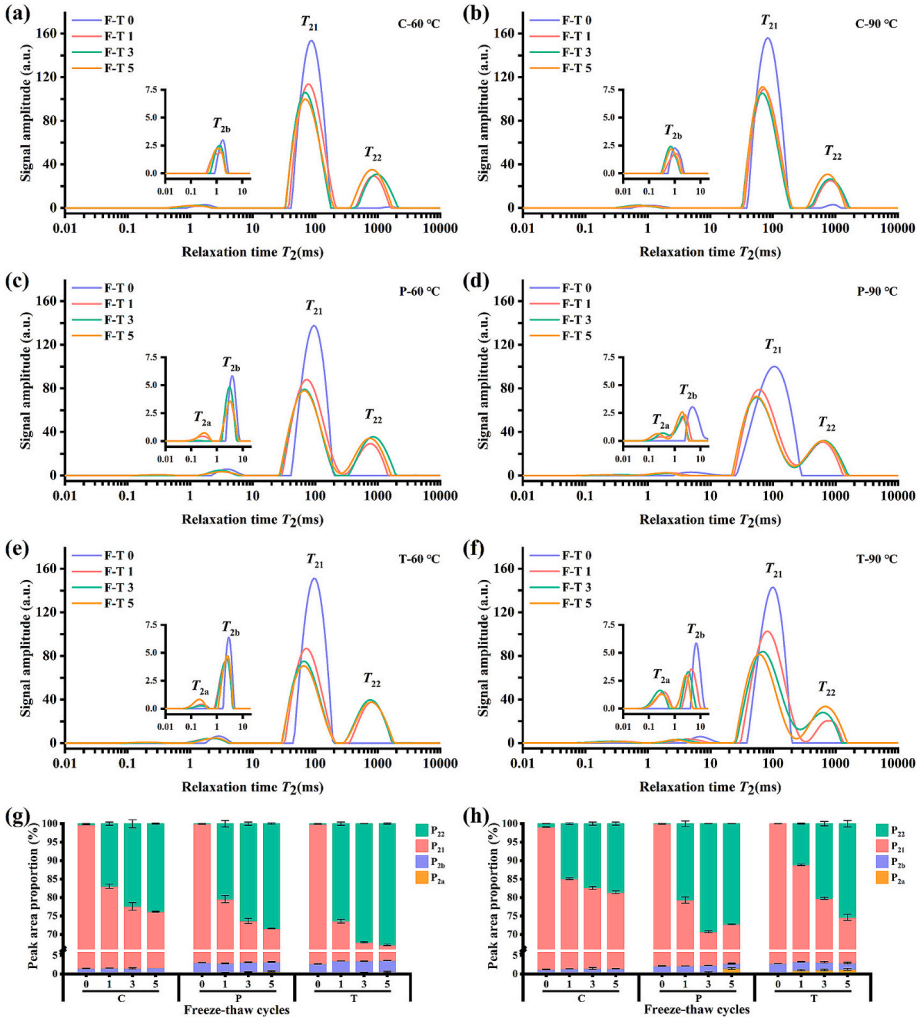


Fig. 5. Changes in the water migration (a-f) and relative water content (g, h) of surimi gels during repeated freeze-thaw. Lowercase letters indicate the difference in a gel subjected to freeze-thaw cycles ($P < 0.05$), and the values are expressed as mean ± SD.

3.4. Lf-NMR

Water distribution is a key parameter for the analysis of water stability during food processing and the characterization of food quality (Walayat et al., 2022). The peak relaxation time of bound water (T_{2b}, 0.1–10 ms), immobile water (T_{21}, 10–200 ms), and free water (T_{22}, 200–10,000 ms) in surimi gels subjected to freeze-thaw treatment is shown in Fig. 5(a-f). There was no significant change in the T_{2b} after freeze-thaw treatment of the C gels heated at 60 °C ($P > 0.05$). Nevertheless, the C gels prepared at high temperatures showed a reduction in T_{2b} following freeze-thaw cycles. The rightward shift of the bound water of the starch- surimi gels prior to the freeze-thaw treatment was associated with the starch gelatinization, which led to a change in the bound water. In the case of starch-surimi gels subjected to freeze-thaw cycles, the bound water underwent a change in its peak time, shifting from a single peak (0.1–10 ms) to two distinct peak (0.1–1 ms and 1–10 ms). The emerging peak of bound water was presumed to be water that bound to polar groups on the starch surface by hydrogen bonding (Pan et al., 2017). The starch-surimi gels obtained at high temperatures of 90 °C migrated with a higher relative content of bound water (Fig. 5), which resulted from the starch gelatinization. For immobile water, freeze-thaw cycles promoted a leftward shift in relaxation time and a decrease in relative content. The lack of relative immobile water content corresponded to an increased free water content, which provided evidence that immobile water was migrating to the free water. And same results were presented in Tuankriangkrai and Benjakul (2010) and Shen et al. (2019), well associated with the decline of WHC.

3.5. Breaking force and deformation

The breaking force and deformation parameters of surimi gel are indicative of firmness and elasticity, respectively (Wasinnitiwong et al., 2022). The breaking force in C gels heated at 60 °C and 90 °C was reduced from197.68 ± 2.31 g to 138.47 ± 3.83 g and from 152.69 ± 5.73 g to 88.15 ± 2.13 g, respectively, as depicted in Fig. 4(c, d). The formation of ice crystals during repeated freezing and thawing of the gel results in the squeezing of the surimi matrix and a subsequent weakening of the gel's firmness. The breaking forces of P and T gels subjected to the temperature of 60 °C found to be low, which was ascribed to the reduced relative content of the surimi matrix and the inactive filling of starch. Furthermore, breaking forces exhibited minimal variation with the repeated freeze-thaw cycles. However, starch swelling could significantly improve the reduction of the breaking force of P and T gels ($P < 0.05$). The decrease in breaking force was 13.32 % in potato starch-surimi gel and 12.94 % in tapioca starch-surimi gel during repeated freezing and thawing, compared to 36.34 % in surimi gel. However, no significant differences were identified in the deformation of surimi gels with or without the incorporation of starch following heating at 60 °C ($P > 0.05$). While following a 90 °C heating, all gels showed a significant drop in deformation subjected to freeze-thaw cycles ($P < 0.05$),

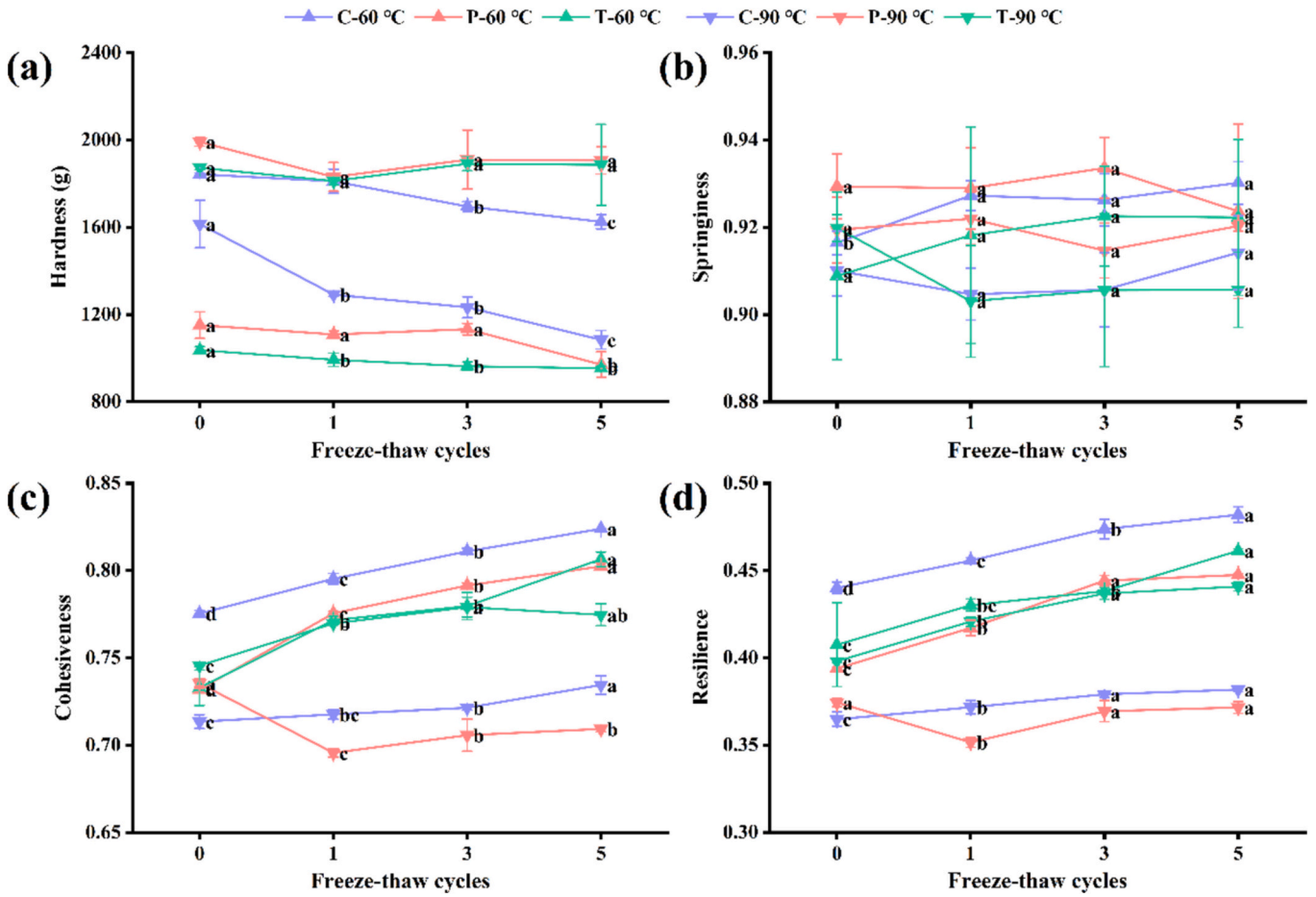


Fig. 6. Changes in the TPA of surimi gels during repeated freeze-thaw. (a) hardness; (b) springiness; (c) cohesiveness; (d) resilience. Lowercase letters indicate the difference in a gel subjected to freeze-thaw cycles ($P < 0.05$), and the values are expressed as mean ± SD.

especially in P and T gels. The reduction in deformation indicated that gels cooked at high temperatures evinced diminished flexibility, which was possibly due to the degree of protein denaturation that occurred as a result of the heat treatment. Nevertheless, it demonstrated a capacity to retain the deformation underlying freeze-thaw cycles when surimi subjected to low-temperature heating. Therefore, while the addition of starch filling was an effective method of improving the freeze-thaw stability of surimi gels, the thermal denaturation produced by high temperatures also rendered the gels more susceptible to environmental stresses.

3.6. TPA

The effects of freeze-thaw cycles on the texture properties of starch-surimi gels are presented in Fig. 6. Hardness is defined as the force produced in the first compression cycle to achieve targeted deformation, showing a high association with breaking force (Jiang et al., 2024; Roy et al., 2021). The hardness of surimi gel without the addition of starch was observed to decrease with the repeated freezing and thawing cycles, which is consistent with the results reported in other studies (Oh et al., 2019). Freeze-thaw cycles caused an undesirable softness in frozen and thawed gels mainly due to the growth of ice crystals. The gel network underwent a transformation from a dense structure to a porous loose structure, which ultimately led to a reduction in gel hardness. Nevertheless, interesting findings were observed whereby the C gels that had been preheated at 90 °C demonstrated a more pronounced decline ($P < 0.05$). It was postulated that the coarser organization of the gel network would exhibit greater resilience to the effects of adverse environments. In case of starch-surimi gel, the thermally induced gelatinization of starch has been demonstrated to provide effective support to the surimi gel network, thereby enhancing the hardness of P and T gels (Yang & Park, 1998). However, the addition of ungelatinized starch to surimi gels resulted in a relatively minor impact of freeze-thaw treatment on hardness. With regard to the springiness of the gels, no significant difference was observed before and after freeze-thaw cycles ($P > 0.05$). Cohesiveness is an indicative of the damage to the gel structure from the first compression, and resilience is calculated by dividing the upstroke energy by the downstroke energy of the first compression (Li et al., 2023; Priyadarshini et al., 2017). The C gels was accompanied by an increase in freeze-thaw cycle, which resulted in an increase in cohesiveness or resilience ($P < 0.05$). This indicated the increased returnability to external pressure after multiple freeze-thaw cycles. Besides, compared to high-temperature heated gels, C gel obtained higher cohesiveness and resilience under low-temperature treatment conditions, which could be as a result of the thicker gel network as shown in Fig. 2. This result was similar to that of the deformation. In summary, the freeze-thaw cycles resulted in a reduction in gel hardness, accompanied by an improvement in gel cohesiveness and resilience.

3.7. Microstructure

The SEM images (Fig. 7) are depicted that freeze-thaw cycles severely affect the organization of surimi gels. The surimi gels exhibited a compact, ordered, three-dimensional network structure, which correlated with higher gel strength and greater water-holding capacity in the resulting gel samples (Fang et al., 2021). The SEM images revealed

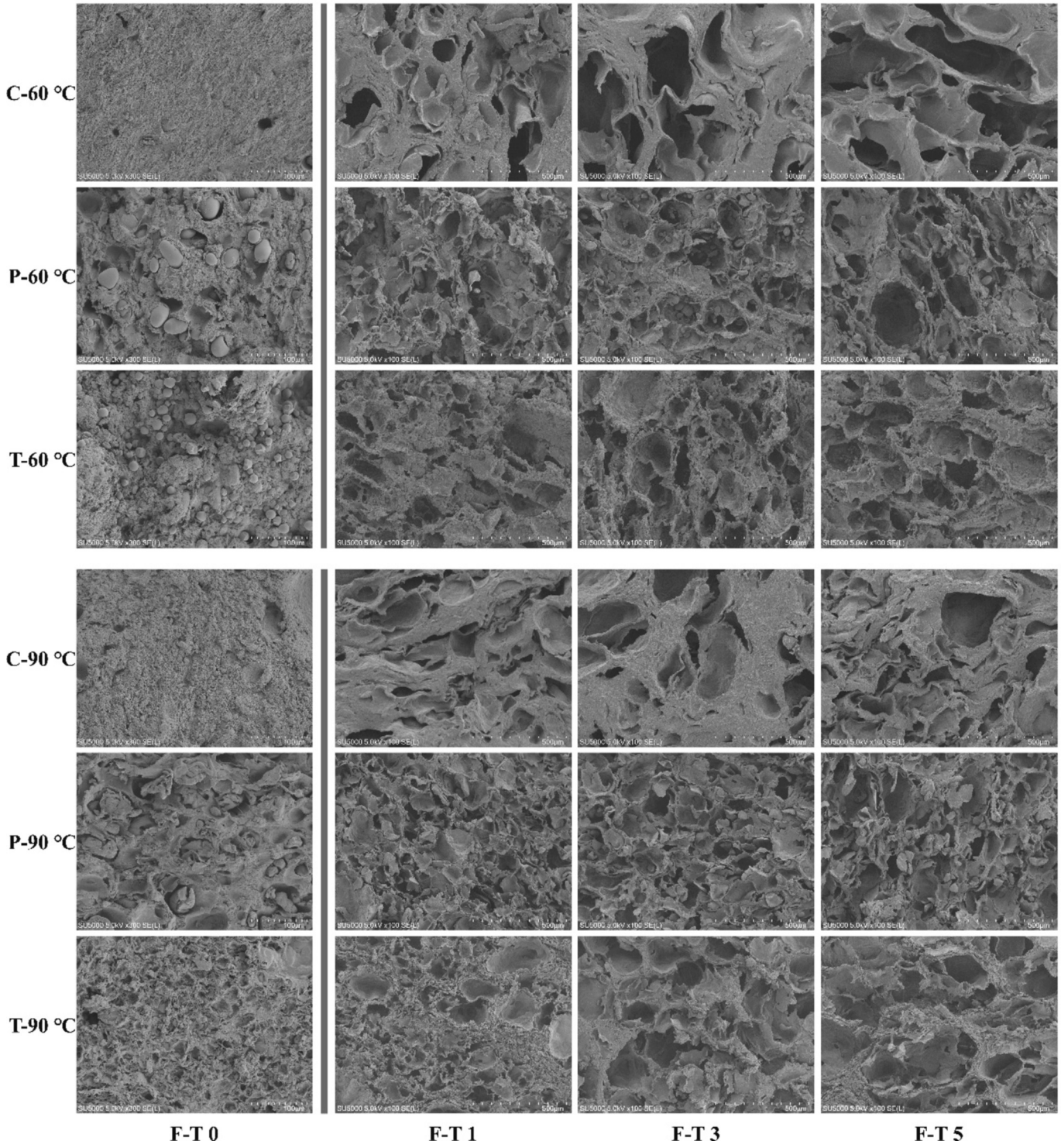


Fig. 7. SEM images of surimi gel with and without exposure to freeze-thaw cycles.

that the surimi gel had been subjected to a high temperature treatment, resulting in a coarser surface texture in comparison to the gel treated at a lower temperature. However, following the repeated freeze-thaw treatment, the formation of smaller pores was observed, which indicated that the gel produced by the high-temperature treatment was more resistant to the formation of ice crystals during the freeze-thaw cycles. Similarly to the results presented in Fig. 2, the ungelatinized starch was embedded in the surimi matrix, resulting in a notable reduction in the pore size in comparison to the C gels. For surimi gels containing gelatinized starch, it was clear that starch underwent significant morphological changes as a result of freeze-thaw cycles, particularly in the case of potato starch, where the larger particle size was more readily discernible. The microstructure provided further evidence of the disruption of the gel structure by ice crystal formation, as well as demonstrating that starch affected ice crystal formation.

3.8. Color

The perception of whiteness affects consumer preferences for surimi products (Wasinnitiwong et al., 2022). Table 1 presents the changes in

Table 1
Effect of freeze-thaw cycles on color of surimi gels prepared at different cooking temperatures of 60 °C and 90 °C.

Color parameter	Sample	Freeze-thaw cycles			
		0	1	3	5
L^* value	C-60 °C	73.33 ± 0.12^{a}	70.93 ± 0.29^{b}	69.33 ± 0.15^{c}	68.27 ± 0.55^{d}
	C-90 °C	74.47 ± 0.25^{a}	71.70 ± 0.00^{b}	71.27 ± 0.15^{c}	70.47 ± 0.15^{d}
	P-60 °C	74.80 ± 0.20^{a}	71.13 ± 0.15^{b}	70.87 ± 0.15^{b}	70.10 ± 0.30^{c}
	P-90 °C	69.90 ± 0.10^{a}	69.63 ± 0.15^{b}	69.50 ± 0.10^{b}	69.00 ± 0.10^{c}
	T-60 °C	77.70 ± 0.10^{a}	74.37 ± 0.06^{b}	74.13 ± 0.21^{bc}	74.00 ± 0.10^{c}
	T-90 °C	69.03 ± 0.15^{a}	68.33 ± 0.06^{b}	68.33 0.06^{b}	67.90 ± 0.10^{c}
a^* value	C-60 °C	−1.83 ± 0.06^{a}	−2.17 ± 0.06^{b}	−2.20 ± 0.00^{b}	−2.23 ± 0.06^{b}
	C-90 °C	−1.30 ± 0.00^{a}	−1.43 ± 0.06^{b}	−1.57 ± 0.06^{c}	−1.57 ± 0.06^{c}
	P-60 °C	−1.50 ± 0.00^{a}	−1.73 ± 0.06^{b}	−1.73 ± 0.06^{b}	−1.80 ± 0.00^{b}
	P-90 °C	−1.97 ± 0.06^{b}	−1.73 ± 0.06^{a}	−1.67 ± 0.06^{a}	−1.63 ± 0.06^{a}
	T-60 °C	−0.97 ± 0.06^{b}	−1.00 ± 0.00^{b}	−0.90 ± 0.00^{a}	−0.90 ± 0.00^{a}
	T-90 °C	−1.97 ± 0.06^{b}	−1.70 ± 0.10^{a}	−1.63 ± 0.06^{a}	−1.60 ± 0.00^{a}
b^* value	C-60 °C	5.07 ± 0.06^{a}	4.47 ± 0.06^{b}	4.07 ± 0.06^{c}	3.90 ± 0.10^{d}
	C-90 °C	5.73 ± 0.15^{a}	5.50 ± 0.00^{b}	5.20 ± 0.10^{c}	5.17 ± 0.06^{c}
	P-60 °C	5.13 ± 0.12^{a}	4.40 ± 0.10^{b}	4.13 ± 0.12^{c}	4.10 ± 0.10^{c}
	P-90 °C	3.93 ± 0.06^{b}	4.03 ± 0.12^{b}	3.97 ± 0.06^{b}	4.20 ± 0.10^{a}
	T-60 °C	6.03 ± 0.06^{a}	5.83 ± 0.06^{b}	5.87 ± 0.06^{b}	5.57 ± 0.06^{c}
	T-90 °C	3.67 ± 0.06^{a}	3.60 ± 0.10^{a}	3.57 ± 0.06^{a}	3.53 ± 0.06^{a}
Whiteness	C-60 °C	72.79 ± 0.12^{a}	70.51 ± 0.29^{b}	68.99 ± 0.15^{c}	67.95 ± 0.55^{d}
	C-90 °C	73.80 ± 0.25^{a}	71.13 ± 0.00^{b}	70.76 ± 0.15^{c}	69.98 ± 0.16^{d}
	P-60 °C	74.24 ± 0.22^{a}	70.75 ± 0.14^{b}	70.52 ± 0.16^{b}	69.77 ± 0.31^{c}
	P-90 °C	69.58 ± 0.11^{a}	69.32 ± 0.14^{b}	69.20 ± 0.11^{b}	68.67 ± 0.11^{c}
	T-60 °C	76.88 ± 0.08^{a}	73.69 ± 0.05^{b}	73.46 ± 0.21^{c}	73.40 ± 0.09^{c}
	T-90 °C	68.75 ± 0.15^{a}	68.08 ± 0.05^{b}	68.09 ± 0.06^{b}	67.67 ± 0.09^{c}

Lowercase letters indicate the difference in a gel subjected to freeze-thaw cycles ($P < 0.05$), and the values are expressed as mean ± SD.

the color of surimi gel following repeated freezing and thawing. The whiteness of C, P, and T gels showed a gradual decrease following freeze-thaw cycles ($P < 0.05$), and the change in gel whiteness was more pronounced following a single freeze-thaw cycle in comparison to unfrozen gels. Possible causes included network structure deterioration and pigment degradation (Zhou & Wang, 2021). Oh et al. (2019) discovered that following nine freeze-thaw cycles, the whiteness of surimi gels significantly deteriorated. By comparing the changes in L^*, a^*, and b^* values, it was determined that the L^* value exerted the most pronounced effect on the variations in the gel's whiteness. In addition, the addition of gelatinized starch to the surimi gels resulted in a reduction in the impact of the freeze-thaw process, although the whiteness was diminished in the absence of a frozen treatment. Besides, it was worth noting that the a^* value of starch-surimi gels heated at 90 °C increased with repeated freeze-thaw cycles. It was hypothesized that the change of a^* value was related to the morphological alterations of starch that occurred during freeze-thaw cycles, as well as changes in water migration. Therefore, the maintenance of color stability by starch was reflected in the slowing down of the reduction of L^*, a^*, and b^* values, which was underpinned by its inherent gelatinization properties and water holding capacity.

4. Conclusions

The present study examined the effects of freeze-thaw treatment on the migration and distribution of ice crystals, as well as the textural and water holding properties of starch-surimi gels. Freeze-thaw cycles had a detrimental impact on the water holding capacity of the gels, as well as on their strength and hardness. Conversely, the gels exhibited enhanced cohesiveness or resilience. The addition of active filling starch to surimi gels led to a reduction in the conversion of immobile water to free water, thereby enhancing the WHC of surimi matrices throughout the freeze-thaw process. Moreover, the appropriate gelatinization of starch guaranteed the freeze-thaw stability of the gel, thus maintaining its whiteness. It was notable that the starch present in surimi gel could be attributed not only to the absorption of water, but also to its potential role in modifying the formation of ice crystals. This resulted in alterations to the ice crystal size and the promotion of the formation of smaller ice crystals. These findings advanced the understanding of the role of starch in surimi gels and laid the groundwork for the starch utilization in surimi gels.

CRediT authorship contribution statement

Xin Jiang: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Qianqian Liang:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Wenzheng Shi:** Supervision, Resources, Project administration, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the Yantai Science and Technology Innovation Development Plan Project [grant number 2022ZDCX010] and the National Key Research and Development Program of China [grant number 2019YFD0902003].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.101995.

References

Benjakul, S., Visessanguan, W., Ishizaki, S., & Tanaka, M. (2001). Differences in gelation characteristics of natural actomyosin from two species of bigeye snapper, *Priacanthus tayenus* and *Priacanthus macracanthus*. *Journal of Food Science, 66*(9), 1311–1318. https://doi.org/10.1111/j.1365-2621.2001.tb15207.x

Cao, Y., Zhao, L. Y., Huang, Q. L., Xiong, S. B., Yin, T., & Liu, Z. Y. (2022). Water migration, ice crystal formation, and freeze-thaw stability of silver carp surimi as affected by inulin under different additive amounts and polymerization degrees. *Food Hydrocolloids, 124*, Article 107267. https://doi.org/10.1016/j.foodhyd.2021.107267

Fan, L. X., Ruan, D. N., Shen, J. D., Hu, Z. L., Liu, C. K., Chen, X., Xia, W. S., & Xu, Y. S. (2022). The role of water and oil migration in juiciness loss of stuffed fish ball with the fillings of pig fat/meat as affected by freeze-thaw cycles and cooking process. *LWT- Food Science and Technology, 159*, 113244. https://doi.org/10.1016/j.lwt.2022.113244

Fang, Q., Shi, L. F., Ren, Z. Y., Hao, G. X., Chen, J., & Weng, W. Y. (2021). Effects of emulsified lard and TGase on gel properties of threadfin bream (*Nemipterus virgatus*) surimi. *LWT- Food Science and Technology, 146*, Article 111513. https://doi.org/10.1016/j.lwt.2021.111513

Gao, Y. P., Fukushima, H., Deng, S. G., Jia, R., Osako, K., & Okazaki, E. (2018). Effect of pH and heating conditions on the properties of Alaska Pollock (*Theragra chalcogramma*) surimi gel fortified with fish oil. *Journal of Texture Studies, 49*(6), 595–603. https://doi.org/10.1111/jtxs.12365

Han, H. J., Hou, J. W., Yang, N., Zhang, Y. H., Chen, H. F., Zhang, Z. P., Shen, Y. Y., Huang, S. T., & Guo, S. R. (2019). Insight on the changes of cassava and potato starch granules during gelatinization. *International Journal of Biological Macromolecules, 126*, 37–43. https://doi.org/10.1016/j.ijbiomac.2018.12.201

He, X. L., Lv, Y. A., Li, X. P., Yi, S. M., Zhao, H. L., Xu, Y. X., & Li, J. R. (2023). Effect of oat β-glucan on gel properties and protein conformation of silver carp surimi. *Journal of the Science of Food and Agriculture, 103*(7), 3367–3375. https://doi.org/10.1002/jsfa.12525

Hunt, A., Getty, K. J. K., & Park, J. W. (2009). Roles of starch in surimi seafood: A review. *Food Reviews International, 25*(4), 299–312. https://doi.org/10.1080/87559120903155834

International Organization for Standardization, Frozen surimi - Specification. (2021). ISO Standard No. 23855:2021 https://www.iso.org/standard/77169.html.

Jia, R., Hiraoka, Y., Tung, Y. L., Nakazawa, N., Osako, K., & Okazaki, E. (2018). "setting-freezing-reheating" procedure improves the gel properties of frozen starch-surimi gel. *Food Science and Technology Research, 24*(6), 999–1006. https://doi.org/10.3136/fstr.24.999

Jia, R., Jiang, Q. Q., Kanda, M., Tokiwa, J., Nakazawa, N., Osako, K., & Okazaki, E. (2019). Effects of heating processes on changes in ice crystal formation, water holding capacity, and physical properties of surimi gels during frozen storage. *Food Hydrocolloids, 90*, 254–265. https://doi.org/10.1016/j.foodhyd.2018.12.029

Jia, R., Katano, T., Yoshimoto, Y., Gao, Y., Nakazawa, N., Osako, K., & Okazaki, E. (2020). Effect of small granules in potato starch and wheat starch on quality changes of direct heated surimi gels after freezing. *Food Hydrocolloids, 104*, Article 105732. https://doi.org/10.1016/j.foodhyd.2020.105732

Jia, R., Katano, T., Yoshimoto, Y., Gao, Y., Watanabe, Y., Nakazawa, N., Osako, K., & &Okazaki, E. (2018). Sweet potato starch with low pasting temperature to improve the gelling quality of surimi gels after freezing. *Food Hydrocolloids, 81*, 467–473. https://doi.org/10.1016/j.foodhyd.2018.03.024

Jiang, Q. Q., Huang, S. Y., Du, Y. F., Xiao, J. B., Wang, M. F., Wang, X. C., Shi, W. Z., & Zhao, Y. L. (2023). Quality improvement of tilapia fillets by light salting during repeated freezing-thawing: Contribution of structural rearrangement and molecular interactions. *Food Chemistry, 406*, 135097. https://doi.org/10.1016/j.foodchem.2022.135097

Jiang, Q. Q., Nakazawa, N., Hu, Y. Q., Osako, K., & Okazaki, E. (2019). Changes in quality properties and tissue histology of lightly salted tuna meat subjected to multiple freeze-thaw cycles. *Food Chemistry, 293*, 178–186. https://doi.org/10.1016/j.foodchem.2019.04.091

Jiang, X., Chen, Q., Xiao, N. Y., Du, Y. F., Feng, Q., & Shi, W. Z. (2022). Changes in gel structure and chemical interactions of *Hypophthalmichthys molitrix* surimi gels: Effect of setting process and different starch addition. *Foods, 11*(1). https://doi.org/10.3390/foods11010009

Jiang, X., Liu, J. Y., Xiao, N. Y., Zhang, X. H., Liang, Q. Q., & Shi, W. Z. (2024). Characterization of the textural properties of thermally induced starch-surimi gels: Morphological and structural observation. *Food Bioscience, 58*, Article 103675. https://doi.org/10.1016/j.fbio.2024.103675

Li, X. X., Huang, R. N., Wu, D., Li, D. P., Yin, T., Xiong, S. B., & Huang, Q. L. (2024). Micro- and nano-sized starch to inhibit gel deterioration and myofibrillar protein strands bunching by molecular interactions under multiple freeze-thaw cycles. *Food Hydrocolloids, 152*, Article 109890. https://doi.org/10.1016/j.foodhyd.2024.109890

Li, Y. Y., Kong, L. R., Zhang, X. T., Wen, R. X., & Peng, X. Y. (2023). Protection of whey polypeptide on the lipid oxidation, color, and textural stability of frozen-thawed Spanish mackerel surimi. *Foods, 12*(24). https://doi.org/10.3390/foods12244464

Luo, H. B., Guo, C. X., Lin, L., Si, Y. L., Gao, X., Xu, D. L., Jia, R., & Yang, W. G. (2020). Combined use of rheology, LF-NMR, and MRI for characterizing the gel properties of hairtail surimi with potato starch. *Food and Bioprocess Technology, 13*(4), 637–647. https://doi.org/10.1007/s11947-020-02423-y

Oh, J. H., Karadeniz, F., Gao, Y., Kim, H. K., Kim, S. J., Jung, J. M., Cheon, J. H., & Kong, C. S. (2019). Gel-forming ability of surimi from aquacultured *Pagrus major* as affected by freeze-thaw cycle. *Turkish Journal of Fisheries and Aquatic Sciences, 19*(5), 423–430. https://doi.org/10.4194/1303-2712-v19_5_07

Pan, T., Guo, H. Y., Li, Y., Song, J. H., & Ren, F. Z. (2017). The effects of calcium chloride on the gel properties of porcine myosin–κ-carrageenan mixtures. *Food Hydrocolloids, 63*, 467–477. https://doi.org/10.1016/j.foodhyd.2016.09.026

Park, J. W. (2005). *Surimi and Surimi Seafood* (2th ed.). CRC Press (Chapter 13).

Park, J. W. (2014). *Surimi and Surimi Seafood* (3th ed.). CRC Press (Chapter 4).

Priyadarshini, B., Xavier, K. A. M., Nayak, B. B., Dhanapal, K., & Balange, A. K. (2017). Instrumental quality attributes of single washed surimi gels of tilapia: Effect of different washing media. *LWT- Food Science and Technology, 86*, 385–392. https://doi.org/10.1016/j.lwt.2017.08.022

Qin, L. J., Fu, Y., Yang, F., Chang, Z. Y., Zou, C. J., Gao, H. L., Jiang, D. M., & Jia, C. F. (2022). Effects of polysaccharides autoclave extracted from Flammulina velutipes mycelium on freeze-thaw stability of surimi gels. *LWT- Food Science and Technology, 169*, 113941. https://doi.org/10.1016/j.lwt.2022.113941

Roy, V. C., Chamika, W. A. S., Park, J. S., Truc, C. H., Khan, F., Kim, Y. M., & Chun, B. S. (2021). Preparation of bio-functional surimi gel incorporation of fish oil and green tea extracts: Physico-chemical activities, in-vitro digestibility, and bacteriostatic properties. *Food Control, 130*, Article 108402. https://doi.org/10.1016/j.foodcont.2021.108402

Shen, X. L., Li, X. H., Yu, J., Wang, F. X., Wang, J. H., Huang, Y. Q., & Liu, Y. L. (2019). Effect of combination of soy protein isolate, tapioca starch and transglutaminase on gel quality of carp surimi. *Food & Machinery*, (9), 26–31. https://doi.org/10.13652/j.issn.1003-5788.2019.09.006

Sun, X. Y., Li, Q., Ding, N., Liang, S. J., Mubango, E., Zheng, Y. Y., Yu, Q. Y., Dai, R. T., & Hong, H. (2024). Cryoprotective effect of fistular onion stalk polysaccharide on frozen surimi derived from bighead carp: Physicochemical properties and gel quality during storage. *Food Hydrocolloids, 148*, 109404. https://doi.org/10.1016/j.foodhyd.2023.109404

Tee, E. T., & Siow, L. F. (2017). Effect of tapioca and potato starch on the physical properties of frozen spanish mackerel (*Scomberomoru guttatus*) fish balls. *International Food Research Journal, 24*(1), 182–190. https://doi.org/10.47836/ifrj.30.4.11

Tuankriangkrai, S., & Benjakul, S. (2010). Effect of modified tapioca starch on the stability of fish mince gels subjected to multiple freeze-thawing. *Journal of Muscle Foods, 21*(3), 399–416. https://doi.org/10.1111/j.1745-4573.2009.00190.x

Walayat, N., Wang, X. K., Liu, J. H., Nawaz, A., Zhang, Z. L., Khalifa, I., Cervera, M. A. R., Pateiro, M., Lorenzo, J. M., Nikoo, M., & Siddiqui, S. A. (2022). Kappa-carrageenan as an effective cryoprotectant on water mobility and functional properties of grass carp myofibrillar protein gel during frozen storage. *LWT- Food Science and Technology, 154*, 112675. https://doi.org/10.1016/j.lwt.2021.112675

Wang, Y. D., Zhuang, Y., Zhang, J. Y., Chen, Y., & Yang, H. (2024). Effects of different pH values and monovalent/divalent cations in washing on the physicochemical characteristics of silver carp surimi gel. *LWT- Food Science and Technology, 196*, Article 115865. https://doi.org/10.1016/j.lwt.2024.115865

Wasinnitiwong, N., Benjakul, S., & Hong, H. (2022). Effects of kappa-carrageenan on gel quality of threadfin bream (*Nemipterus* spp.) surimi containing salted duck egg white powder. *International Journal of Biological Macromolecules, 221*, 61–70. https://doi.org/10.1016/j.ijbiomac.2022.08.200

Yang, H., & Park, J. W. (1998). Effects of starch properties and thermal-processing conditions on surimi-starch gels. *LWT- Food Science and Technology, 31*(4), 344–353. https://doi.org/10.1006/fstl.1997.0366

Yasui, T., Ishioroshi, M., & Samejima, K. (1982). Effect of actomyosin on heat-induced gelation of myosin. *Agricultural and Biological Chemistry, 46*(4), 1049–1059. https://doi.org/10.1080/00021369.1982.10865182

Zhang, X. H., Xie, W. X., Liang, Q. Q., Jiang, X., Zhang, Z., & Shi, W. Z. (2023). High inner phase emulsion of fish oil stabilized with rutin-grass carp (*Ctenopharyngodon idella*) myofibrillar protein: Application as a fat substitute in surimi gel. *Food Hydrocolloids, 145*, Article 109115. https://doi.org/10.1016/j.foodhyd.2023.109115

Zhang, X. X., Mao, M., Zhang, S. T., Wang, Z. F., Liu, S. Q., Yang, W. G., Gao, Y. P., & Jia, R. (2023). Investigation of the changes in gelation properties of hydroxypropyl distarch phosphate-surimi gel under different gelation-freezing treatments. *Journal of the Science of Food and Agriculture, 103*(15), 7877–7887. https://doi.org/10.1002/jsfa.12871

Zhou, F., & Wang, X. C. (2021). Assessing the gelling properties of the silver carp surimi gel prepared with large yellow croaker processing by-product in freeze-thaw cycles. *Journal of Food Processing and Preservation, 45*(5), Article e15479. https://doi.org/10.1111/jfpp.15479

Zhou, X. X., Lin, H. H., Zhu, S. C., Xu, X., Lyu, F., & Ding, Y. T. (2020). Textural, rheological and chemical properties of surimi nutritionally-enhanced with lecithin. *LWT- Food Science and Technology, 122*, Article 108984. https://doi.org/10.1016/j.lwt.2019.108984.9