Food Science of Animal Products

Review Article

The mechanisms and control strategies for quality deterioration in surimi gel during freeze-thawing cycles

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Received: August 25, 2024; Revised: September 19, 2024; Accepted: October 8, 2024

Abstract: Freezing is the primary preservation method for surimi gel. However, repeated freezing and thawing during storage, processing, or consumption can cause ice crystal growth and recrystallization, leading to mechanical damage to muscle cells and tissue. Additionally, it can induce protein denaturation and oxidation, ultimately resulting in a decline in the quality of surimi gel. This includes moisture loss, nutrient depletion, as well as deterioration in taste and texture. Therefore, it is crucial to incorporate cryoprotectants or utilize innovative freezing/thawing technologies to enhance the quality of freeze-thawed surimi gel. This review aims to elucidate the mechanisms underlying the quality deterioration of surimi gel during freeze-thawing cycles, summarize changes in myofibrillar protein and alterations in surimi gel quality after freeze-thawing cycle treatment, and finally strategies for enhancing the quality of surimi gel throughout the freeze-thawing cycles are discussed. This review will offer valuable references for improving the stability of freeze-thawed surimi gel and provide insights into the development of novel cryoprotectants and freezing/thawing technologies.

Keywords: freeze-thawing stability; surimi gel; quality deterioration; cryoprotectant

Citation: Q. L. Zhao, B. Zheng, Y. Q. Gao, et al., The mechanisms and control strategies for quality deterioration in surimi gel during freeze-thawing cycles, Food Sci. Anim. Prod. 2 (2024) 9240088. https://doi.org/10.26599/FSAP.2024.9240088.

1 Introduction

Surimi, a highly concentrated protein extracted from the myofibrils of fish meat, is obtained through a series of procedures including mechanical mincing, rinsing, fine filtration, dewatering, molding, and cooking. It gains consumers preference owing to its delightful taste, convenient consumption and high protein content[1–2]. Freezing is a widely employed method to effectively preserve surimi gels for extended periods by reducing the activity of endogenous enzymes and inhibiting microbial metabolism[3]. During the freezing process, over 90% of the water in surimi gel solidifies into ice. However, the resulting ice crystals are inherently unstable and exhibit an uneven size distribution. Imperfections in cold chain technology during processing and consumption can lead to repeated freezing and thawing that promote ice crystal growth and subsequent recrystallization[4]. The growth of ice crystals disrupts the cellular structure, leading to the release of lysosomal enzymes and an increase in the concentration of pro-oxidant. Consequently, proteins undergo denaturation, oxidation, and degradation due to freeze-thawing treatment. Furthermore, sublimation of ice crystals creates pores in frozen surimi gel that enhance air contact area, thereby further accelerating protein and lipid oxidation[5].

Protein denaturation can irreversibly modify essential amino acids such as tryptophan, methionine, cysteine and histidine, thereby decreasing the solubility and digestibility of proteins. In general, frozen storage induces two major denaturation modes in surimi proteins: unfolding peptide chains within proteins and aggregation between protein molecules[6]. On one hand, the freezing process disrupts the binding between protein molecules and water, resulting in alterations in secondary bonds within proteins and changes in their spatial configuration. On the other hand, the freeze-thawing cycle treatment induces protein stretching and folding, promoting the exposure of hydrophobic groups and hydration of nonpolar groups, which ultimately leads to protein aggregation[7]. The occurrence of protein denaturation prevents gel formation during the heat-induced gel process, causing a weaker gel network with reduced elasticity, gel properties, and water holding capacity[8]. Overall, the denaturation, oxidation, and aggregation of proteins are crucial factors that negatively impact the functional properties of myofibrillar protein during freeze-thawing cycles, thereby leading to irreversible quality deterioration of surimi gel[8–9]. Therefore, it is crucial to explore novel freezing/thawing technologies or incorporate cryoprotectants to effectively improve the quality of freeze-thawed surimi gel.

In the past few years, there has been a significant focus on investigating methods to prevent the deterioration of frozen surimi gel quality. These studies have primarily concentrated on employing physical field-assisted freezing technologies such as high pressure and ultrasound to regulate ice crystal growth as well as protein denaturation and oxidation[10]. However, the industrial

application of these technologies is limited due to their complex equipment requirements and high costs. Regarding antifreeze agents, there are promising prospects for their utilization in protecting frozen surimi gel. The current commercially available antifreeze agent, which is a mixture of 4% (*m*/*m*) sucrose and 4% (*m*/*m*) sorbitol, has received criticism due to its high caloric content and sweetness, as it does not align with the preferences of modern consumers who are seeking low-sugar and low-calorie alternatives[11–13]. The addition of polyphosphates can effectively regulate the pH level of surimi products, causing proteins to deviate from their isoelectric point and subsequently reducing protein aggregation. However, it is crucial to strictly control the consumption of polyphosphates as excessive usage may impede calcium absorption[14]. Polyphenols possess excellent antioxidant properties, which enable them to effectively inhibit protein and lipid oxidation in surimi products by scavenging free radicals, thereby enhancing their anti-damage capability. However, the addition of exogenous polyphenols may impact the whiteness and flavor of frozen surimi gel. For instance, incorporating dark-colored tea polyphenols can significantly reduce the whiteness of frozen surimi gel, while introducing α-tocopherol can improve its whiteness[15–16]. The introduction of apple polyphenol in frozen surimi gel exhibits a pronounced bitter taste; however, this bitterness can be masked by embedding it with hydroxypropyl-β-cyclodextrin[13]. In recent years, new alternatives such as low-sugar, low-phosphorus, and green antifreeze polysaccharides, antifreeze peptides, protein hydrolysates, Pickering emulsion, and exogenous oils have gained popularity due to their excellent antifreeze properties.

The purpose of this paper is to comprehensively summarize the mechanisms underlying quality deterioration in surimi gel during freeze-thawing cycles, as well as the alterations occurring in myofibrillar protein after freeze-thawing cycles. Moreover, the effects of freeze-thawing cycle treatment on water distribution, textural characteristics, microstructure, rheological properties, color, freshness, and lipid oxidation products of surimi gels are summarized. Furthermore, strategies for enhancing the quality of freeze-thawed surimi gel are discussed. This review aims to offer valuable theoretical insights that can support the development of environmentally friendly, safe, and health-promoting novel cryoprotectants or innovative freezing/thawing technology.

2 Mechanisms of quality deterioration in surimi gel during freeze-thawing cycles

Freezing is the most prevalent preservation method for surimi gel. However, repeated freezing and thawing during storage, processing, transportation, or consumption can lead to a deterioration in the quality of surimi gel (such as loss of juice, discoloration, and texture degradation), which reduces consumers' purchasing inclination and causes substantial economic losses for surimi product manufacturers[17–18]. The freezing process of surimi gels can be divided into three distinct stages. Initially, rapid cooling occurs until the gels reach the freezing point, leading to the nucleation of ice crystals. In the second stage, approximately 80% of the water freezes, which is commonly referred to as the maximum zone for ice crystal formation. Subsequently, in the third stage, any remaining moisture within the surimi gels continues to freeze rapidly as the temperature further decreases[19]. By assessing the time required for traversing this maximum zone for ice crystal formation, it becomes feasible to assess both the freezing rate of surimi gel and infer about the size of formed ice crystals and their impact on the texture characteristics of surimi gel.

The freezing curve obtained through real-time temperature monitoring is commonly employed for the analysis of frozen surimi gel. As illustrated in Figure 1A, the maximum zones for ice crystal formation occur at approximately 100 min for the control group, indicating a slow freezing process that signifies significant quality damage in the surimi gel. This can be attributed to the fact that a slow freezing process results in increased growth of ice crystals (as shown in Figure 1B) that mechanically disrupts the fish's sarcoplasmic reticulum structure, which results in expansion within the myofibrillar protein space and subsequently deteriorates texture properties, coloration, and nutritional quality of surimi gel[5]. However, a noticeable difference was observed in the freezing curve between surimi gels supplemented with varying levels of inulin and the control group. There was a reduced time required to pass through the maximum zone for ice crystal formation (< 90 min), suggesting that incorporating inulin had a substantial impact on mitigating freezing damage[5]. Xu et al.[20] pointed out that the total freezing time of immersion freezing and ultrasound-assisted immersion freezing (20, 40, and 60 kHz) was 420 and 215 s, respectively, indicating that ultrasound-assisted immersion freezing shortened the freezing process quickly. Furthermore, the average diameter of ice crystals formed by slow immersion freezing was 28 μm, while it was only 8 μm in rapid ultrasound-assisted immersion freezing, thus reducing the mechanical damage of ice crystal to prawn meat.

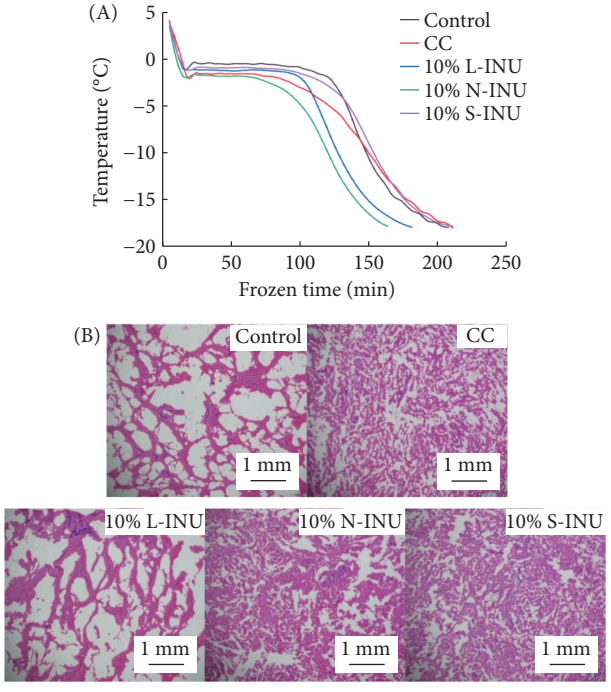

Figure 1 (A) Freezing curves of surimi gel without and with the addition of 10% (*m*/*m*) long-chain inulin (L-INU), nature inulin (N-INU), and short-chain inulin (S-INU)[5]. (B) Micrographs of ice crystals in surimi gel without and with the addition of 10% (*m*/*m*) L-INU, N-INU, and S-INU[5]. CC, commercial cryoprotectant.

In addition to ice crystal formation, proteins undergo frozen denaturation and oxidative damage during repeated freezing and thawing, which further diminishes their functional properties. The gelation behavior of myofibrillar proteins in surimi is primarily

influenced by the dissociation of myosin molecules under salt conditions followed by aggregation during heating. Non-frozen native myofibrillar proteins tend to undergo dissociation into myosin monomers at an optimal salt concentration. These myosin monomers can further aggregate through head-head and tail-tail cross-linking during the heating process, thereby forming a well-structured gel network. However, freeze-thawing cycles inevitably alter the conformation of myofibrillar proteins, leading to denaturation/oxidation-induced aggregation forms that negatively impact the dissociation process of myosin under salt conditions[11]. It has been proven that freeze-thawed myofibrillar protein exhibits relatively low salt solubility. Consequently, undissociated aggregates coexist with monomeric forms of myosin, inducing the formation of amorphous intermolecular crosslinks that interfere with heat-induced aggregates during gelation. It is anticipated that freeze-thawed surimi gels may exhibit a damaged three-dimensional structure with large clusters, resulting in reduced gel strength, water holding capacity, and storage modulus (G')[11].

Currently, the mechanism of protein denaturation during the freeze-thawing cycles can be classified into four types. 1) Denaturation theory based on disengagement of bound water. In fresh surimi products, tightly bound water on the protein surface forms strong interactions with protein molecules. As freezing progresses, this closely bound water transforms into ice crystals, disrupting its binding to proteins, and impeding their rehydration ability. Simultaneously, the contact probability of protein side chain groups increases after dehydration, facilitating cross-linking and leading to protein aggregation and denaturation. Another perspective suggests that in fresh surimi products, the protein presents a tightly folded spatial conformation with most hydrophobic amino acids buried within its internal core structure, and some water molecules are found to play a role in maintaining this folded conformation. However, as freezing progresses, these water molecules separate from the amino acid side chains of protein and form ice crystals. This process leads to protein dehydration and subsequent unfolding of the originally folded structure. Consequently, the protein exists in an open-chain state with low hydration degree, ultimately resulting in protein denaturation[21]. 2) Denaturation theory based on cell fluid concentration. During frozen storage, the freezing of water leads to an increase of cellular solute concentration, osmotic pressure, ions levels, and a shift in pH value, ultimately resulting in protein denaturation. 3) Protein oxidation theory. Ice crystals formation and recrystallization during the freezing process can disrupt cell structure, causing the leakage of reactive nitrogen and reactive oxygen levels, which leads to protein oxidation and subsequent fragmentation of protein backbones, intra-molecular cross-linking or inter-molecular polymerization. Furthermore, protein oxidation can also occur indirectly through covalent binding between electrophilic lipids and amino acid side chains, thereby inducing alterations in protein structure[22]. 4) Lipid oxidation theory. Muscle cells contain a substantial amount of lipids, which undergo oxidation and degradation during repeated freezing and thawing process, leading to the formation of small molecules such as aldehydes and ketones. The oxidized lipids have the ability to interact with various amino acids in proteins (such as methionine, cysteine, and lysine) to form protein-lipid complexes, resulting in protein aggregation. Based on the aforementioned theory, it is evident that ice crystal formation, frozen-induced denaturation and oxidative damage of proteins, as well as lipid oxidation, are the primary factors contributing to the deterioration of freeze-thawed surimi gel quality. Therefore, effectively controlling these primary factors that contribute to gel quality deterioration during the freeze-thawing cycles is crucial for improving the freeze-thawing stability of surimi gel.

3 Changes of myofibrillar protein after freeze-thawing cycles

3.1 Changes of structure

During the freeze-thawing cycle process, the most visually apparent physical change is the formation of unevenly distributed and large ice crystals. These ice crystals have the potential to induce mechanical damage to muscle tissue, subsequently leading to denaturation and aggregation of myofibrillar protein[23]. Frozen-induced denaturation results in significant conformational changes in myofibrillar protein, destabilizing its secondary and tertiary structures, ultimately impacting the quality of surimi gels. After undergoing freeze-thawing cycles, there is a drastic decrease in α-helix and β-sheet contents within myofibrillar protein present in surimi gels, accompanied by an increase in random coil and β-turn contents. Previous studies have also reported that freezing can induce the conversion of stable conformations (α-helix and β-sheet) in myofibrillar protein into less stable ones (β-turn and random coil), thereby significantly compromising the secondary structure of myofibrillar protein molecules[12].

The tertiary structure of proteins is stabilized by ionic bonds, hydrogen bonds, hydrophobic interactions, and hydration of polar residues, which governs the physiological activity of proteins[24]. Tryptophan residues are typically located in the core of myofibrillar protein and exhibit strong fluorescence intensity at the wavelength with maximum emission. Generally, folded proteins demonstrate higher fluorescence intensity compared to their partially or completely unfolded counterparts. Therefore, fluorescence intensity can provide valuable insights into alterations in the tertiary structure of myofibrillar protein by reflecting variations in the polarity of the surrounding environment where tryptophan residues are located[8]. As the number of freeze-thawing cycle increases, there is a decrease in the fluorescence intensity of myofibrillar protein, indicating a reduction in tryptophan residue content. Firstly, ice crystal formation disrupts cell structures and results in the release of pro-oxidants that cause oxidative damage to tryptophan residues. Secondly, freezing-induced unfolding of proteins exposes previously buried tryptophan residues to a hydrophilic environment, facilitating their reaction with peroxyl radicals and subsequent formation of stable compounds that cause fluorescence quenching. Furthermore, aggregation of myofibrillar proteins and enhanced hydrophobic interactions contribute to steric hindrance, resulting in further reduction in fluorescence intensity.

3.2 Changes of molecular forces

The surimi gels are connected through various types of chemical interactions, including electrostatic interactions, hydrogen bonds, hydrophobic interactions, and covalent bonds. Covalent bonds within this system consist of dityrosine bonds and disulfide bonds. Dityrosine is formed through the C–C coupling between two tyrosine radicals, which can be located on either the same or different protein chains. Nevertheless, the impact of freeze-thawing cycles on the dityrosine content in surimi gel has not yet been reported and requires further investigation.

Sulfhydryl groups, also known as thiol groups, are located on the external surface of proteins. These groups are predominantly found in the myosin head and play a crucial role in maintaining the tertiary structure of proteins. During frozen storage of surimi gel, the presence of reactive oxygen can induce a transformation in cysteine's sulfhydryl groups, leading to the formation of disulfide bonds. Consequently, there is a gradual reduction in sulfhydryl group content and an increase in disulfide bond content. Furthermore, ice crystal growth during the freeze-thawing cycle alters the conformation of myofibrillar protein, making its sulfhydryl group more susceptible to reactive oxygen and subsequent formation of disulfide bonds[3]. This conversion from sulfhydryl groups to disulfide bonds plays a pivotal role as an indicator for protein oxidation. In addition to enhancing the disulfide bond content within myofibrillar protein, frozen storage possesses the potential to modify their bonding configurations, which serves as additional indicators of protein tertiary structures and can be assessed using Raman spectroscopy. The most energetically stable conformation is known as *gauche-gauche-gauche* (*g-g-g*), but it may undergo noticeable transformation into less stable conformations, namely *gauche-gauche-trans* (*g-g-t*) and *trans-gauche-trans* (*t-g-t*), during the freezing storage process. This alteration in disulfide bond conformation is accompanied by a decrease in bonding potential energy, implying the destabilization of myofibrillar protein structure during frozen storage[25]. Meanwhile, the hydrophobic amino acid residues within the surimi gel are exposed and the myofibrillar protein molecules undergo unfolding during freeze-thawing cycle treatment, which diminishes the hydrophobic interactions within myofibrillar protein and promotes the formation of hydrogen bonds on protein surfaces, thereby resulting in a deterioration of surimi gel quality[12]. In another work, it has been found that freeze-thawing cycle treatment can reduce electrostatic repulsion between myofibrillar protein molecules and induce their aggregation.

Carbonylation is another important indicator of protein oxidation. Initially, the carbonyl levels of surimi gel were measured at 1.28 nmol/mg and subsequently increased to 2.82 nmol/mg after undergoing five freeze-thawing cycles. This elevation in carbonyl content can be ascribed to the attack of reactive oxygen radicals on the –NH and $–NH_2$ side chains of proteins during the freezing process, leading to conformational changes and aggregation of myofibrillar proteins. Moreover, it is possible that the presence of metal ions contributes to the carbonylation of amino acid side chains, resulting in an increase in the content of carbonyl groups within surimi gel after freeze-thawing cycles[26].

3.3 Changes of physicochemical properties

The physicochemical properties of myofibrillar protein is negatively affected by freeze-induced denaturation and aggregation, resulting in a noticeable reduction in Ca^{2+}-ATPase activity and the content of salt-soluble proteins. The Ca^{2+}-ATPase activity of myofibrillar protein is closely associated with the spherical head structure of myosin, which serves as an indicator for assessing both denaturation degree and structural integrity of myofibrillar protein in surimi gel during frozen storage. The occurrence of denaturation and aggregation of proteins lead to structural alterations within myosin molecules along with a reduction in Ca^{2+}-ATPase activity[12]. The decrease in salt-soluble protein content in surimi gel after undergoing freeze-thawing cycles can be attributed to the exposure of sulfhydryl groups and hydrophobic amino acids in myofibrillar protein caused by freeze-induced denaturation, leading to the formation of disulphide bonds and hydrophobic interactions, thereby promoting the aggregation of myofibrillar protein. Consequently, this ultimately results in decreased solubility of myofibrillar proteins[3].

4 Effects of freeze-thawing cycles on the quality of surimi gels

4.1 Water holding capacity and water distribution

The water holding capacity of surimi gel is a critical characteristic that directly influences its taste, texture, and shelf-life stability by reflecting the interaction between myofibrillar proteins and water molecules[27]. Generally, the densely packed and well-organized structure of the gel matrix facilitates efficient entrapment of water molecules, leading to limited mobility and relatively high water holding capacity. Freeze-thawing cycle treatment has been reported to reduce the water holding capacity of surimi gels. On one hand, repeated freezing and thawing can induce a more relaxed gel structure and increased permeability, thus promoting the release of water and other small molecules. Furthermore, the binding affinity between myofibrillar protein and water primarily depends on exposed carboxyl and hydroxyl groups. Temperature fluctuations during repeated freezing and thawing cause the unfolding of myofibrillar protein structure, which hinders the re-absorption of water by surimi gel and consequently reduces its water holding capacity[5]. Both the freezing rate and thawing rate can influence the water holding capacity of surimi gels. It has been observed that rapid freezing, rather than slow freezing, enhances the water holding capacity of surimi gels. Conversely, rapid thawing has minimal impact on water holding capacity compared to slow thawing[11].

The freeze-thawing process not only decreases the stability of moisture but also increases its mobility. Low-field nuclear magnetic resonance is extensively used to analyze the distribution of water molecule in surimi gels, enabling the identification of different water states present in these gels through peak area examination. The water states observed in surimi gels include free water, immobilized water, and bound water. Bound water surrounds the protein and forms a tight association with it through surface-charged groups. Its presence remains relatively stable even under mechanical stress or changes in microstructure. Immobilized water is located within the myofibrils and is maintained through a combination of structural constraint forces, osmotic pressure, and electrostatic force. These factors play a vital role in determining the water holding capacity of surimi gel. Free water is present in the area surrounding the muscle cell, particularly within muscle bundles and fibers, where capillary forces come into effect. During the freezing process, ice crystals puncture the muscle tissue while structural proteins undergo denaturation, resulting in an accelerated release of immobilized water into the extracellular space. Some of this released immobilized water may convert to free water and subsequently be expelled as exudate during the thawing process, thus demonstrating that repeated freezing and thawing enhance the mobility of water molecules within surimi gel[23,28].

4.2 Textural characteristics

The textural characteristics of surimi gels mainly include gel strength, elasticity, adhesion, hardness, and chewiness. These

characteristics can be used as parameters to monitor the overall macroscopic alterations of the spatial arrangement of surimi gels. Surimi gels generally exhibit a dense three-dimensional network structure, which contributes to their higher gel strength and water holding capacity. It has been reported that freeze-thawing cycle treatment negatively affects the hardness, springiness, and gel strength of surimi gels. This may be attributed to protein denaturation induced by temperature fluctuations and the formation of ice crystals during the freeze-thawing cycles, ultimately resulting in a looser and weaker gel network structure. Furthermore, an increase in the number of repeated freezing and thawing gradually leads to a reduction in chewiness, breaking force, and cohesiveness of surimi gels, which further indicates quality deterioration during frozen storage[5]. Previous research has indicated that rapid freezing yields higher gel strength compared to slow freezing. Similarly, compared to slow thawing methods such as refrigerator thawing, air thawing and water immersion thawing, rapid thawing techniques like ultrasound-assisted immersion thawing (100 kHz, 45 min) and ultrasound-assisted vacuum thawing have also been found to enhance the gel strength and overcome the quality defects of surimi gel[29–30]. On one hand, ultrasound-induced cavitation effects enhance heat and mass transfer, thereby accelerating the rate of thawing and reducing protein denaturation. Frozen surimi absorbs both internal and external energy generated by ultrasound in the resonance process, allowing it to rapidly pass through the zone of maximum ice crystal dissolution between the frozen layer and the thawed layer. This effectively prevents uneven thawing caused by localized high temperatures within the sample. On the other hand, thawing at an appropriate ultrasound frequency can minimize damage to secondary and tertiary structures of myofibrillar proteins, increase immobilized water content, and promote free water backflow, thus positively impacting gel properties of surimi gel. It is worth noting that these effects are consistent with those observed in frozen small yellow croaker, carp, and large yellow croaker[29–31].

4.3 Microstructure

The microstructure of surimi gel matrix is generally examined using a confocal laser scanning microscope (CLSM) and a scanning electron microscope (SEM), which facilitate the identification of alterations in the gel network structure[32–33]. Figure 2 shows the SEM and CLSM images of fresh surimi gel and freeze-thawing cycle-treated surimi gel. The native surimi gel exhibits a typical fibrous structure characterized by an organized arrangement, while the surface displays a homogeneous dispersion of micropores along with distinct spatial layering and compactness. However, after undergoing freeze-thawing cycle, the internal structure of surimi gels is severely disrupted and collapses, resulting in an uneven surface and loss of their porous spatial structure. This degradation can be ascribed to the repetitive formation of ice crystals within the gel matrix, which exerts mechanical strain and induces denaturation of myofibrillar proteins. Consequently, this causes a partial disturbance in their spatial conformation and inhibits the cross-linking of amino acid side chains, resulting in the formation of a gel network with reduced viscoelastic properties[3,28]. For example, Xie et al.[12] pointed out that fresh surimi gel exhibited a compact and uniform fiber network structure. However, repeated freezing and thawing caused severe damage to the network structure of surimi gel, accompanied by gradual enlargement of pores. Subsequently, large cracks appeared on its roughened surface. After undergoing five freeze-thawing cycles, the protein fiber network structure experienced a collapse, suggesting a progressive deterioration in the performance of the surimi gel with an increasing number of freeze-thawing cycles. Recent studies have

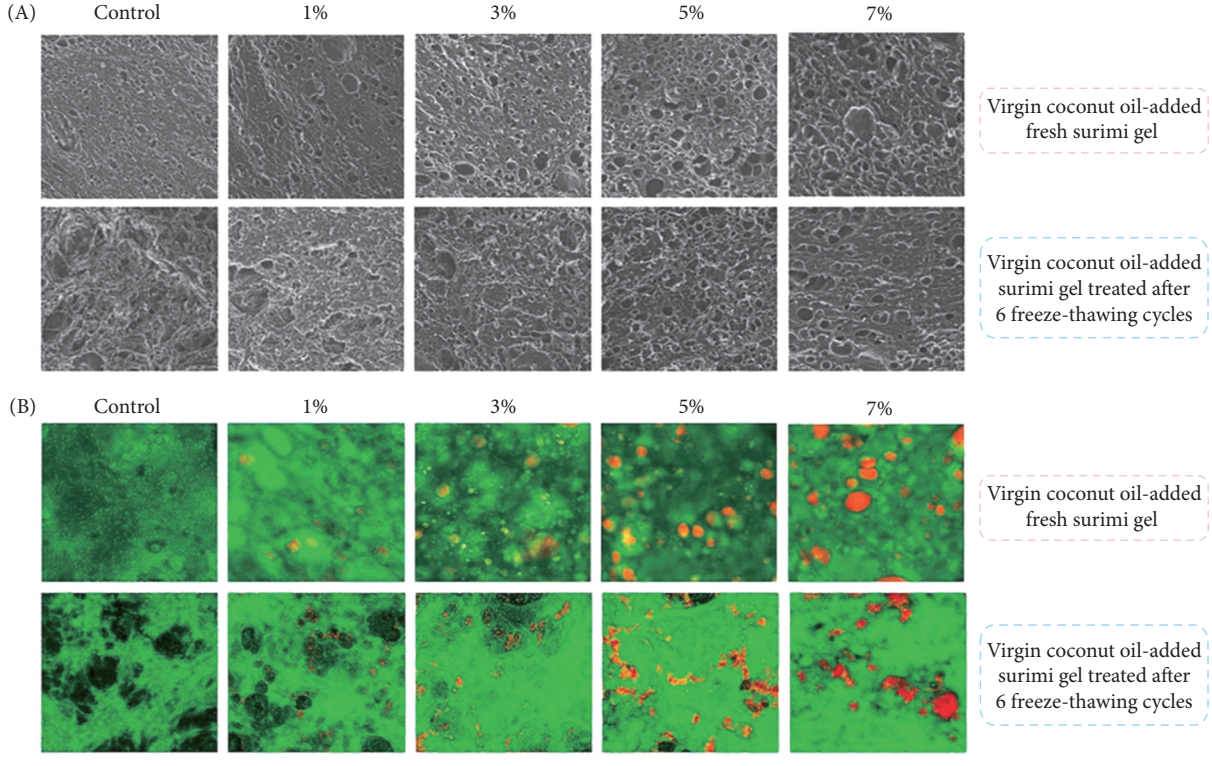

Figure 2 (A) SEM images and (B) CLSM images of fresh surimi gel and freeze-thawing cycle-treated surimi gel with different levels of virgin coconut oil (1%, 3%, 5%, and 7%, *m*/*m*)[28]. Control: fresh surimi gel and freeze-thawing cycle-treated surimi gel.

extensively investigated how different rates of freezing or thawing affect the microstructural characteristics of surimi gels. Surimi gels obtained from rapid freezing or thawing processes typically display smaller and more uniform pores compared to those formed from slow freezing or thawing methods.

4.4 Rheological properties

The rheological properties of surimi gels can be evaluated by examining the G' and loss modulus (G''). G' reflects gel's solid-like attributes, such as elasticity and deformability, while G'' represents its viscous fluid-like behavior[34]. An enhancement in G' indicates increased elasticity and strength of surimi gel. Prior to frozen storage, a gradual increase in both G' and G'' was observed with increasing angular frequency for surimi gel. Moreover, the value of G' consistently surpassed that of G'', indicating solid-like gel behavior characteristics. However, after undergoing freeze-thawing cycles, a significant decrease in both G' and G'' was observed due to the degradation of the microstructural integrity of surimi gels, suggesting a reduction in the elasticity of the surimi gel[25,35]. The oxidation of myofibrillar protein induced by repeated freezing and thawing results in a degradation in its functional properties, such as heat-induced gel-forming capacity, thereby hindering the formation of a well-structured gel network. Additionally, the aggregation and cross-linking of myofibrillar protein during frozen storage can impede the structural unfolding during heat-induced gelation process, ultimately leading to a poorer gel network structure[8].

When the surimi gel is heated at 40–60 ℃, G' initially exhibits a significant decrease followed by an increase, known as the "Modori" phenomenon. This phenomenon mainly results from the disruption of hydrogen bonds, resulting in the degradation of protein aggregates. Moreover, within this temperature range, there is an enhancement in the activity of endogenous protein hydrolases that contribute to the breakdown of myofibrillar proteins. As heating progresses further, the G' gradually rises in the surimi gel, indicating the formation of a gel network structure and a progressive increase of solid-like properties[28]. After undergoing freeze-thawing cycle treatment, the "modori" range of surimi gels exhibited a slight shift towards higher temperatures compared to fresh sample. This elevation can be ascribed to the adverse effects of repeated freezing and thawing on the spatial conformation of myofibrillar proteins, which requires higher temperatures for their degradation. Additionally, compared to fresh surimi gels, those subjected to freezing and thawing exhibit lower G' while G'' experiences a slight increase. These findings suggest that freeze-thawing cycle treatment diminishes both solid-like properties and elastic behavior of surimi gels due to protein denaturation during this process, which affects their gel-forming ability[28].

4.5 Color

Color is a crucial sensory parameter for evaluating the quality of surimi gels, which is characterized by the lightness value (L^*), red-green value (a^*), and yellow-blue value (b^*). Generally, greater popularity of surimi gels is associated with a higher L^* and a lower b^*. Frozen-induced protein denaturation causes significant changes in the color of surimi gels, typically resulting in a reduction in L^* and an enhancement in b^*. These alterations are closely associated with water loss, muscle damage, as well as adverse reactions such as lipid and protein oxidation[5]. Whiteness also plays a crucial role in assessing the commercial value of surimi gels. Protein denaturation and oxidation, along with lipid oxidation during freeze-thawing cycles, are the primary factors contributing to the decrease in whiteness of surimi gels. For instance, Du et al.[23] observed that the whiteness of the surimi gel decreased from 50.3 to 40.4 after five freeze-thawing cycles. Temperature fluctuations during frozen storage can result in the formation of irregular and large ice crystals that penetrate muscle tissue and cause loss of inner contents, thereby leading to a decrease in whiteness. Furthermore, mechanical damage caused by these ice crystals on muscle cells can induce lipid oxidation and accelerate the generation and transfer of free radicals, ultimately resulting in cross-linking between muscle proteins/amino acid side chain residues and pigment proteins.

4.6 Freshness

The total volatile basic nitrogen is a complex mixture of various volatile alkaline ammonia compounds, including trimethylamine, dimethylamine, and ammonia, which serve as indicators of fish freshness[36]. Freezing conditions can lead to the conversion of trimethylamine oxide to trimethylamine through the action of trimethylamine oxide-demethylase, contributing to the development of a fishy odor. However, it should be noted that freshwater fish generally exhibit lower levels of trimethylamine oxide. It has been reported that both total volatile basic nitrogen and trimethylamine oxide levels increase in surimi gels during five freeze-thawing cycles, while there is a decrease in the concentration of trimethylamine oxide. Eventually, the total volatile basic nitrogen value in the surimi gel reaches 20.2 mg/100 g, exceeding the acceptable range at 15 mg/100 g. The freezing process induces lactate accumulation in surimi gel due to anaerobic respiration. Additionally, the presence of ice crystals punctures muscle tissue and releases endogenous enzymes like cathepsin that interact with amino acids, resulting in the production of volatile compounds[23].

4.7 Lipid oxidation products

During the process of repeated freezing and thawing, ice crystal growth and recrystallization occur, resulting in cellular damage within muscle cells. This subsequently triggers the release of lipoxidases, as well as catalysts such as heme irons that facilitate lipid oxidation[4]. Lipid oxidation may adversely affect the quality of surimi products by generating unpleasant odors and harmful compounds. Two commonly used indicators for measuring the primary and secondary products of lipid oxidation are the peroxide value and the thiobarbituric acid reactive substances[23]. During freeze-thawing cycles, there is an initial enhancement followed by a subsequent decline in peroxide values in surimi gels. The highest peroxide values were found after five freeze-thawing cycles, suggesting an increased risk of oxidative spoilage due to hydrogen peroxides generated from fatty acid oxidation. Conversely, the decline in peroxide values may be attributed to decomposition into secondary oxidation products such as thiobarbituric acid reactive substances, which significantly increase with an increasing number of freezing-thawing cycles. For instance, silver carp surimi gel exhibits a 3.38-fold increase in thiobarbituric acid reactive substances after undergoing six freezing-thawing cycles. Furthermore, repeated freezing and thawing promotes lipid oxidation, resulting in elevated hexanal levels in surimi products. Peng et al.[37] found that the hexanal content increased from 323.79 to 709.27 ng/g after six cycles of freezing and thawing.

5 Strategies for enhancing the quality of surimi gel during freeze-thawing cycles

5.1 Incorporation of exogenous oils

The fluctuation in temperature during freeze-thawing cycles can cause denaturation of myofibrillar protein, thereby impairing its cross-linking ability. Additionally, the repetitive process of crystallization and melting of water within the surimi gel also disrupts the structure of myofibrillar protein, resulting in the formation of a loosely structured gel with an undesirable taste. Interestingly, myofibrillar protein exhibits hydrophobic interactions with the surfaces of exogenous oil droplets, forming stable interfacial films[38]. When subjected to repeated freezing and thawing, the bound structure of myofibrillar protein shows increased resistance against temperature fluctuations compared to its free-floating state. Moreover, the presence of exogenous oils hinder ice crystal growth and protects myofibrillar protein from further damage. Consequently, exogenous oils serve to preserve the gel-forming ability of myofibrillar protein and improve the texture properties of surimi gels. In addition, lipid oxidation occurring within exogenous oils plays a vital role in improving the flavor profiles of surimi gels[28]. For instance, the addition of virgin coconut oil demonstrated an obvious improvement in water holding capacity and gel strength of freeze-thawed surimi gels. It also effectively hindered the migration of immobilized water into free water. Additionally, Shen et al.[28] emphasized that the incorporation of virgin coconut oil exerted positive effects on enhancing various flavors substances while reducing undesirable fishy components in freeze-thawed surimi gels. Specifically, freezing and thawing cycles induced chemical reactions such as protein degradation and lipid oxidation in the surimi, accelerating the production of diverse small molecules. The accumulation of these volatile compounds resulted in an overly strong and pungent surimi odor. However, with the inclusion of virgin coconut oil, there was a significant decrease in fishy-smelling components within freeze-thawed surimi. This decline could be attributed to interactions between certain degradation products of unsaturated fatty acids present in virgin coconut oil and these fishy-smelling substances within the surimi, leading to their reduced content. Furthermore, due to its inherent antioxidant properties, virgin coconut oil could react with free radicals in the surimi, thereby reducing the oxidative production of these fishy substances. Moreover, incorporating virgin coconut oil increased levels of certain alcohols, aldehydes, and ketones, which predominantly contributed fresh plant-like aromas, thus enhancing the flavor profile of freeze-thawed surimi gels[28]. In another work, compared to liquid fish oil and soybean oil, solid lard oil exhibits larger fat particles and demonstrates reduced aggregation and increased hardness within the surimi gels during frozen storage. Moreover, incorporating lard oil combined with vacuum packaging exhibits a relatively optimal preservation of surimi gel quality during freeze-thawing cycles[39] (as shown in Table 1).

5.2 Addition of cryoprotectants

Currently, research on improving the deterioration of surimi gel quality during repeated freezing and thawing primarily focuses on three key aspects: reducing ice crystal size, inhibiting protein denaturation, and delaying lipid oxidation. These factors are often regulated through the introduction of various cryoprotectants[14,40]. Presently, the most extensively studied cryoprotectants mainly include polysaccharide, protein hydrolysates, antifreeze peptides, and antioxidants (as shown in Table 1).

Table 1 Effects of various of cryoprotectants on the gel properties of surimi gels and their underlying interaction mechanisms.

Cryoprotectant varieties		Concentration	Freeze-thawing conditions	Enhanced indicators of surimi gel	Interaction mechanism	Reference
Exogenous oils	Virgin coconut oil and fish oil	3 g/100 g	Frozen at −20 °C for 48 h then thawed at 4 °C for 12 h	Exhibited a notable enhancement in gel strength, water holding capacity, impeding the conversion of physically bound water to free water, increasing ester and alkane content while lowering the undesirable fishy compounds	Inhibiting the growth of ice crystals and minimizing damage to surimi	[28]
Polysaccharides	Inulin	8% (*m*/*m*)	Frozen at −20 °C for 48 h then thawed at 4 °C for 12 h	Enhanced water holding capacity, gel strength, whiteness, and texture properties	Changed water distribution, decreased freezing temperature, prevented ice crystal growth, interacted with proteins to facilitate their stabilization	[5]
	Trehalose and sodium pyrophosphates	8% and 0.5% (*m*/*m*)	Frozen at −20 °C for 90 days then thawed at 4 °C for 18 h	Improve the gel-forming ability and rheological properties	Inhibited myofibrillar protein oxidation and structural changes in surimi during frozen storage	[8]
	Tamarind seed polysaccharide	1.0% (*m*/*m*)	Frozen at −40 °C for 10 min then thawed at 25 °C	Declined the Ca^{2+}-ATPase activity and stabilized the secondary, tertiary, and quaternary structure of myofibrillar protein	Exhibited superior ice recrystallization inhibitory effect	[12]

Table 1 (*Continued*)

Cryoprotectant varieties		Concentration	Freeze-thawing conditions	Enhanced indicators of surimi gel	Interaction mechanism	Reference
Polysaccharides	Konjac glucomannan	0.15% (*m*/*m*)	Frozen at –20 °C for 1 month then thawed at 5 °C for 12 h	Improved the low-salt surimi gel strength and whiteness, accompanied by less liquid loss	Enhance freezing-thawing stability by the modification of ice crystals, limited water migration, and inhibition of network destruction	[41]
	Flammulina velutipes polysaccharides	0.2% (*m*/*m*)	Frozen at –20 °C for 20 h then thawed at 4 °C for 12 h	Improve the water holding capacity, hardness, springiness, and cohesiveness of surimi gels during the repeated freeze-thaw cycles	Inhibited the growth of ice crystals	[42]
	Fistular onion stalk polysaccharide	4% (*m*/*m*)	Frozen at –20 °C for 30 days then thawed at 4 °C for 24 h	Improved the gel strength, chewiness, and springiness of the surimi gel	Delayed the decline of Ca^{2+}-ATPase activity and the increase of carbonyls, while stabilizing the secondary structure of myofibrillar protein, prevented protein denaturation	[43]
	Tea polysaccharides	3% (*m*/*m*)	Frozen at –18 °C for 48 h then thawed at 4 °C for 24 h	Reduced the total sulfhydryl and reactive sulfhydryl contents contents and increased the surface hydrophobicity	Inhibited freeze-induced crystallization, recrystallization, prevented myosin oxidation and denaturation	[44]
	Konjac oligosaccharides	3% (*m*/*m*)	Frozen at –18 °C for 24 h then thawed at 4 °C for 3 h	Restricted the increase in surface hydrophobicity, declined in sulfhydryl groups and Ca^{2+}-ATPase activity, enhanced the gel strength of surimi	Inhibited the freeze induced oxidative changes by prompting the intermolecular interactions between protein molecules	[45]
	Konjac oligo-glucomannan	0.5% (*m*/*m*)	Frozen at –18 °C for 50 days then thawed at 4 °C for 24 h	Increased salt soluble protein and the total sulfhydryl contents, enhanced the gel strength of surimi	Inhibited protein denaturation and lipids oxidation	[46]
	Konjac oligo-glucomannan	3% (*m*/*m*)	Frozen at –24 °C for 24 h then thawed at 4 °C for 3 h	Enhanced the stability of α-helix content by inhibiting the hydrophobic residue exposure and change in aromatic amino acids, enhanced the textural properties of surimi gel	Inhibiting the freeze induced protein denaturation	[47]
	Carrageenan oligosaccharide	3 g/100 mL	Frozen at –20 °C for 12 h then thawed at 4 °C for 12 h	Maintained the better integrity of protein and the capacity of water retention, preserved the gel properties and thermal stability of protein	Inhibited protein degradation, degeneration, and lipid oxidation	[48]
	Xylooligosaccharides	5% (*m*/*m*)	Frozen at –18 °C for 42 h then thawed at 25 °C for 6 h	Improved the myofibrillar protein gel-forming ability, gel strength, and gel water holding capacity	Increased the stability of myofibrillar protein conformation	[49]
	Sodium alginate	1% (*m*/*m*)	Frozen at –18 °C for 7 days then thawed at 4 °C for 4 h	Decreased ice production, thawing loss, and total volatile base nitrogen value, increased chewiness and whiteness of fish balls	Inhibited the formation of ice crystals, reducing water migration and loss while minimizing damage to the meat structure	[50]
	Nanocrystalline cellulose	4% (*m*/*m*)	Frozen at –18 °C for 60 days then thawed at 25 °C	Showed compact structure and improved gel strength	Protecting the structural integrity and functions of myofibrillar protein	[51]
Protein hydrolysates	Chickpea protein hydrolysates	4% (*m*/*m*)	Frozen at –20 °C for 30 h then thawed at 4 °C for 18 h	Exhibited a more stable microstructure with evenly distributed water, improved elasticity, gel strength, and water holding capacity	Prevented denaturation and oxidation of myofibrillar protein during freeze-thawing cycles	[26]

Table 1 (*Continued*)

Cryoprotectant varieties		Concentration	Freeze-thawing conditions	Enhanced indicators of surimi gel	Interaction mechanism	Reference
Protein hydrolysates	Whey protein hydrolysates	15% (*m*/*m*)	Frozen at −18 °C for 5 days then thawed at 4 °C for 12 h	Improved the antioxidant properties, enzymatic activity retention, and structural integrity of myofibrillar protein	Effectively reduced protein denaturation during repeated freeze-thaw processes	[37]
	Silver carp protein hydrolysates	2% (*m*/*m*)	Frozen at −20 °C for 15 h then thawed at 4 °C for 9 h	Maintained its network structure's integrity of surimi gel even after undergoing 6 freeze-thawing cycles	Effectively prevented myosin from unfolding and aggregating by tightly binding to basic amino acids and hydrophobic amino acids residues in the myosin head pocket	[52]
	Silver carp protein hydrolysates	4% (*m*/*m*)	Frozen at −18 °C for 12 h then thawed at 4 °C for 12 h	Decreased the formation of malondialdehyde and the change rate of flavor compounds in surimi, forming a gel network with good water retention and stable structure	Alleviated the formation of carbonyls of myofibrillar protein, inhibited the decrease of free sulfhydryl content and maintained the protein bands stability	[53]
	Silver carp by-products protein hydrolysates	2% (*m*/*m*)	Frozen at −25 °C for 12 h then thawed at 4 °C for 12 h	Displayed the highest actomyosin extractability, Ca^{2+}-ATPase activity and correspondingly, lowest surface hydrophobicity of actomyosin	Protected protein from freeze-induced damage	[54]
	Bighead carp gill protein hydrolysates	2% (*m*/*m*)	Frozen at −18 °C for 4 months then thawed at 5 °C for 8 h	Exhibited higher sulfhydryl and salt-soluble protein concentrations, greater Ca^{2+}-ATPase activity, lower disulfide bonds, carbonyls and hydrophobicity, as well as better gel strength and texture	Inhibited oxidation and denaturation of myofibrillar proteins during frozen storage	[55]
	Silver carp protein hydrolysates	0.4% (*m*/*m*)	Frozen at −18 °C for 12 h then thawed at 4 °C for 12 h	Decreased the formation of lipid peroxide malondialdehyde and the change rate of flavor compounds in unwashed surimi, alleviated the water loss and structural collapse of the gel, forming a gel network with good water retention and stable structure	Inhibited oxidation, aggregation, and denaturation of myofibrillar protein	[56]
	Rice bran hydrolysates	2% (*m*/*m*)	Frozen at −18 °C for 24 h then thawed at 5 °C for 1 day	Prevented the migration of fat	Reduced lipid oxidation	[57]
	Rice bran hydrolysates	2% (*m*/*m*)	Frozen at −18 °C for 16 h then thawed at 5 °C for 8 h	Exhibited higher total sulfhydryl group content, protein solubility, *G*′, and lower surface hydrophobicity	Reduced protein denaturation	[58]
	Gelatin hydrolysates	10% (*m*/*m*)	Frozen at −20 °C for 18 h then thawed at 4 °C for 4 h	Exhibited higher Ca^{2+}-ATPase activity, total sulfhydryl, and solubility while coincidentally exhibiting lower disulfide bond content	Prevented protein denaturation and lipid oxidation in natural actomyosin induced by the freeze-thawing process	[59]
	Gelatin hydrolysates	0.8% (*m*/*m*)	Frozen at −20 °C for 24 h then thawed at 25 °C for 30 min	Exhibited highest Ca^{2+}-ATPase activity with the coincidental lowest surface hydrophobicity	Showed the higher protective effect on denaturation of myosin heavy chain, especially globular head domain	[60]
Antifreeze peptides	Eel head protein hydrolysates	10% (*m*/*m*)	Frozen at −20 °C for 80 days then thawed at 4 °C for 4 h	Decreased the activity of Ca^{2+}-ATPase, increased the amount of salt soluble protein	Inhibited protein denaturation and oxidation	[61]

Table 1 (*Continued*)

Cryoprotectant varieties		Concentration	Freeze-thawing conditions	Enhanced indicators of surimi gel	Interaction mechanism	Reference
Antifreeze peptides	Silver carp scales antifreeze peptides	4% (*m*/*m*)	Frozen at −20 °C for 72 h then thawed at 25 °C for 1 h	Exhibited a higher Ca^{2+}-ATPase activity, salt-soluble protein concentration and sulfhydryl group content, while decreased surface hydrophobicity, carbonyl content, and disulfide bond content, improved the gel properties, and water holding capacity of surimi gel	Regulating the size of ice crystals during freeze-thaw process	[3]
	Antifreeze peptides	4% (*m*/*m*)	Frozen at −20 °C for 28 days then thawed at 4 °C for 12 h	Reducing the loss of Ca^{2+}-ATPase activity, slowing oxidation of sulfhydryl groups to disulfide bonds, and maintaining surface hydrophobicity and solubility of myofibrillar protein, decreasing the loss of immobilized water and bound water	Exhibited a strong inhibition of ice crystal recrystallization	[62]
	Takifugu obscurus skin antifreeze peptides	4% (*m*/*m*)	Frozen at −25 °C for 3 days then thawed at 25 °C for 6 h	Reducing the moisture variation and maintaining protein solubility of surimi at macro level, inhibiting the degeneration and structure changes of myofibrillar proteins at micro level	Prevented the freeze denaturation of proteins by inhibiting the growth and recrystallization of ice crystals, maintained the spatial structure and water retention ability of proteins by directly binding to the structural cavity of myosin, thus inhibiting protein freezing-induced oxidation	[63]
	Antifreeze peptides	2% (*m*/*m*)	Frozen at −20 °C for 5 days then thawed at 25 °C for 4 h	Improved the rheological properties of surimi gels	Inhibition of ice crystal recrystallization	[64]
Natural solvents	Deep eutectic solvents	4% (*m*/*m*)	Frozen at −18 °C for 7 days then thawed at 4 °C for 12 h	Reduced water migration and loss, inhibited ice crystal growth and recrystallization, and inhibited quality deterioration	Inhibited oxidation and denaturation of myofibrillar proteins during frozen storage	[23]
Protein-polyphenol complexes	Pea protein isolate-epigallocatechin gallate (EGCG) complexes	0.3 g/kg	–	The rate of colour deterioration and off-odour development were delayed, prolonging the shelf life (more than 6 days) of tilapia surimi during chilled storage	Reduced the microbial activity and delayed the lipid and protein oxidation of surimi during frozen storage	[65]
Amino acids	γ-Polyglutamic acid	0.04% (*m*/*m*)	Frozen at −20 °C for 24 h then thawed at 4 °C for 12 h	Improved gel quality with less water loss and higher gel strength	Inhibited denaturation and oxidative aggregation of frozen sol	[66]
Pickering emulsions	Pickering emulsion stabilized by soy protein isolate	12% (*m*/*m*)	Frozen at −20 °C for 2 days then thawed at 25 °C for 4 h	Reduced lipid oxidation level, and enhanced freeze-thaw stability, improved the texture properties	Played a more stable filling role in the gel matrix, improved the densification and homogeneity of the gel network structure; enhanced the freezing rate of the surimi gels, resulting in the formation of smaller ice crystals during freezing	[38]
	Quinoa protein Pickering emulsion	7.5% (*m*/*m*)	Frozen at −20 °C for 24 h then thawed at 4 °C for 6 h	Enhanced the juiciness and gel strength of myofibrillar protein gels, retarded the protein oxidation, stabilized water distribution and tertiary structure of myofibrillar protein gels	Reduced the ice crystal size in fish protein gel, decreased the freezing point of fish myofibrillar protein gels	[67]

Table 1 (*Continued*)

Cryoprotectant varieties		Concentration	Freeze-thawing conditions	Enhanced indicators of surimi gel	Interaction mechanism	Reference
Pickering emulsions	Quinoa protein Pickering emulsion	7.5% (*m*/*m*)	Frozen at −20 °C for 24 h then thawed at 4 °C for 6 h	Increased *G*′, gel strength and water holding capacity	Promoted the changes of *α*-helix to other secondary structures in myofibrillar protein gels, the *g-g-g* conformation turned to *g-g-t*	[68]
	Quinoa protein Pickering emulsion	7.5% (*m*/*m*)	Frozen at −20 °C for 24 h then thawed at 4 °C for 6 h	Improved freeze-thaw stability of myofibrillar protein gels	Maintained the structural stability, slowed down the protein denaturation and oxidation of myofibrillar protein gels after freeze-thaw cycles	[69]
	Sodium starch octenyl succinate-based Pickering emulsion	2% (*m*/*m*)	Frozen at −20 °C for 48 h then thawed at 4 °C for 12 h	Improved whiteness, water holding capacity, *G*′, texture properties, and freeze-thaw stability of hairtail myofibrillar protein gel	Inhibited recrystallisation and freezing shrinkage of the proteins	[70]
Polyphenols	*α*-Tocopherol	0.1% (*m*/*m*)	Frozen at −16 °C for 18 weeks then thawed at 4 °C for 12 h	Maintained the breaking force, deformation, gel strength, water holding capacity, and microstructure of sturgeon surimi	Inhibited oxidation and denaturation of myofibrillar proteins during frozen storage	[15]
	EGCG	0.03% (*m*/*m*)	Frozen at −20 °C for 72 h then thawed at 4 °C for 12 h	Inhibited the decline of texture and gel strength, the microbial growth and the formation of off-odor compounds such as total volatile basic nitrogen and malondialdehyde	Retarding protein oxidation	[71]
	Seaweed polyphenols and ascorbic acid	0.1 g/100 g	Frozen at −18 °C for 70 days then thawed at 4 °C for 12 h	Decreased thiobarbituric acid-reactive substances, retarded the inactivation of Ca^{2+}-ATPase	Retarding protein oxidation	[72]

5.2.1 *Poysaccharides*

Saccharides are commonly employed as cryoprotectants in frozen products. Currently, a popular approach involves the utilization of a combination comprising 4% (*m*/*m*) sucrose and 4% (*m*/*m*) sorbitol to mitigate protein denaturation and maintain the quality of freeze-thawed surimi gels. However, these commercially available cryoprotectants result in excessive sweetness and caloric, which can restrict their appeal among specific consumers with diabetes and obesity in the market. Recently, novel polysaccharides have demonstrated effectiveness in preserving surimi gel quality during freeze-thawing cycles due to their exceptional ability to inhibit ice recrystallization[5,73–74]. The presence of hydroxyl groups in the molecular structure of polysaccharides enables them to form hydrogen bonds with polar residues on myofibrillar proteins or water molecules. This interaction effectively impedes the formation of ice crystals during the freezing process and protects the protein structure against denaturation or aggregation caused by freeze-thawing cycles. Moreover, polysaccharides have been observed to attach to the surface of ice or become embedded within its layers, effectively inhibiting the growth of ice crystals and minimizing mechanical damage caused by them on cellular tissues[50–51]. For instance, the addition of tamarind seed polysaccharide results in the generation of a more compact and regular gel network structure by hydrogen bonding, thereby promoting the binding between myofibrillar protein and water molecules. This effectively retards the decrease in Ca^{2+}-ATPase activity and maintains the stability of myofibrillar protein's secondary and tertiary structure during repeated freezing and thawing, ultimately preventing quality deterioration of surimi gel[12]. The addition of inulin into surimi gel can enhance its whiteness, breaking force, texture properties, and water holding capacity. Additionally, the protective effects of inulin on surimi gel vary depending on its polymerization degree and the amount added. Specifically, 8% (*m*/*m*) long-chain inulin exhibits a more pronounced impact on restricting water fluidity within surimi gels, while 8% (*m*/*m*) short-chain inulin and natural inulin demonstrate greater efficacy in reducing freezing temperature and inhibiting ice crystal formation[5]. The incorporation of konjac glucomannan to low-salt frozen surimi has the potential to enhance its freezing-thawing stability through ice crystal modification, water migration restriction, and network destruction inhibition[41]. Similarly, other high-molecular weight polysaccharides, such as flammulina velutipes polysaccharides, fistular onion stalk polysaccharide, and tea polysaccharides have also been used as cryoprotectants to prevent deterioration of surimi gel quality during freeze-thawing cycles[42–44].

In addition to polysaccharides, various oligosaccharides including rice bran feruloyl oligosaccharides, konjac oligosaccharides, konjac oligo-glucomannan, carrageenan oligosaccharide, and xylooligosaccharides have also been found effective in protecting myofibrillar proteins against denaturation and oxidation caused by freezing. Consequently, the gel strength and flavor profile of surimi gels are improved[45–48,75]. The incorporation of 0.3% (*m*/*m*) rice bran feruloyl oligosaccharides

into surimi gel exhibits superior smell, taste and overall acceptability, potentially attributed to the reaction between ferulic acid and oligosaccharides present in it with odorous substances during the heating process, leading to the formation of novel substances that mask the odor[76]. Notably, the cryoprotective effect of oligosaccharides on surimi gel is commonly enhanced through their combination with phosphate. The synergistic effect of trehalose and sodium pyrophosphate effectively strengthens their cryoprotective effect by preventing oxidation of myofibrillar protein and structural changes during freeze-thawing cycles, thus significantly enhancing the gel properties of surimi gel[8]. This synergistic regulatory effect was also reported in the study conducted by Gao et al.[74]. The combination of soluble soybean polysaccharides and liquid nitrogen freezing effectively prevents denaturation and structural alterations in myofibrillar proteins, thereby enhancing the quality of surimi gel obtained from bighead carp during frozen storage.

5.2.2 Protein hydrolysates

Protein hydrolysates are commonly derived from enzymatic hydrolysis and consist of small-molecule polypeptides[52–53]. The cryoprotective effect of protein hydrolysates in surimi gel is closely linked to the abundance of hydrophilic polypeptides, which possess the capability to interact with water molecules surrounding myofibrillar proteins, thus impeding the formation and recrystallization of ice crystals and inhibiting protein aggregation[52,67]. By carefully selecting protein sources and optimizing enzymatic conditions, the obtained protein hydrolysates may exhibit excellent antioxidant properties and effectively reduce ice recrystallization, thereby preventing freeze-induced protein denaturation and oxidation[54]. Numerous studies have demonstrated that incorporating protein hydrolysates into surimi gels enhances their quality during freeze-thawing cycles[55–57]. Till now, animal protein hydrolysates derived from poultry, livestock and fish have been extensively investigated as cryoprotectants for surimi gels. Additionally, plant protein hydrolysates derived from lentils and peas have also been explored as cryoprotectants for surimi gels[26,58]. For instance, the addition of 15% (*m*/*m*) whey protein hydrolysate to surimi gels reduces oxidative damage and protein denaturation during freeze-thawing cycles, significantly improving their rheological properties and water holding capacity[37]. The incorporation of silver carp protein hydrolysates can inhibit the generation of malondialdehyde and minimize alterations in flavor compounds within surimi gel. Additionally, these protein hydrolysates can interact with myofibrillar protein to produce a gel network characterized by enhanced water retention ability and stable structure[56]. Zhang et al.[53] demonstrated that silver carp protein hydrolysates can serve as effective cryoprotectants, effectively inhibiting protein oxidation and denaturation while improving the microstructure and gel properties of surimi gels. The chickpea protein hydrolysate shows potential in preventing denaturation and oxidation of myofibrillar protein during repeated freezing and thawing process, as evidenced by its enhanced sulfhydryl content, Ca^{2+}-ATPase activity, and solubility, as well as reduced levels of disulfide bonds, carbonyl content, and surface hydrophobicity. Furthermore, incorporating chickpea protein hydrolysate into surimi gels results in a more stable microstructure characterized by uniform water distribution along with improved elasticity strength and water retention capacity[26]. Similar phenomena have also been observed in surimi gels added with rice bran hydrolysates, bighead carp gill protein hydrolysates, eel head protein hydrolysates, and gelatin hydrolysates[54,59–61,68].

Antifreeze peptides, with a molecular weight range of 180–3 000 Da, demonstrate remarkable efficacy in inhibiting the growth and recrystallization of ice crystals, making them highly regarded as exceptional regulators of ice crystal formation[77]. The depiction of the cryoprotective effect of antifreeze peptides on surimi gel during freeze-thawing cycles is displayed in Figure 3A[62]. Antifreeze peptides possess the capability to adsorb onto the interface between ice and water through van der Waals forces, hydrogen bonding, and hydrophobic interactions. This impedes the movement of ice crystals at this interface and their interaction with water molecules, ultimately leading to a decrease in the freezing point of solutions and preventing ice crystal growth. In other words, antifreeze peptides exhibit excellent thermal hysteresis activity and effectively inhibit recrystallization of ice crystals. Furthermore, antifreeze peptides have the potential to hinder myofibrillar protein degeneration by decreasing Ca^{2+}-ATPase activity, retarding sulfhydryl group oxidation into disulfide bonds, and increasing solubility and surface hydrophobicity of myofibrillar protein. Additionally, antifreeze peptides possess the capability to inhibit the impact of freezing stress on water mobility, thus protecting surimi gel against loss of bound water and immobilized water during freeze-thawing cycles[62]. For instance, collagen antifreeze peptides contain many hydrophilic amino acid residues (such as lysine, aspartic acid, and aspartic acid), which facilitate the formation of hydrogen bonds with water molecules, thereby impeding water loss from the protein and protecting the integrity of hydrogen bonds within the protein structure. This interaction also contributes to stabilizing both functional and structural properties by binding to specific functional groups on the protein surface, thus preventing significant alterations in its spatial conformation. Moreover, collagen antifreeze peptides possess the ability to interact with ice crystals present in surimi, effectively inhibiting their growth. Consequently, incorporating collagen antifreeze peptides into surimi gel facilitates the development of a denser gel network while simultaneously improving quality damage caused by freeze storage. In addition, antifreeze peptides obtained from the skin of takifugu obscurus have been discovered to possesses the capability to directly bind with the structural cavity of myosin, preventing protein denaturation and oxidation caused by freeze-thawing cycles and maintaining the quality of surimi gel[63]. Silver carp scales antifreeze peptides exhibit a significant protection effect on surimi gel during freeze-thawing cycles. The incorporation of 4% (*m*/*m*) of these antifreeze peptides effectively delays the degradation of myofibrillar proteins, exposure of hydrophobic residues, carbonylation of amino acids, and oxidation of sulfhydryl groups by restraining ice crystal growth. Moreover, the rheological properties, water holding capacity, and gel properties of the surimi gel are also enhanced[3]. In another work, it has been observed that the addition of an appropriate amount of antifreeze peptides effectively protect the rheological properties of surimi gel and render it suitable for 3D printing even after undergoing freeze-thawing cycles[64].

5.2.3 Novel cryoprotectants

In recent years, the utilization of natural polysaccharides, protein hydrolysates, and antifreeze peptides for regulating ice crystal growth to inhibit quality deterioration of surimi gel has garnered significant attention. However, the extensive application of these cryoprotectants is hindered by their high production cost and stringent preparation conditions. Recently, it has been discovered that certain metabolites (such as choline derivatives, organic acids, and amino acids) produced by cold-blooded animals can form

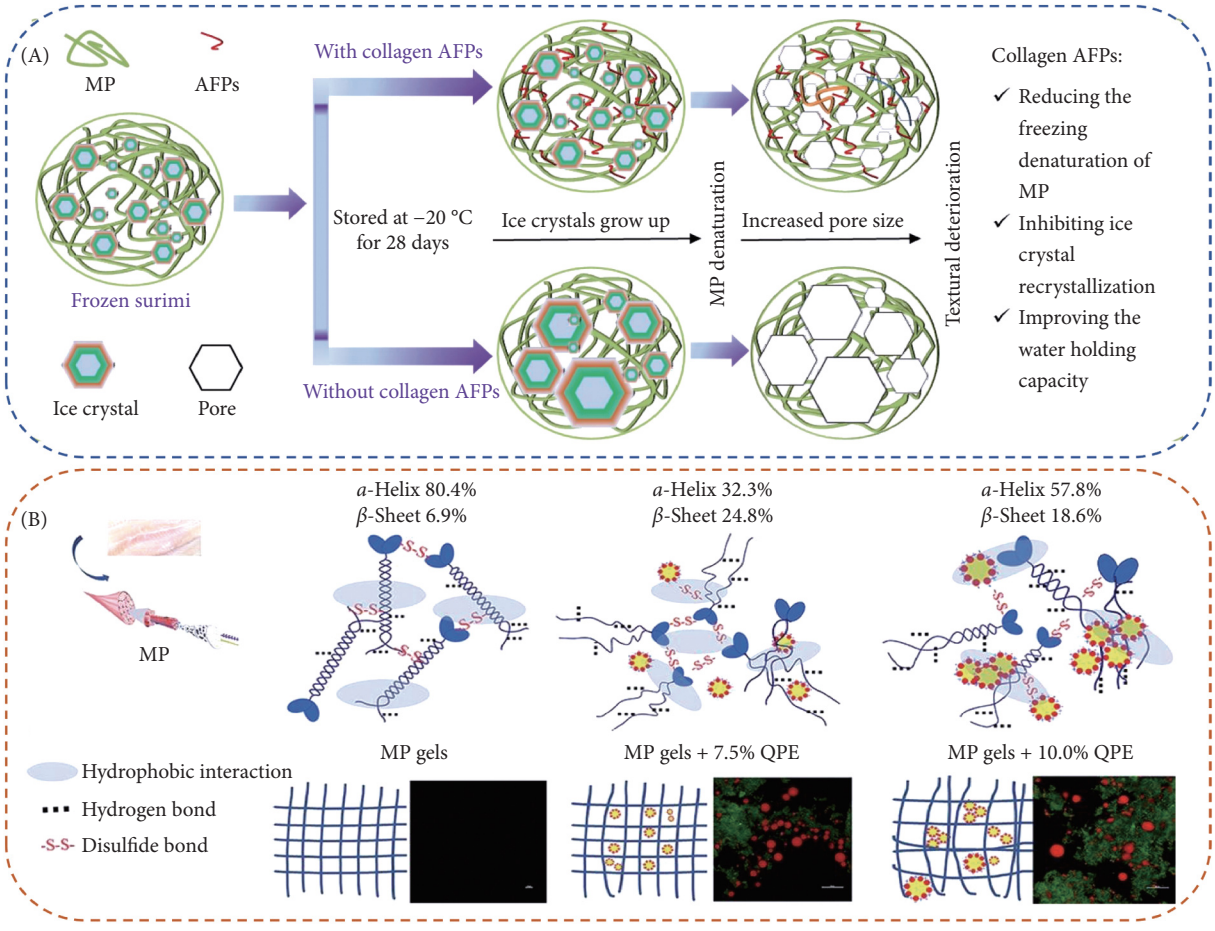

Figure 3 The schematic diagram of the cryoprotective effect of (A) antifreeze peptides and (B) quinoa protein Pickering emulsion on surimi gel during freeze-thawing cycles[62,68]. AFPs, antifreeze peptides; QPE, quinoa protein Pickering emulsion; MP, myofibrillar protein.

natural deep eutectic solvents at specific molar ratios through hydrogen bonding. These solvents form a highly viscous supramolecular network that restricts the free movement and orientation of water molecules, thereby inhibiting ice crystal formation and offering potential as novel cryoprotectants. For instance, the deep eutectic solvents prepared with trehalose and citric acid in a molar ratio of 2:1 with the addition of 10 g/100 mL distilled water exhibit strong freezing resistance and relatively low viscosity. By incorporating these deep eutectic solvents into surimi gels can obviously minimize water loss and migration, prevent ice crystal growth and recrystallization, decrease mechanical damage to cell tissue, thus improving their quality during freeze-thawing cycles[23].

In addition to deep eutectic solvents, the protein-polyphenol complexes holds promising potential for enhancing the quality of surimi gel during repeated freezing and thawing. A recent study demonstrated that the incorporation of pea protein isolate-EGCG complexes effectively reduced microbial activity and inhibited the oxidation of proteins and lipids in surimi gel during frozen storage. The content of total volatile base nitrogen and thiobarbituric acid reactive substances in surimi gel added with pea protein isolate-EGCG complexes decreased by 54.46% and 68.67%, respectively, compared to fresh surimi gel. Additionally, it was observed that the deterioration of color and development of off-odors were also delayed, indicating an enhanced preservation effect on surimi gel[65].

5.2.4 *Polyphenols*

Apart from the denaturation of myofibrillar protein caused by ice crystal-induced destruction of the hydration layer, protein or lipid oxidation is also a significant factor contributing to quality deterioration in frozen storage of surimi gel. Recently, antioxidant polyphenols have been used as cryoprotectants for surimi gel to inhibit protein or lipid oxidation during freeze-thawing cycles[78]. The addition of α-tocopherol as a cryoprotectant during frozen storage has shown great potential in preserving the quality of surimi gel, offering enhanced protection effects compared to conventional cryoprotectants. After 16 weeks of frozen storage, notable enhancements were observed in the water holding capacity, breaking force, gel strength, and microstructure of the sturgeon surimi gel[15]. EGCG, known for its potent antibacterial and antioxidant properties, plays a vital role in preserving the freshness of food. Additionally, as a natural additive utilized in frozen food, EGCG has been scientifically proven to effectively maintain the quality of aquatic products. Incorporating 0.01%–0.02% (*m*/*m*) EGCG is advantageous in preventing the quality deterioration of surimi gel during freeze-thawing cycles[71]. In addition, brown seaweed polyphenols have been discovered to effectively inhibit oxidative reactions and thus maintain the structural integrity of fish mince gel during frozen storage[72]. The sensory evaluations regarding the overall acceptability of silver carp surimi with the addition of citrus fruit peel extract consistently receive higher scores throughout the freeze-thawing cycles compared to surimi without extract, indicating the long-term quality preservation efficiency of

the extract. This improvement is possibly attributed to incorporating bioactive rich extract with higher antioxidant activities, which exerts preventive effects on protein and lipid deterioration, thereby maintaining sensory characteristics[79]. However, it should be noted that most polyphenol compounds possess inherent pigmentation that may potentially impact the sensory attributes of predominantly white surimi products.

5.3 Addition of Pickering emulsion

Pickering emulsion is generally fabricated by solid particles that possess interfacial activity. In comparison to traditional emulsifiers, the adsorption of these solid particles at the biphase interface is irreversible owing to their significantly higher desorption energy. This irreversibility imparts strong steric hindrance to Pickering particles, effectively preventing droplets aggregation[70,80]. Proteins are considered as ideal solid particles for Pickering emulsion stabilization due to their exceptional surface activity, biocompatibility, and biodegradability[69]. In the process of freezing and thawing, emulsion generally exhibits unstable phenomena such as droplet coalescence, phase separation, and sedimentation. These issues primarily arise from the crystallization of the emulsion in both the oil and water phases during freezing, as well as droplet aggregation during thawing. Several researches indicate that solid particles can adsorb onto oil droplets, forming a thick interfacial layer. This layer effectively withstands the stress exerted by expanding ice crystals during freezing, thereby contributing to the maintenance of excellent emulsion stability after freezing and thawing. Furthermore, protein-based Pickering emulsions can form a dense gel network structure, which significantly reduces ice crystal size during freezing while minimizing damage caused by them, thus enhancing the freeze-thawing stability of the emulsion (as depicted in Figure 3B)[68].

Recently, Yuan et al.[38] discovered that the incorporation of soy protein isolate-stabilized Pickering emulsion into sturgeon surimi gel resulted in the formation of a more uniform and compact network structure, thereby enhancing its textural properties and freeze-thawing stability, while inhibiting lipid oxidation. Cen et al.[69] demonstrated the feasibility of incorporating Pickering emulsion fabricated by quinoa protein as a novel cryoprotectant to improve the freeze-thawing stability of myofibrillar protein gels. In the process of freezing, the addition of quinoa protein-stabilized Pickering emulsion effectively reduces the freezing point of myofibrillar protein gels, leading to the formation of smaller ice crystals and a shorter time required to pass through the zone where maximum ice crystal formation occurs. This mitigates damage to the myofibrillar protein gel network and promotes the stabilization of protein structure. Furthermore, adding 7.5% (*m*/*m*) quinoa protein-stabilized Pickering emulsion also reduces free water content, delays protein oxidation, and improves water holding capacity of myofibrillar protein gels. In another work, it has been noted that adding quinoa protein-stabilized Pickering emulsion can fill the gaps in the gel network and form a denser gel structure by cross-linking with myofibrillar proteins, ultimately enhancing the water holding capacity, whiteness, viscoelasticity, and gel strength of myofibrillar protein gels[81]. Feng et al.[67] also demonstrated that the introduction of Pickering emulsion fabricated by quinoa protein improved the freeze-thawing stability of myofibrillar protein gels by reducing protein denaturation and oxidation without compromising their digestion properties. Therefore, quinoa protein-stabilized Pickering emulsion can be considered as a sustainable and efficient cryoprotectant in surimi products. However, whether Pickering emulsion fabricated by other solid particles can serve as cryoprotectants of surimi gels is worthy of further investigation.

5.4 The utilization of promising freezing technologies

In conventional freezing methods, such as air freezing, the heat exchange between cold air and food occurs through natural or forced convection, which is typically characterized by a low freezing rate. However, it is worth noting that air freezing may result in alterations in the moisture content and distribution within meat tissues during the freezing process, leading to the formation of uneven and large ice crystals, which may have negative effects on textural properties, cause undesirable color changes, and contribute to excessive oxidation of proteins and lipids upon thawing. Additionally, freezing may cause intracellular water molecules to migrate towards intermolecular spaces, leading to the production of large ice crystals that can mechanically damage muscle fibers and deteriorate texture. Moreover, during thawing, muscle cells are unable to reabsorb migrated water due to destruction of cell membranes and tissue structures. Consequently, this leads to significant juice loss that greatly impacts the quality of surimi products. In comparison to air freezing, there has been considerable interests in liquid nitrogen spray freezing and liquid nitrogen immersion freezing within the frozen aquatic industry. These methods show great potential for reducing the freezing time of surimi gels to pass through the maximum zone of ice crystal formation, effectively delaying water migration and texture deterioration in frozen gels, as well as minimizing the accumulation of carbonyl contents and thiobarbituric acid reactive substances[74,82–83]. In addition, soaking freezing has emerged as a promising low-temperature processing method that is garnering significant attention due to its cost-effectiveness and high heat transfer capacity. This method involves direct contact between the frozen material and the carrier refrigerant, facilitating rapid temperature decrease and freezing through efficient heat exchange. In comparison to traditional air freezing, soaking freezing accelerates the freezing speed by surpassing water penetration rate with an enhanced heat transfer rate, resulting in the formation of numerous uniform and small-sized ice crystals that effectively preserve food's structural organization[84].

Recently, freezing technologies have been continuously updated by incorporating additional physical fields such as ultrasound, pressure, and electric field (Table 2)[85]. Ultrasound-assisted freezing can induce the formation of numerous small bubbles that function as ice nuclei and facilitate the generation of evenly distributed ice crystals. The rupture of these bubbles exerts a mechanical force capable of breaking down larger ice crystals into smaller ones. Furthermore, the rapid movement of these cavitation bubbles enhances convective heat and mass transfer within surimi matrices, resulting in an accelerated freezing rate[86]. Consequently, quality deterioration of surimi gels caused by the formation of undesirable large ice crystals can be mitigated by ultrasound-assisted freezing treatment[25,87]. The incorporation of adenosine monophosphate at a minimal concentration of 0.08% (*m*/*m*) into ultrasound-assisted freezing surimi effectively alleviates the denaturation and aggregation of myofibrillar protein, as evidenced by an increase in sulfhydryl content, Ca^{2+}-ATPase activity, and protein solubility, as well as a decrease in particle size and surface hydrophobicity. Consequently, the resulting surimi gels exhibit more homogeneous microstructures with enhanced water holding capacity, elasticity,

Table 2 Emerging freezing and thawing technologies for surimi gels.

Freezing/thawing technologies		Freeze-thawing conditions	Enhanced indicators of surimi gel	Interaction mechanism	Reference
Promising freezing technologies	Ultrasound-assisted freezing	Frozen at –18 °C for 20 days then thawed at 4 °C for 20 h	Demonstrated more stabilized microstructures, uniform water distributions, enhanced mechanical properties and water holding capacities	Mitigated the denaturation and aggregation of myofibrillar protein	[25]
	Soluble soybean polysaccharides combined with liquid nitrogen freezing	Frozen at –18 °C for 4 weeks then thawed at 4 °C for 12 h	Minimized the elapsed time of maximum-ice-crystal formation zone, mitigated the quality deterioration of surimi gel during frozen storage	Synergistic effect emerged on preventing myofibrillar protein denaturation and protein structure change	[74]
	Liquid nitrogen immersion freezing	Frozen at –18 °C for 24 h then thawed at 4 °C for 12 h	Delayed texture deterioration and water migration in frozen gels, as well as reduced the accumulation of carbonyl contents and thiobarbituric acid reactive substances	Increasing cross-linking degree of myofibrillar protein	[82]
	Liquid nitrogen spry freezing	Frozen at –18 °C for 24 h then thawed at 4 °C for 12 h	Formed smaller pores and the structure of gel gradually became denser	Shorten the freezing time of surimi gels in the maximum ice crystal formation zone	[83]
	Low-frequency alternating magnetic fields freezing	Frozen at –20 °C for 24 h then thawed at 4 °C for 12 h	Increased the solubility, emulsification, and emulsion stability of myofibrillar protein, exposed more reactive sulfhydryl and hydrophobic groups, leading to reduced average particle size	Inhibited the changes in conformational and functional characteristics of myofibrillar protein	[85]
	Pressure shift freezing	Frozen at –20 °C for 48 h then thawed at 4 °C for 12 h	Enhanced breaking force, minimized mechanical damage to the sample structure, positively influencing physicochemical properties of surimi gel	Generating smaller ice crystals	[88]
	Pressure shift freezing	Frozen at –20 °C for 48 h then thawed at 4 °C for 12 h	Improved the gelling properties, water holding capacity, gel strength, breaking strength, breaking depth, hardness, gumminess, and chewiness of the grass carp surimi gel	Generating smaller ice crystals	[89]
Promising thawing technologies	Ultrasound-assisted thawing	Ultrasonic power of 300 W, ultrasonic frequency of 80 kHz	Enhanced chewiness, hardness, and springiness	Minimizing damage to the structure of myofibrillar proteins	[29]
	Sweep frequency ultrasound thawing	The center frequency is 28 kHz, and the range of frequency rise and fall is 2 kHz	Improved water holding capacity, gel strength, and rheological properties of myofibrillar protein gel	Protecting the structure of myofibrillar protein	[30]

mechanical properties, and whiteness (Figure 4A). Notably, the synergistic cryoprotective effects achieved through adenosine monophosphate and ultrasound-assisted freezing treatment even surpass those obtained using a commonly employed commercial antifreeze agent (4% (*m*/*m*) sucrose + 4% (*m*/*m*) sorbitol) in surimi products[25].

Pressure shift freezing is another innovative technology aimed at enhancing the quality of frozen food and optimizing ice crystal formation during the freezing process[90–91]. This technique involves subjecting the sample to high pressure, which significantly lowers the freezing point of water compared to atmospheric pressure, resulting in increased supercooling of water. Subsequently, rapid depressurization occurs, causing a sharp increase in temperature due to latent heat release during ice crystal formation[92]. Consequently, numerous small-sized ice crystals are generated, even when subsequent freezing takes place under atmospheric conditions, fine ice crystals are retained in frozen products. These fine ice crystals formed by pressure shift freezing treatment help minimize mechanical damage and juice loss in food materials compared to larger ice crystals formed through traditional air freezing methods. The research conducted by Zhang et al.[88] demonstrated that the utilization of pressure shift freezing effectively inhibits the quality deterioration of grass carp surimi gel caused by traditional air freezing and even enhances its inherent characteristics. The breaking force of surimi gel after pressure shift freezing treatment was found to be 2.5 times higher compared to traditional air freezing. The possible reason was that pressure shift freezing treatment minimizes mechanical damage to tissue structure by generating smaller ice crystals, as opposed to larger ice crystals formed during traditional air freezing. Furthermore, pressure shift freezing treatment induces alterations in both water mobility and protein structure within the surimi gel, thereby positively influencing its physicochemical properties. Zhang et al.[89] also reported that the utilization of pressure shift freezing treatment leads to significant enhancements in surimi gel quality, effectively preventing any adverse effects on the gel properties caused by freezing.

Magnetic field, as a non-thermal treatment technology for the preservation of frozen food, has garnered increasing concerns. Magnetic field-assisted freezing is an emerging immersion freezing technique that facilitates the formation of uniform and fine ice crystals by altering the molecular properties of water, thereby

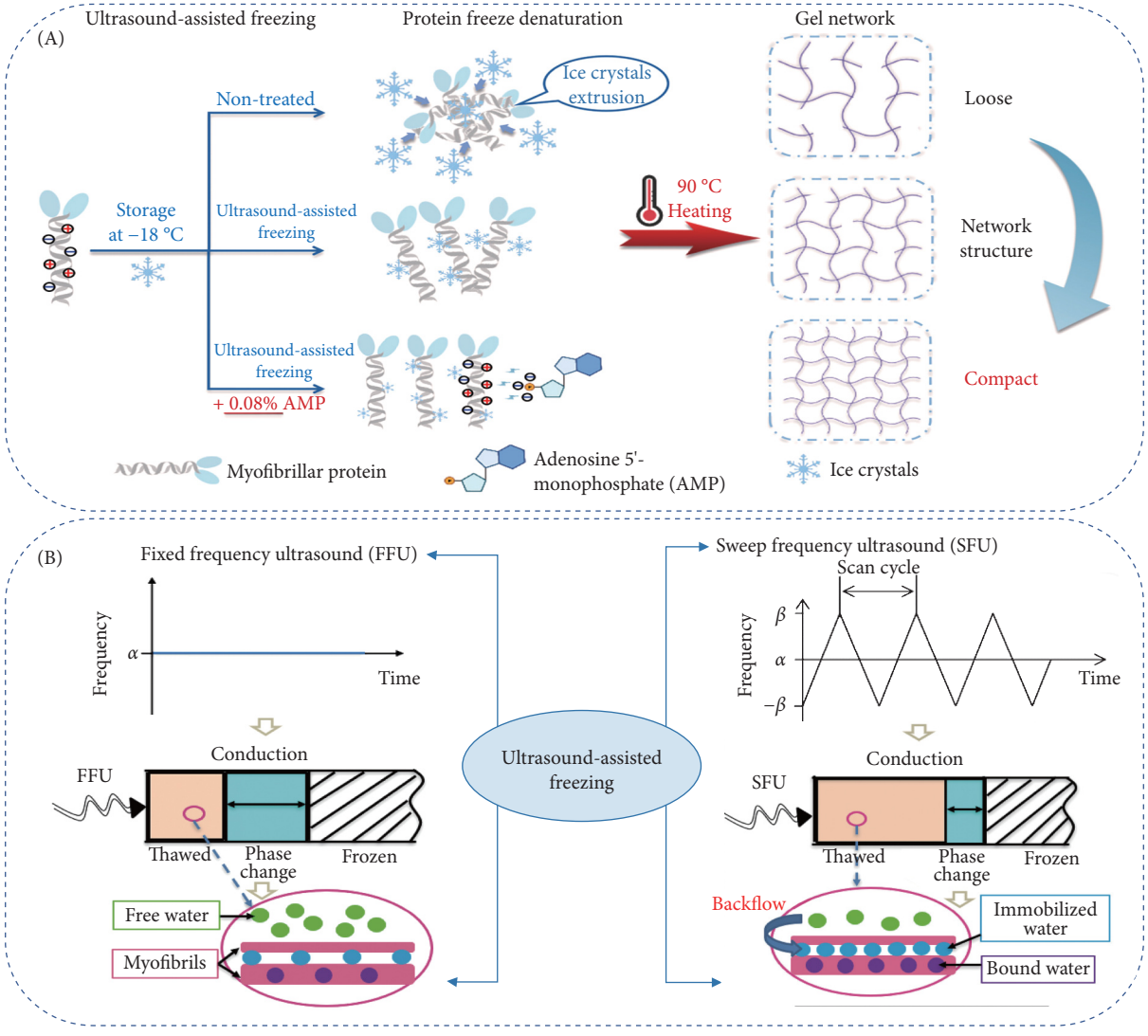

Figure 4 (A) Schematic representation of ultrasound-assisted freezing/adenosine phosphate-mediated cryoprotections to myofibrillar protein in frozen surimi and its reinforced gelling behaviors[25]; (B) the possible mechanism schematic diagram of fixed frequency ultrasound thawing and sweep frequency ultrasound thawing[84].

enhancing the quality of frozen food[85]. Numerous researches have demonstrated the significant potential of magnetic fields in improving protein structure and functionality[84]. Lu et al.[84] reported that the utilization of magnetic field-assisted freezing can greatly enhance the quality of thawed surimi compared to conventional soaking freezing. Furthermore, incorporating 0.6% (*m*/*m*) curdlan further enhances its gel strength, water holding capacity, whiteness, and textural characteristics. Additionally, the combination of magnetic field-assisted freezing and curdlan addition facilitates conformational changes from *α*-helix to *β*-sheet and random coil, while promoting the exposure of hydrophobic groups within myofibrillar protein molecules. These changes improve protein-molecule interactions and inhibit protein aggregation, ultimately resulting in the formation of a dense microstructure with small pores. Moreover, these modifications also reduce water release during the thawing process and promote the transformation from free water to immobilized water, thereby improving sensory attributes of surimi gel. Another work demonstrated that low-frequency alternating magnetic field treatment can effectively inhibit structural and functional deterioration of myofibrillar protein after repeated freezing and thawing, making it a promising quality-improving method in the frozen meat industry[85].

5.5 The utilization of promising thawing technologies

The thawing process is a crucial step in the preparation of frozen food for further processing, as it significantly impacts the quality of the thawed food. Traditional techniques such as water immersion thawing and air thawing are time-consuming and can lead to undesirable changes in quality attributes. To address these concerns, innovative thawing methods have been developed to overcome these limitations. In recent years, ultrasound-assisted thawing technology has garnered considerable attention in the field of food processing due to its environmentally friendly nature. It has been found that ultrasound-assisted thawing treatment can reduce the required time by 13.5%–40.4% compared to water immersion thawing. Furthermore, appropriate frequencies (80–100 kHz) of ultrasound-assisted thawing have proven effective in minimizing damage to the myofibrillar protein structure and preserving the quality of surimi gel, which exhibits high chewiness, hardness, and springiness after steam heating[29].

In recent years, many researches have shown growing interest in enhancing the functional properties of food materials using various ultrasonic equipment. The multi-frequency sonochemical reactor has demonstrated superior effectiveness compared to the single-frequency sonochemical reactor due to its ability to generate

a more favorable sound field that enhances cavitation effect[30]. For instance, when compared to traditional fixed frequency ultrasound thawing and flow water thawing, sweep frequency ultrasound thawing leads to myofibrillar protein gel with improved rheological properties, gel strength, and water holding capacity. This suggests that sweep frequency ultrasound thawing positively influences the gel characteristics of small yellow croakers (a possible mechanism schematic diagram is shown in Figure 4B)[30]. In addition, other novel thawing methods like microwave thawing, radio frequency thawing, high-voltage electrostatic field thawing, and ultrasonic-microwave thawing have been employed for thawing frozen food[93–95]. However, further investigation is needed to evaluate the influence of these thawing technologies on surimi gel quality.

6 Conclusions and future perspective

Surimi products are popular among consumers because of their unique texture characteristics, high protein content, and convenient consumption. Freezing is the main method for preserving surimi gel, but temperature fluctuations during storage and processing can lead to ice crystals growth and recrystallization, resulting in structural damages of cells that may significantly reduce the functional properties of surimi gel. In addition, protein oxidation and denaturation are inevitable due to repeated freezing and thawing processes, further deteriorating the quality of surimi gels. The incorporation of cryoprotectants (such as polysaccharides, protein hydrolysates, antifreeze peptides, natural deep eutectic solvents, protein-polyphenol complexes, and polyphenols) or the utilization of promising freezing/thawing technologies can enhance the freeze-thawing stability of surimi gel, while simultaneously improving its gel properties, rheological properties, color, flavor, freshness, and decreasing the content of lipid oxidation products. However, high cost and complex equipment requirements have limited the application of cryoprotectants and advanced freezing/thawing equipment in the food industry. Pickering emulsions with their inherent advantages and high freeze-thawing stability have opened up new possibilities for developing antifreeze agents for surimi gel. Future research should focus on exploring innovative and effective methods to enhance the freeze-thawing stability of surimi gel in order to improve its quality preservation during frozen storage. 1) Recently, it has been discovered that the incorporation of safe and cost-effective amino acids, such as *L*-arginine and *L*-lysine, can improve the solubility and gel properties of myofibrillar protein. These enhancements result in improved water holding capacity, color, and texture characteristics of meat products. Furthermore, the addition of *L*-arginine and *L*-lysine effectively enhances the G' and gel strength of myofibrillar protein gel during freeze-thawing cycles[96–97]. Additionally, the incorporation of 0.04% (*m*/*m*) γ-polyglutamic acid demonstrates effective inhibition against protein oxidation in frozen myofibrillar protein gels while preserving the conformational integrity of salt-soluble myofibrillar proteins and preventing excessive cross-linking induced by oxidation. Moreover, γ-polyglutamic acid positively influences the quality of heat-induced myofibrillar protein gels during freeze-thawing cycles[66]. These findings highlight significant potential for utilizing amino acids in surimi gel freezing protection, emphasizing the importance of exploring their application for enhancing freeze-thawing stability in surimi gel. 2) Emerging thawing technologies, such as radio frequency thawing, microwave thawing, and high-voltage electrostatic field thawing, have been utilized for the thawing of pork tenderloin and fresh cut fish due to their low energy consumption and rapid thawing speed. These technologies have demonstrated minimal disruption to the structure of myofibrillar protein and preservation of texture properties in heat-induced gel during the thawing process, thereby mitigating the quality deterioration of frozen products. However, these techniques have not yet been applied to surimi gel thawing, thus further research is necessary to explore their impact on the quality of freeze-thawed surimi gel. 3) Although adding Pickering emulsions can improve the quality of surimi gel during freeze-thawing cycles, there remains a lack of clarity regarding the relationship between characteristics of Pickering particles, composition of interfaces, properties of interface films, and the quality of surimi gel. Moreover, the specific regulatory mechanism has not yet been fully understood. Further investigation is warranted to explore the impact of protein-based high internal phase emulsions with good freeze-thawing stability on the frozen storage quality of surimi gel.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgement

This research was supported by National Natural Science Foundation of China (32402136), Program for Scientific Research Start-up Funds of Guangdong Ocean University (060302042402), Guangdong Basic and Applied Basic Research Foundation (2023A1515010005), and Special Fund for Universities in Guangdong Province in the Key Area of Biomedicine and Health (2023ZDZX2025).

Author contributions

Qiaoli Zhao: Conceptualization, methodology, investigation, and writing-original draft preparation. **Bin Zheng:** Writing-reviewing & editing. **Yongqin Gao:** Methodology. **Enlin Li:** Methodology. **Xinyue Huo:** Methodology. **Xueer Li:** Methodology. **Mi Zhang:** Methodology. **Saiyi Zhong:** Writing-reviewing & editing, supervision, project administration, and funding acquisition.

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