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Improvement of gelation properties of silver carp surimi through ultrasound-assisted water bath heating

Xueli He, Yanan Lv, Xuepeng Li, Shumin Yi, Honglei Zhao *, Jianrong Li, Yongxia Xu *

College of Food Science and Engineering, Bohai University, National R&D Branch Center of Surimi and Surimi Products Processing, Jinzhou, Liaoning 121013, China

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ABSTRACT

The present work investigated the effects of water bath heating coupled with different ultrasound treatments on the gel properties, protein conformation, microstructures and chemical interactions of silver carp surimi at low/high salt levels. Results showed that the gel strength, hardness, springiness and water holding capacity (WHC) of surimi gels at low salt concentration were inferior to those at high salt content, regardless of the treatments. Compared with the traditional water bath heating, ultrasonic-assisted treatments significantly improved the gelation properties of surimi at the same salt level. In fact, ultrasound treatment also facilitated the unfolding of α-helix structure of the protein, with the resulting exposure of internal groups further enhancing hydrophobic interactions and hydrogen bonds between protein molecules, thereby leading to the formation of denser microstructures with smaller holes. Furthermore, the most noteworthy ultrasonic treatment group was ultrasound-assisted preheating (U + W) group, whose gelation performance under low salt condition, was comparable with that of the traditional two-stage heating (W + W) group with high salt content. Overall, ultrasound-assisted water bath preheating proved to be a feasible approach to improve the gel properties and microstructures of low-salt surimi gels.

1. Introduction

Surimi products, as an important part of aquatic processed food, are deeply favored by consumers due to their high protein, low fat, high nutrition as well as convenient consumption [1], and currently, these products have become indispensable in people's daily lives. Myofibrillar proteins, the main component of surimi, are salt-soluble and play a key role in the heat-induced gelling of surimi [2]. Hence, salt also plays a crucial role in the gelation of surimi by facilitating the dissolution of myofibrillar proteins, which contributes to the formation of a dense gel network structure [3]. Although adding salt can improve the flavor of food [4], excessive amounts can induce hypertension, high cholesterol, and cardiovascular diseases, thus endangering people's health [5]. However, at the same time, decreased salt content can not only reduce the solubility of proteins in surimi but also have an adverse effect on its gel properties, thereby further affecting the sensory characteristics of the ultimate product [6].

Currently, in order to obtain low-salt surimi with strengthened gel properties, exogenous additives, such as starch, non-starch polysaccharides, hydrocolloids, plant-derived oils or animal oils are incorporated [7,8,9,10]. In addition, different processing methods involving high pressure, ultrasound and microwave have also been adopted to enhance gel properties [11,12]. Among these, ultrasonic treatment represents one of the most popular approaches since it is green, safe, economic and easy to operate [11]. Yet, applications of ultrasound in the food industry mainly involved the freezing, thawing, drying, heating, and sterilization of foodstuffs such as fish, meat, fruits and vegetables, cereals and dairy products [13]. Xing et al. [14] reported that high intensity ultrasound (HIU) treatments promoted the transformation of α-helix into stable β-sheet structure, which reduced cooking loss of chicken wood breast. At present, the application of ultrasound in surimi or protein gels is gradually increasing, with Zhang et al. [15] concluding that ultrasound-based treatments could activate endogenous glutamine transaminases and proteases in tilapia surimi for facilitating the cross-linking of proteins and thereby improving the gel strength. Similarly, Liu et al. [16] discovered that high intensity ultrasonic pretreatment, prior to the salt cutting of surimi, could form more non-covalent bonds and disulfide bonds which significantly increased the water holding capacity (WHC) and improved the microstructure of surimi gels.

* Corresponding authors at: College of Food Science and Engineering, Bohai University, No. 19, Keji Road Jinzhou 121013, PR China.
E-mail addresses: cristy320@163.com (H. Zhao), xuyx1009@126.com (Y. Xu).

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It is well documented that ultrasound could induce the unfolding of myofibrillar proteins and promote hydrophobic interactions which would be conducive to forming dense gel networks and enhancing gel properties [17,18]. Indeed, some studies have confirmed the enhanced effects of ultrasound on the gel properties of surimi but the influence of water bath heating supplemented with ultrasonic treatment, along with different salt concentrations, is yet to be reported. Therefore, the present work investigated the influence of different ultrasound-assisted water bath heating treatments on the gelation properties of silver carp surimi at different salt contents. It is expected that the results would provide a feasible reference for the improvement of the gel properties of low-salt surimi.

2. Materials and methods

2.1. Materials

Silver carp surimi of AAA grade was supplied by Honghu Jingli Aquatic Food Co., Ltd. (Jingzhou, Hubei, China) and froze at −18 ℃. The moisture content of the surimi was 75.54% (w/w). Plastic casing with a folding diameter of 3.2 cm was supplied by Tianjin Kangtai Plastic Packaging Co., Ltd. (Tianjin, China).

2.2. Preparation of surimi gels under different treatment conditions

Small pieces of semi-thawed surimi were first chopped for 3 min (1000 rpm) using a vacuum cutter (Stephan Machinery Co., Hameln, Germany). This was followed by the addition of 1.0% and 2.5% NaCl (w/w) before performing a second round of chopping at 1800 rpm for 2.5 min. After adjusting the moisture content to 78% (w/w) with iced water, the mixture was then chopped for another 3 min at 3000 rpm and the resulting surimi paste was packed into plastic casings, with both ends tightly sealed. Then, the gelation of surimi sol was carried out by means of ultrasound, combined with water bath heating. The ultrasound intensity in this study was 75.60 W cm^{-2}, which was measured according to the method of Hu et al. [19]. Specific heating modes were as shown in Table 1. Finally, the obtained surimi gels were immediately transferred to flowing water and stored at 4 °C until analysis.

2.3. Texture profile analysis (TPA)

Textural properties of surimi gel samples were measured by a TA-XT-Plus texture analyzer (Stable Micro Systems Ltd., Godalming, UK) with a P/50 spherical plunger and testing speed was 1 mm/s.

2.4. Gel strength

Gel strength of the cylinder gel samples with height of 2.5 cm was determined by texture analyzer with P/5S spherical plunger [20]. The trigger force was 5.0 g, compression distance was 10 mm and operated at a constant speed of 1.00 mm/s.

Table 1
Preparation of surimi gels using different treatments.

Different treatments	Specific explanatory notes
W + W	Preheated in a 40 °C water bath for 30 min and then heated in a 90 °C water bath for 30 min.
U + W	Preheated in a 40 °C water bath for 30 min assisted by ultrasound (500 W power output at 25 kHz frequency), and then heated in a 90 °C water bath for 30 min.
U + U	Heated in a 40 °C and a 90 °C water bath, assisted by ultrasound (500 W power output at 25 kHz frequency) for 30 min in both cases.

2.5. Water-holding capacity (WHC)

Determination of the WHC was performed referring to Wang et al. [21]. The surimi gel pieces were accurately weighed as W_1 and centrifuged with three layers of filter paper at 5000 g for 30 min at 4 °C. The samples after centrifugation were weighed as W_2. The WHC was evaluated based on the following Eq (1):

$$WHC\ (\%) = W_2/W_1 \times 100 \quad (1)$$

2.6. Low-field nuclear magnetic resonance (LF-NMR)

The surimi gels of 0.5 cm in diameter and 2 cm in height were loaded into glass nuclear magnetic tubes and then inserted and measured in a low field NMR analyzer (NMI20, Shanghai, China). The measured parameters were as follows: the proton resonance frequency SFI was 22 MHz, the temperature was 32 °C, τ-value of the pulses at 90° and 180° was 400 us. The scan was repeated 8 times with an interval of 3000 ms. Finally, the relaxation times and corresponding peak areas were recorded to represent the characteristics and content changes of water in surimi gels [22].

2.7. Raman spectroscopy

Raman spectroscopy analysis of surimi gels were performed by confocal Raman spectrometer (Labram HR Evolution, Horiba, Ltd., Shanghai, China). The gel samples were sliced and placed on the slide. Typical spectra ranged from 400 to 3600 cm^{-1} was scanned and the resolution ratio was set at 1 cm^{-1}. The relative contents of secondary structures were obtained according to the method of Xu et al. [23].

2.8. Chemical interactions

Chemical forces of interactions between protein molecules were measured according to Liu et al. [24]. The chopped gel samples were separately dispersed in four different chemical reagents (0.5 mol/L NaCl (S_A), 0.6 mol/L NaCl (S_B), 1.5 mol/L urea solution + 0.6 mol/L NaCl (S_C), 8 mol/L urea solution + 0.6 mol/L NaCl (S_D)) and homogenized for 3 min. Then the mixture was incubated 4 ℃ for 1 h, followed by centrifugation at 10,000 r/min for 15 min. The chemical forces were reflected by the difference of the protein content in supernatant. The calculation of chemical forces adopted the method of Gao et al. [25].

2.9. Scanning electron microscopy (SEM) and light microscopy (LM)

SEM was used to observe the microstructures of surimi gels based on the method of Kocher et al. [26]. For this purpose, gel slices were soaked into a glutaraldehyde solution for 12 h, followed by gradient elution with ethanol. Finally, the naturally dried samples were sputter-coated with gold and observed by SEM (S-4800, Hitachi, Ltd., Tokyo, Japan) with an accelerating voltage of 1.0 kV.

The LM was also adopted to observe microstructure according to Zhuang et al. [27]. Gel samples were frozen at −80 ℃ for 20 min, and then cut into 8 μm slices by frozen slicer (CM-1850, Leica Instrument Co. Ltd., Germany). The thin sections were placed on slides, followed by hematoxylin-eosin staining, and the microstructure was observed and photographed with light microscope under 40 × magnification.

2.10. Data analysis

All experimental data were statistically analyzed by IBM SPSS Statistics (SPSS Inc., Chicago, USA) and mapped by Origin 2018. Data were presented as mean ± standard deviation. By Duncan's multiple analysis, significant differences among means were set at $P < 0.05$.

3. Results and discussion

3.1. Texture profile analysis (TPA)

As clearly seen from Table 2, the hardness of different treatment groups at low salt concentration was significantly lower than that at the high salt level ($P < 0.05$), with the springiness, adhesiveness, chewiness and resilience of the gels also showing a similar trend [28]. It was likely that the myofibrillar proteins could have been fully dissolved at the high salt level and this led to the exposure of internal active groups, thereby promoting both molecular interactions as well as the formation of elastic gels during the heat-induced gelling process [25]. Therefore, it was hypothesized that the enhancement of textural properties was due to changes in protein structure caused by the salt content.

Compared with the W + W group, the hardness of gels in the other two ultrasound-assisted groups were significantly increased ($P < 0.05$), especially for the U + W group. The increase of hardness could be related to the conformational changes of proteins induced by ultrasound treatment. Indeed, the shock effect of ultrasonic waves could improve the solubility of proteins and contribute to their unfolding which facilitated interactions between protein molecules [29]. In this context, as reported in our results, Wang et al. [30] also proposed that the hardness of tilapia surimi gels, pretreated with high-intensity ultrasound, was superior to the control. However, ultrasound, combined with high temperatures, probably reduced the activity of endogenous proteases, with this having a negative effect on the gel properties [15]. Therefore, the hardness of the U + U group was slightly lower than that of U + W. In addition, the myofibrillar proteins could have been overextended after prolonged ultrasonic treatment, and this could have seriously impaired the conformation of the proteins, resulting in poor textural properties [31].

3.2. Gel strength

Gel strength reflected the aggregation ability of proteins during heat-induced gelling. As shown in Fig. 1, the gel strength, after the different treatments of W + W, U + W and U + U with high salt content, was 2958.85 g•mm, 4234.72 g•mm and 4005.87 g•mm respectively, with these values being higher than those obtained with low salt content. It is well known that, in high salt environment, proteins are more soluble and are able to expose more sulfhydryl groups which can facilitate protein cross-linking, hence forming compact network structures that improve the gel properties [25]. Gao et al. [25] reported that the deformation and breaking force of surimi gels were promoted as the NaCl content increased from 0% to 5%, and these results were consistent with ours. Similarly, Tang et al. [32] also concluded that the gel strength of surimi with 0.5% NaCl addition was lower than that with a 2.0% NaCl addition.

As described in Fig. 1, compared with the samples heated in a conventional two-stage water bath, ultrasonic treatment significantly increased the gel strength ($P < 0.05$), particularly in the case of the U + W group for which the most improvement was observed. The gel strength of the U + W group at low salt content reached the highest value of 3934.72 g•mm, and it was even better than that of the W + W group at high salt concentration. This observation could be attributed to the fact that ultrasound could have promoted protein dissolution and

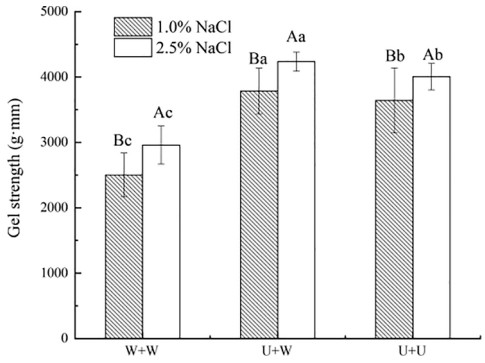

Fig. 1. Effect of ultrasound treatments on the gel strength of surimi gels with different salt contents. Different capitals at same treatments mean significant differences at different salt levels ($P < 0.05$). Different lowercases at same salt levels mean significant differences among different treatments ($P < 0.05$).

activated endogenous enzymes in the surimi during the low-temperature heating stage. These enzymes could subsequently catalyze the covalent cross-linking and aggregation of protein molecules [15]. At the same time, it is likely that ultrasound-assisted heating at 40 °C was beneficial to the unfolding of proteins, thus accelerating the gelation process at high temperature and forming surimi gels with high gel strength. Liu et al. [33] revealed that ultrasound treatment was beneficial for exposing more active groups of myosin, thereby further enhancing molecular interactions, which was positively correlated with gel strength. However, the decrease in gel strength for the U + U group could have been due to the oxidation and degradation of proteins caused by long-time exposure to ultrasounds at a high temperature [33]. This would lead to large voids and incompact aggregates during the surimi gelling process, thus reducing the gel strength.

3.3. Water-holding capacity (WHC)

The ability of gels to effectively retain water molecules in a three-dimensional network structure is very important [34], with higher WHC indicating a more compact gel network structure [1]. As shown in Fig. 2, irrespective of the treatment conditions, the WHC of surimi gels were significantly improved at high salt content ($P < 0.05$). High salt environment could shield some charges on the surface of myosin, which could weaken the electrostatic attraction among protein molecules [35]. Meanwhile, the high concentration of salt could strengthen interactions between proteins and water molecules through hydrogen bonds, thus allowing more water molecules to be trapped in the gel network and improving the WHC [25]. In fact, with better dispersion of myosin at the high salt concentration, more reactive groups were exposed during the heating process, therefore enhancing the interactions between proteins and water, which was closely related to the high WHC of the surimi gels [25].

Although ultrasonic-assisted heating improved the WHC of surimi gels, the improvement was more prominent for the U + W group, with these results being in accordance with those obtained for the gel strength

Table 2
Effect of ultrasound treatments on the texture profile of surimi gels with different salt contents.

Different treatments	Salt contents	Hardness /g	Springiness	Adhesiveness	Chewiness /g	Resilience
W + W	1.0% NaCl	1804.32 ± 211.959^{Be}	0.92 ± 0.021^{Ba}	0.81 ± 0.008^{Bd}	1395.73 ± 27.683^{Bb}	0.50 ± 0.008^{Bc}
	2.5% NaCl	2151.03 ± 41.163^{Abc}	0.94 ± 0.005^{Aa}	0.82 ± 0.006^{Acd}	1655.17 ± 30.252^{Aa}	0.51 ± 0.000^{Ab}
U + W	1.0% NaCl	$2030.54 \pm 112.825^{Bcd}$	0.93 ± 0.012^{Ba}	0.83 ± 0.004^{Bcd}	1562.39 ± 78.625^{Ba}	0.52 ± 0.008^{Bb}
	2.5% NaCl	2358.58 ± 62.337^{Aa}	0.95 ± 0.014^{Aa}	0.84 ± 0.006^{Abc}	1866.93 ± 72.494^{Aa}	0.53 ± 0.006^{Aa}
U + U	1.0% NaCl	$1947.12 \pm 179.515^{Bde}$	0.93 ± 0.023^{Ba}	0.82 ± 0.004^{Bb}	1556.58 ± 30.129^{Bb}	0.52 ± 0.004^{Bb}
	2.5% NaCl	2219.89 ± 52.937^{Aab}	0.94 ± 0.018^{Aa}	0.82 ± 0.011^{Aa}	1789.13 ± 34.343^{Aa}	0.52 ± 0.004^{Ab}

Different capitals in the same column mean significant differences at different salt levels ($P < 0.05$). Different lowercases in the same column mean significant differences among different treatments ($P < 0.05$).

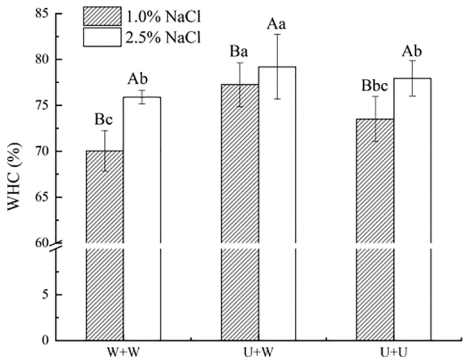

Fig. 2. Effect of ultrasound treatments on the WHC of surimi gels with different salt contents. Different capitals at same treatments mean significant differences at different salt levels ($P < 0.05$). Different lowercases at same salt levels mean significant differences among different treatments ($P < 0.05$).

and texture properties (Table 2 and Fig. 1). In this case, the cavitation effect and shear stress induced by ultrasounds could have contributed to the exposure of more hydrophobic residues which were advantageous for cross-linking as well as the aggregation of proteins [36]. Therefore, ultrasound-assisted heating contributed to the formation of a denser and more ordered gel network structure which allowed more water to be trapped for increasing the WHC [12]. In addition, ultrasound also induced water molecules to produce more free radicals which could easily react with the active groups on proteins, thus the water retention capacity of surimi was improved. Gao et al. [16] illustrated this possibility by reporting that ultrasound pre-treatment before salt-chopping could improve the WHC of silver carp surimi gels. Similarly, Ma et al. [37] stated that thawing based on multi-frequency ultrasounds improved WHC while reducing cooking loss in large yellow croakers. Meanwhile, we observed that the WHC of the U + U group was lower than that of the U + W group. This could have been because ultrasound treatment at high power and for long periods of time caused protein oxidation and degradation [33], thereby disrupting its orderly aggregation and forming a non-uniform three-dimensional network structure of the surimi gels [31]. In turn, such a non-uniform structure could have weakened the ability to hold onto water molecules, resulting in a decline in water content. Our results were similar to those of Zhang et al. [38] who found that the use of high power during ultrasound treatment heavily denatured chicken myofibrillar proteins, resulting not only in loose and irregular microstructures but also in low WHC of gels.

3.4. Low-field nuclear magnetic resonance (LF-NMR)

Fig. 3A depicts the continuous distribution of the T_2 relaxation time for gel samples at various salt contents and under different treatment conditions. There were three distinct peaks at 1–10 ms (T_{21}), 90–110 ms (T_{22}) and 800–1000 ms (T_{23}) and among these, T_{22}, with the highest peak, represented the immobile water in the surimi gels networks, and thus reflected the WHC of the gels. T_{21}, on the other hand, represented water bound to the protein macromolecules while T_{23} represented free water [22]. As exhibited in Fig. 3A, gel samples at the high salt level had a higher peak value for T_{22} along with a shorter relaxation time compared with those at low salt content. These results, in suggesting that water molecules in the gel network were immobilized to a high degree, supported the higher WHC (Fig. 2).

As illustrated in Fig. 3B, ultrasonic-assisted treatments increased the proportion of immobile water in surimi gels. This observation suggested that ultrasound could restrict the fluidity of water and promote the conversion of free water into immobile one. Additionally, the T_{22} of gels from the U + W group was higher than for the U + U group, hence indicating that ultrasound-assisted heating at the low temperature contributed to the unfolding of protein structures, promoting the interactions protein–protein and protein-water during the gelling process at the high temperature. This eventually allowed more water to be trapped in the surimi gel network and become immobilized. This possibility was supported by Liang et al. [12] who found that the use of ultrasound and microwave, combined with water bath heating, could strengthen protein cross-linking and aggregation, while favoring the formation of a regular and ordered network structures which weakened the fluidity of water in the gels. Xing et al. [14] also reported that HIU treatments could greatly improve the retention capacity of free water in meat batter of chicken wood breast in the presence of low salt condition.

3.5. Protein secondary structure

As shown in Fig. 4, a reduction of roughly 4% or 5% of the α-helix content was observed at high salt concentration, while β-sheet and β-turn contents displayed an opposite trend, no matter what kind of treatment. This indicated that high salt condition helped to induce more protein unfolding [32], which promoted structural transformations from α-helix to β-sheet structure [39]. In fact, this increase in β-sheet content reflected an enhancement of the number of hydrogen bonds which could maintain stable protein conformation and strengthen the intermolecular forces between proteins so as to form an ordered gel network structure [14,40]. Similar results were reported by Tang et al. [32] who concluded that surimi gels of threadfin bream at 2% NaCl content had less α-helix but more β-sheet, thus confirming that high NaCl level induce a higher degree of unfolding in proteins. Xiong et al. [2] reported that the protein

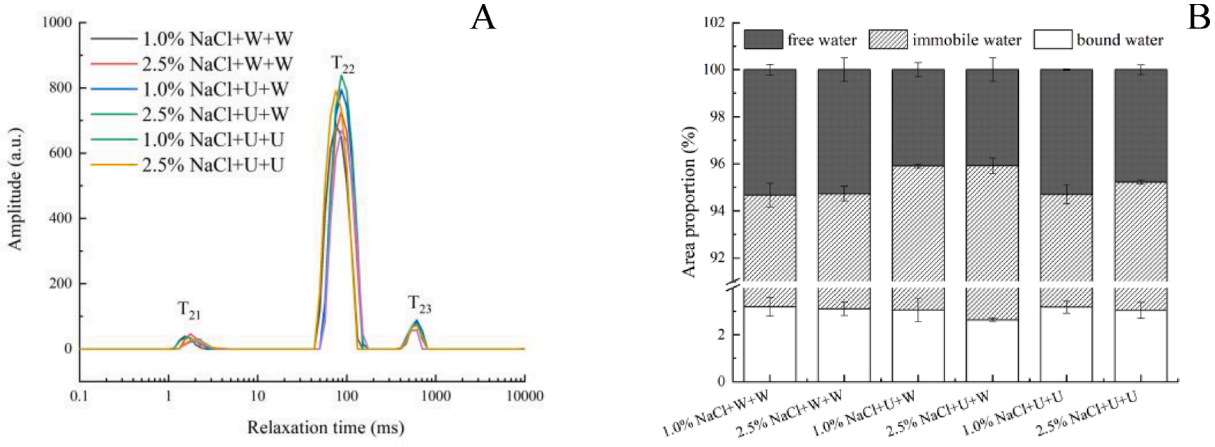

Fig. 3. Effect of ultrasound treatments on the relaxation time (A) and areas proportion of various peak (B) of surimi gels with different salt contents.

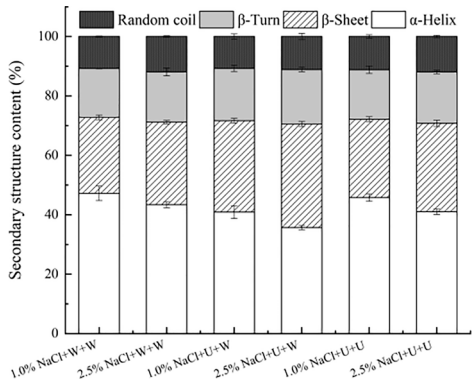

Fig. 4. Effect of ultrasound treatments on the protein secondary structure of surimi gels with different salt contents.

secondary structures in bighead carp surimi gels presented a higher β-sheet content at 3% NaCl addition compared with 0.5% NaCl addition.

Fig. 4 also shows that the use of ultrasound reduced the α-helix content and increased that content of β-sheet. Hence, it was likely that the ultrasound could have promoted protein unfolding. Xing et al. [14] came to similar conclusions that HIU treatments could decrease the α-helix content and increase the amount of other secondary structures. This is because proteins can have better unfolding behavior after ultrasonic treatment as it can facilitate the cross-linking and aggregation of proteins, thus contributing to the formation of compact gel networks and good gel properties during the heating process [32]. However, it was also observed that gels from the U + U group had lower β-sheet content and more random coil content compared with the U + W group. This could be attributed to the fact that ultrasound-assisted heating for a long time and at high power could have caused protein degradation [31]. As a result, the α-helix could have been destroyed and converted into random coils that produced more disordered structures which were not conducive to the required surimi gel quality [31].

3.6. Chemical interactions

Intermolecular chemical interactions were investigated to determine the enhancing effects of ultrasound-assisted heating on surimi gels at different salt concentrations as well as the underlying mechanism. The chemical interactions were represented by the soluble protein content as shown in Fig. 5. Based on the results, it was found that hydrophobic interactions played a dominant role during the gelation process of surimi [41]. Compared to the gel samples at low salt content, hydrogen bonds and hydrophobic interactions presented a significantly increasing trend

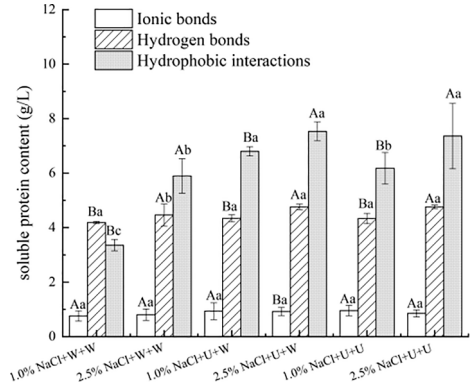

Fig. 5. Effect of ultrasound treatments on chemical interactions of surimi gels with different salt contents. Different capitals in the same species mean significant differences at different salt levels ($P < 0.05$). Different lowercases mean significant differences among different treatments ($P < 0.05$).

at high salt addition ($P < 0.05$), while the ionic bonds decreased slightly. This could be because within high salt environment, proteins can disperse fully and expose more hydrophobic groups which was beneficial to strengthen hydrophobic interactions during the heat-induced gelling [42]. In this context, Gao et al. [25] reported that, with increasing salt content, hydrophobic interactions were enhanced, resulting in the high strength of silver carp surimi gels as observed with our current results. According to the report by Mi et al. [20], the β-sheet structure of proteins was positively related to the hydrogen bond content. As mentioned above, high salt condition facilitated the transformation of α-helix structure to β-sheet structure, the number of hydrogen bonds therefore increased accordingly. Similarly, Dai et al. [43] demonstrated that high salt content could promote the formation of hydrogen bonds between protein molecules. At high salt concentration, positive and negative ions in NaCl interacted more easily with opposite charges on the surface of myosin molecules, thereby breaking ionic bonds [25].

Ultrasound could also significantly enhance hydrophobic interactions compared with the W + W group ($P < 0.05$), especially in the case of gels from the U + W group. This was probably because ultrasound contributed to the exposure of hydrophobic groups, and therefore, hydrophobic interactions were heightened during the heat-induced gelation process. However, excessive protein degradation as a result of the prolonged use of ultrasound at high temperature could weaken hydrophobic interactions [31]. Since such interactions represented an important factor for maintaining the gel network structure, this would explain why the strength of gels from the U + U group was lower than for the U + W one. It should also be noted that the ionic bond content was the lowest in silver carp surimi gels, and hence, ionic bonds probably played a non-primary role in maintaining the stability of the gel networks [28]. In addition, there were no significant differences in ionic bond content between samples after different treatments, thus suggesting that ultrasound treatments did not heavily influence the ionic bonds.

3.7. Microstructure

The microstructure of the surimi gels can be intuitively observed through a microscope. In this case, the cavity size of the image obtained by photography reflected the density of the gel network structure. SEM and LM were therefore used to provide more comprehensive details regarding microstructural changes in surimi gels under different treatment conditions.

3.7.1. Scanning electron microscopy (SEM)

SEM images of surimi gels containing 1.0% and 2.5% NaCl after different ultrasonic treatments were as shown in Fig. 6. The network structures of gels with low salt content were relatively rough and unevenly distributed, with many large lumps also clearly observed throughout the networks. This was in accordance with the previously-mentioned poor gel strength and textural properties under low salt condition. Myofibrillar proteins acted a dominant role in the gelation process of surimi [3,25] but in a low salt environment, these proteins have low solubilities. As such, they cannot unfold fully during the heating process, thereby reducing protein cross-linking and aggregation, and resulting in the formation of non-uniform lumps. However, in low salt environment, the microstructures of the gel samples became denser and more orderly, likely due to the higher solubility of myofibrillar proteins as well as enhanced chemical interactions. Similar observations were made by Yang et al. [44] who found that myofibrillar proteins in pearl mussel formed more uniform and ordered gel networks with the increase of NaCl concentration.

Ultrasonic-assisted heating treatments further improved the microstructures of surimi gels, as more ordered and smooth network structures were observed in gels from the U + W group at both low and high salt content. These results actually supported those obtained on the enhancement of gel strength and WHC (Figs. 1 and 2). Ultrasound, in

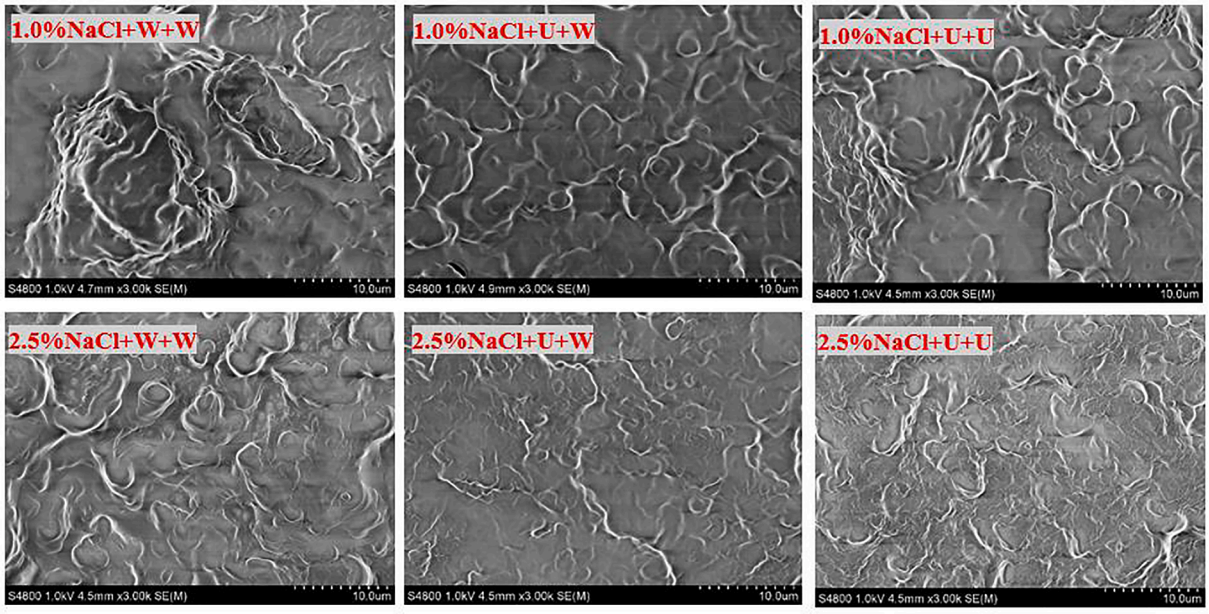

Fig. 6. Effect of ultrasound treatments on SEM micrographs of surimi gels with different salt contents.

facilitating the exposure of more active groups, promoted interactions between protein molecules, and contributed to the formation of more compact gel networks [32]. In this context, a study by Li et al. [45] revealed that ultrasound induced a more orderly aggregation of chicken breast protein, thereby forming denser and organized gel networks. In addition, Gao et al. [16] also reported that compact gel network structures with smaller pores were observed in silver carp surimi gels after HIU pretreatment.

3.7.2. *Light microscopy (LM)*

The surimi gel images of LM with eosin staining were as shown in Fig. 7. It can be seen that nearly-round white cavities of varying sizes were present in the surimi gel matrix. The gels, at a high salt concentration, had smaller voids and a denser structure which could be attributed to the myofibrillar proteins being completely dissolved and assembled into orderly filaments [25]. Furthermore, the network structures of gels after ultrasound-assisted treatments were more compact, with the pores being smaller, especially for the U + W group as reflected in the SEM results. It was, therefore, concluded that ultrasound-assisted heating could strengthen hydrophobic interactions between proteins to help in the formation of more compact network structures [16]. However, larger holes were also formed in surimi gel networks of the U + U group compared with the U + W group. This was likely due to conformational changes and excessive protein degradation as a result of prolonged ultrasound treatment. Sun et al. [31] also reported that prolonged ultrasound treatment caused proteins to aggregate into uneven clumps, and formed a large number of cavities in the three-dimensional network of porcine myosin gels.

4. Conclusion

The gelation properties of surimi in a high salt environment were

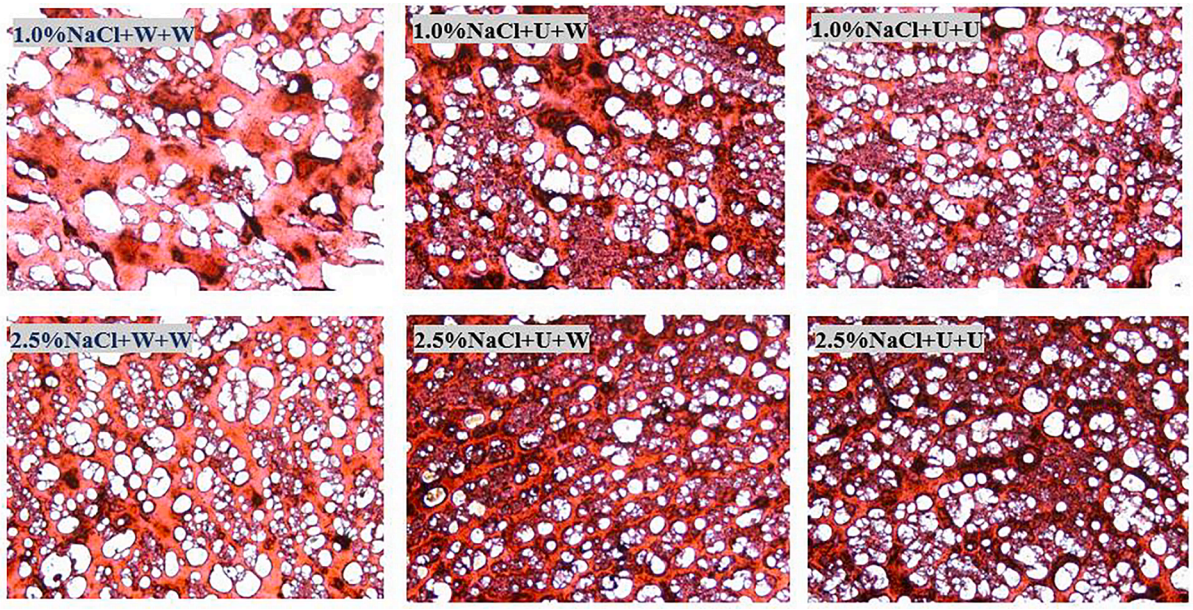

Fig. 7. Effect of ultrasound treatments on LM micrographs of surimi gels with different salt contents.

noticeably superior to those under low salt conditions. In addition, ultrasound-assisted water bath heating could improve the gel strength, textural properties and WHC of surimi gels, irrespective of the salt levels. The use of ultrasound facilitated the conversion of protein conformation from α-helix to β-sheet and β-turn which were beneficial for the formation of hydrogen bonds and other hydrophobic interactions. Furthermore, SEM and LM images illustrated that the microstructures of the surimi gels were more uniform and denser after ultrasound treatment. However, due to the negative effects of prolonged ultrasound treatment, the efficiency of the U + U treatment was inferior to that of U + W. In particular, the strength, texture, WHC and chemical interactions of gels from the U + W group at low salt level were equivalent to or even better than those from the W + W group at high salt content. Overall, this study suggested that ultrasonic-assisted preheating combined with water bath heating could be considered as an efficient approach to obtain low-salt surimi with good gel properties.

CRediT authorship contribution statement

Xueli He: Data curation, Investigation, Writing – original draft. **Yanan Lv:** Methodology, Data curation. **Xuepeng Li:** Supervision. **Shumin Yi:** Validation. **Honglei Zhao:** Visualization. **Jianrong Li:** Resources, Project administration. **Yongxia Xu:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

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

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