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Feasibility of polysaccharide addition for constructing soft golden threadfin bream (*Nemipterus virgatus*) surimi gels as a dysphagia food

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The effect of different polysaccharides including pectin (PC), xanthan gum (XG), guar gum (GM) and gum arabic (GA) on the gelation and dysphagia diet potential of golden threadfin bream (GTB) surimi gels was investigated. The four polysaccharides reduced the gel properties and improved the water retention of GTB surimi gels, reflected by 38.2–69.6% reduction in gel strength, a 49.7–55.5% decrease in the cooking loss rate (CLR) and a 22.9–24.3% increment in water holding capacity (WHC). Furthermore, GTB surimi gels complied with level 7 and the GM group and the XG group could be classified as level 6 (soft and bite-sized) dysphagia food according to International Dysphagia Dietary Standardization Initiative (IDDSI) testing. Moreover, the G' values of the GM group and the XG group were reduced by 12.2% and 29.3% compared with the control. Meanwhile, T_{22} significantly shifted toward higher relaxation times with the addition of GM. Indeed, the amide I band of GTB surimi gels exhibited a redshift from 1652.2 cm^{-1} to 1657.1 cm^{-1} and 1657.2 cm^{-1} with the addition of GM and XG, revealing weaker electrostatic interactions between GTB surimi and polysaccharides. GM and XG enhanced hydrophobic interactions and disulfide bonds of GTB surimi by 12.3–22.3% and 21.4–28.6%, respectively. GM and XG promoted a looser microstructure of GTB surimi gels, with vessel percentage area, the total number of junctions, and total vessel length decreasing by 41.5–73.8% and lacunarity increasing by 70.9–72.5%. These findings could provide GTB surimi gels with addition of GM and XG for developing soft surimi products for people with dysphagia.

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Sustainability spotlight

Dysphagia is prevalent among the elderly, our findings provide practical advice on the expected quality and safety of potential foods for managing dysphagia. The aim of this study was to investigate the softening effect of polysaccharides on GTB surimi gels to develop suitable food products for patients with dysphagia. This study aligns with the "good health and well-being" of the UN's Sustainable Development Goals and provides practical advice on the expected quality and safety of potential foods for managing dysphagia.

1 Introduction

Dysphagia is prevalent among the elderly, and patients with dysphagia have a high risk of choking and food aspiration during eating or drinking.[1] Dysphagia significantly contributes to long-term protein deficiency as a primary etiology; affected individuals demonstrate a progressive reduction in dietary intake, culminating in the loss of muscle mass.[2] Additionally, protein-enriched food could effectively meet nutritional requirements and enhance overall well-being for older adults.[3] Surimi is a common raw material used in dishes like fish balls and fish sausages because it is rich in protein and low in fat.[4] However, during the heating process, the collagen shrinks and myofibrillar protein (MP) coagulation of surimi would result in a hard texture of surimi gels.[5] This resultant texture could pose challenges for people with swallowing disorders.[5] However, research on soft surimi gels for individuals with dysphagia is limited. Therefore, it is essential to develop new surimi products with a suitably soft texture for people suffering from dysphagia.

Currently, reports on the addition of polysaccharides to soften surimi gels are limited, mainly based on threadfin bream

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surimi modified with tamarind kernel powder,[6] sturgeon surimi modified with xanthan gum (XG),[7] Mexican flounder surimi modified with low methoxyl pectin (PC)[8] and Antarctic krill composite shrimp surimi modified with sodium alginate.[9] The use of polysaccharides to enhance the gel properties of surimi gels has been widely investigated. Recent studies have demonstrated that the silver carp surimi modified with curdlan and κ-carrageenan,[10] *Meretrix meretrix* clams modified with gellan gum and fucoidan,[11] sturgeon fish paste modified with konjac gum[12] and threadfin bream surimi modified with psyllium husk powder[13] could show improved gelation performance of surimi gels with high gel strength and a dense network structure by the filling effect. However, the softening effect of polysaccharides on surimi gels is still rarely studied and the corresponding mechanism is unclear. Therefore, further research is needed to explore the mechanism of interactions between polysaccharides and surimi in the development of foods for people with dysphagia.

Golden threadfin bream (*Nemipterus virgatus*) has the advantages of high protein, tender meat and high edible value, and it ranks as the second-biggest species of fish used in the preparation of surimi products.[14] Researchers have extensively studied the gel properties of golden threadfin bream (GTB) due to its wide use and high nutritional value in surimi products. Studies have reported that carboxymethyl cellulose,[15] tapioca starch[14] and modified starches[16] could improve the textural and rheological properties of GTB surimi gels with uniform and small network cavities. However, no studies have been conducted on using guar gum (GM), gum arabic (GA), PC and XG. This lack of knowledge prompted us to investigate the softening effect of polysaccharides on GTB surimi gels to develop suitable food products for patients with dysphagia.

The aim of this study was to investigate the influence of four polysaccharides on gel properties of GTB surimi gels based on textural properties, water holding capacity (WHC), cooking loss rate (CLR), and whiteness. Moreover, the International Dysphagia Diet Standardization Initiative (IDDSI) testing was introduced to categorize GTB surimi gels within IDDSI levels. The rheological properties of GTB surimi were studied before and after heating. Water migration and distribution were observed by low-field nuclear magnetic resonance (LF-NMR) and magnetic resonance imaging (MRI). The mechanism of the combination of GTB surimi gels and polysaccharides was measured using intermolecular force determination. Fourier transform infrared spectroscopy (FTIR) measurement was applied to study the structural changes and cryo-scanning electron microscopy (cryo-SEM) was employed to explore microstructure properties. This study provides practical advice on the expected quality and safety of potential foods for managing dysphagia.

2 Materials and methods

2.1. Materials and chemicals

Frozen GTB was supplied by Beihai Guizhihai Fishery Co., Ltd and stored at −45 °C before use. GM, GA, PC and XG were purchased from Aladdin Co., Ltd (Shanghai, China). All other chemical reagents were of analytical grade.

2.2. Preparation of GTB surimi

Frozen golden threadfin bream was thawed overnight at 4 °C, divided into small pieces, and rinsed with cold water. The moisture on the surface of the fish was wiped away and the flesh was removed from golden threadfin bream. The flesh of golden threadfin bream was chopped in a grinder and cold water (4 °C) was added to maintain the moisture content at 80%.

2.3. Preparation of surimi gels

Each surimi-based mixture was made by mixing surimi, polysaccharides (if added) and salt (Table 1) for 2 min in a food processor. The GTB surimi was centrifuged for 5 min at 5000×*g* and 4 °C. The centrifugation step was employed to remove air bubbles from the GTB surimi. Finally, the GTB surimi was heated based on two steps: 40 °C for 30 min followed by 90 °C for 20 min and the cooled samples were stored at 4 °C overnight for subsequent testing.

2.4. Gel strength

The gel strength of surimi was determined using a TA-XT Plus texture analyzer (Stable Micro Systems, Godalming, UK) equipped with a P/0.5S probe model. The samples were cut into 20 mm-diameter, 10 mm-long cylinders. The following parameters were set: the speed before and during the test was 1 mm s^{-1}, the speed after the test was 10 mm s^{-1}, the compression ratio was 50%, and the trigger force was 0.5 g. Each test was repeated three times to ensure accuracy.

2.5. CLR

The weight of the raw GTB surimi was recorded as m_1. The surimi mixture was then processed according to the procedure described in 2.3 to prepare heat-induced gels. Finally, the weight of GTB surimi gels was recorded as m_2 after the surface water was heated and dried. The CLR of the GTB surimi gel was calculated in accordance with formula (1) as follows:

$$\mathrm{CLR}/\% = (m_1 - m_2)/m_2 \times 100 \quad (1)$$

2.6. WHC

The GTB surimi gel mass (about 2 g) was weighed, and the exact value of the weight m_1 was recorded. Then it was wrapped with

Table 1 Formulation of GTB surimi with and without polysaccharides (GM, GA, PC, and XG)

Ingredient	Control (%)	Polysaccharide treatment (%)
The flesh of *Nemipterus virgatus*	97.5	95.5
Polysaccharide	0	2
Salt	2.5	2.5
Total	100	100

double filter paper and placed in the centrifuge tube. Next, it was centrifuged at 10 000 rpm and 4 °C for 10 min. After that, the GTB surimi gel was removed, accurately weighed and recorded as m_2. Formula (2) for WHC is as follows:

$$\text{WHC}/\% = m_2/m_1 \times 100 \quad (2)$$

2.7. Whiteness

A colorimeter (UltraScan Pro, HunterLab, USA) was used to analyze the color of surimi gel. A reflection method was used to measure lightness (L^*), redness/greenness (a^*), and yellowness/blueness (b^*). The whiteness index was calculated using formula (3).

$$\text{Whiteness} = 100 - ((100 - L^*)^2 + a^{*2} + b^{*2})^{1/2} \quad (3)$$

2.8. IDDSI tests

Manual evaluation. The deformation properties of the samples were evaluated using the spoon tilt test and the fork pressure test and their behavior was categorized according to the IDDSI description. The spoon tilt test involved scooping up a gel sample and slowly tilting the spoon sideways to observe changes in the behavior of the sample. The samples were cut into squares of approximately 1.5 cm × 1.5 cm in size. The fork pressure test was carried out by pressing the samples with the thumb finger using a fork.[17]

Instrumental evaluation. Referring to the method of Qin *et al.*[18] with minor adjustments, the positive distance (mm) and negative area (N s^{-1}) were recorded using a TA-XT Plus texture analyzer (Stable Micro Systems, Godalming, UK). Cube samples with 15 mm side lengths were prepared. A uniform pressure of 2.3 N was applied following the "hold until time" test sequence. Tests were conducted at speeds of 1 mm s^{-1} for samples.

2.9. Rheological properties

The rheological properties of GTB surimi gels were determined using a rotational rheometer (DHR-1, TA-Instruments Menu Co., Ltd, New Castle, USA) with a 20 mm parallel plate and a 1 mm gap size. The linear viscoelastic zone was evaluated by conducting oscillatory strain scans within the range of 0.1–1000% at 1 Hz. The temperature dependent changes in the storage modulus (G') were investigated during heating, with the temperature range set from 20 °C to 90 °C at a heating rate of 5 °C min^{-1}.

2.10. LF-NMR

An LF-NMR analyzer (MesoMR23-060V-1, Niumag Analytical Instrument Co., Ltd, China) was used to determine the spin–spin relaxation time (T_2) of the GTB surimi gels, following the method outlined by Yan *et al.*[19] A magnetic field strength of 0.6 T was used to perform all the tests and a 23.2 MHz proton resonance frequency at 32 °C was used. The experimental parameters encompassed an NS of 4, an NECH of 5000, and a TW of 3300 ms.

2.11. Determination of intermolecular forces

The denaturing solutions including Sa (0.6 mol L^{-1} NaCl), Sb (1.5 mol L^{-1} urea + 0.6 mol L^{-1} NaCl), Sc (8 mol L^{-1} urea + 0.6 mol L^{-1} NaCl), and Sd (0.5 mol L^{-1} β-mercaptoethanol + 8 mol L^{-1} urea + 0.6 mol L^{-1} NaCl) were used to disrupt ionic bonds, hydrogen bonds, hydrophobic interactions, and disulfide bonds, respectively. Initially, 0.5 g of GTB surimi gels was homogenized in the Sa solution at 6000 rpm for 2 min. Subsequently, the supernatant was collected by shaking at 180 rpm for 1 hour at 25 °C and centrifugation at 10 000×g for 20 minutes. Following the same procedure as that for Sa, the residual precipitates were treated sequentially with Sb, Sc and Sd solutions, and the precipitates were treated twice with Sc solution. A Bradford protein assay kit (Takar Biomedical Technology Co., Ltd, Beijing, China) was used for the determination of the concentrations of the dissolved protein.

2.12. FTIR

The freeze-dried powder of each sample was mixed with potassium bromide in an agate mortar. The mixture was ground evenly and pressed into sheets under vacuum. The sample was scanned using a Nicolet iS50 spectrometer (Thermo Fisher Scientific, America) in the wavenumber range of 4000 to 400 cm^{-1}. The scans were performed at a resolution of 4 cm^{-1} and a total of 32 scans were performed.

2.13. Cryo-SEM

The microstructure of the samples was determined using an SU8010 device (Hitachi Co., Tokyo, Japan). The sample was first placed on a copper scaffold and was frozen in liquid nitrogen. After that, the samples were moved into the preparation chamber (PP3010T cryo-SEM preparation system, Quorum Technologies, UK) under vacuum and subjected to fracture, sublimation (−70 °C, 20 min) and platinum sputtering (10 mV for 120 s) successively. Finally, the treated samples underwent further processing as they were delivered to the SEM chamber. At a 10.0 kV accelerating voltage, observations and captures were carried out at a magnification of 5000×.

2.14. Statistical analysis

The results were presented as the mean ± standard deviation. The data were analyzed using SPSS 18.0 software, and the statistical significance of differences was evaluated with a least significant difference test at a significance level of $p < 0.05$.

3 Results and discussion

3.1. Gel strength of GTB surimi gels affected by various polysaccharides

Generally, the gel strength is the key quality indicator for evaluating the quality of gel products.[10] The effect of various polysaccharides on the corresponding visual observations and gel strength of samples is shown in Fig. 1. Overall, the gel strength of GTB surimi gels with the addition of polysaccharides was reduced by 38.2–69.6%, in which XG had the most obvious

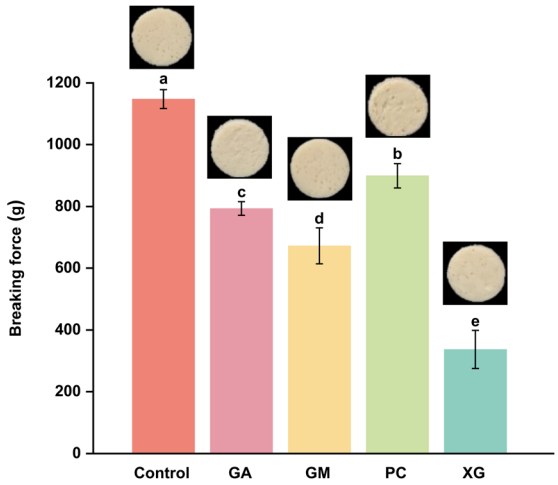

Fig. 1 Influence of various polysaccharides (GA, GM, PC, and XG) on gel strength and the visual appearance of GTB surimi gels. The various letters (a–e) indicate significant differences ($p < 0.05$) among each group, $n = 3$.

softening effects followed by GM, GA and PC. To some extent, the molecular weight of XG is higher than that of the other polysaccharides, which might hinder the construction of the surimi gel network structure.[20] Additionally, the structure of the GM molecule is composed of linear α-1,4-linked mannose units and randomly linked β-1,6-linked galactose units and its entangled galactomannan chains would hinder protein interactions.[21] The PC as an acid anionic polysaccharide contains anionic carboxyl groups, which could decrease the pH of the system thus altering the interaction between protein molecules.[22]

Furthermore, Liu *et al.*[7] found that an apparent decrease (46.4–57.1%) in the gel strength was observed when XG and GM were added into unrinsed sturgeon surimi. Uresti *et al.*[8] demonstrated that the reduction in gel strength of Mexican flounder with higher levels of amidated low methoxyl PC (2–5%) addition could be ascribed to the modification of the natural structure of proteins by interactions between PC and proteins involving both hydrogen bonds and electrostatic interactions. Indeed, XG, PC and GA are anionic in nature and MPs possess anionic charged groups during surimi processing as processing pH is higher than the isoelectric point of MPs.[23] Because polysaccharides and MPs carried the same negative charges, there were electrostatic repulsive forces between polysaccharides and MPs. In addition, studies have confirmed that the incompatibility of the molecular configurations in the system causes steric hindrance and damage to gel structures, resulting in antagonistic effects on gel properties.[24] In these cases, an antagonistic effect could occur when polysaccharides and MPs, two macromolecules, combine together, leading to the softening effect of polysaccharides on surimi gels. In addition, the softening effect on gel strength of GTB surimi gels modified with neutral polysaccharide (GM) could be attributed to excessive aggregation of proteins, with consequent collapse of the crosslinked network.[25] Therefore, it is suggested that the softening effects of polysaccharides on the gel strength of GTB surimi gels could be due to the antagonistic effect and the excessive protein aggregation resulting from neutral polysaccharide addition.

3.2. The CLR and WHC of GTB surimi gels affected by various polysaccharides

The CLR and WHC of GTB surimi gels influenced by the four polysaccharides are shown in Fig. 2. The CLR usually refers to the water loss in the surimi gel caused by the cooking process, and the WHC reflects the capacity of surimi protein to retain water.[10,11] The XG group had the lowest CLR, which was 55.5% lower than that of the control. However, when GA and PC were added, the CLR was increased (Fig. 2A). Liu *et al.*[11] found that the CLR of *Meretrix meretrix* gels reduced by 18–38% with the addition of GM, suggesting that polysaccharides could improve the water retention properties of *Meretrix meretrix* gels by absorbing water and trapping it in the gel three-dimensional structure. To some extent, water could be effectively contained within the network of GTB surimi gels and the migration of

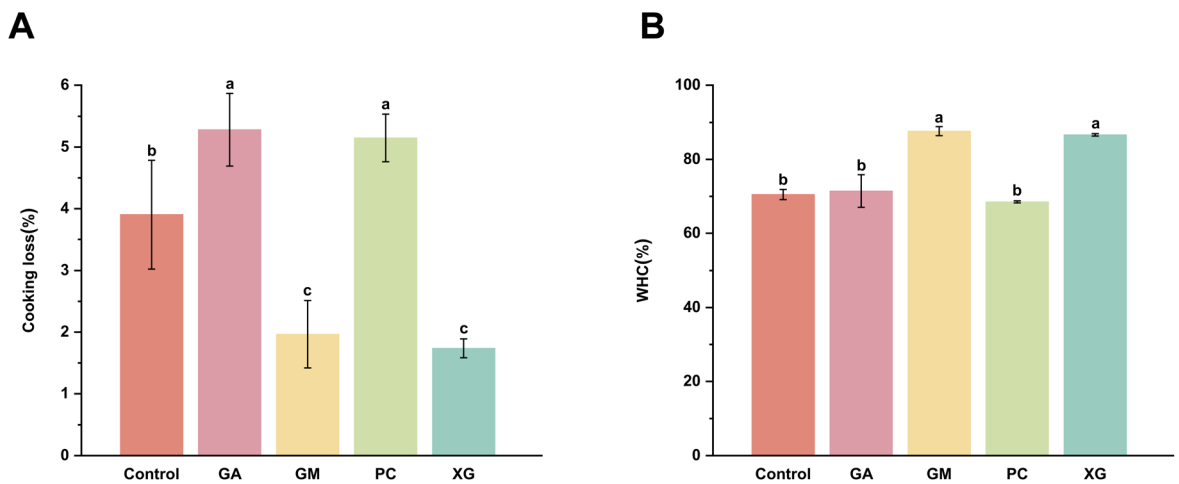

Fig. 2 Influence of various polysaccharides (GA, GM, PC, and XG) on water retention of GTB surimi gels. (A): CLR; (B): WHC. The various letters (a–c) indicate significant differences ($p < 0.05$) among each group, $n = 3$.

water from interior to exterior in gels would be inhibited after the addition of GM and XG. The decrease in the CLR of the GM group and XG group was accompanied by the increase in water retention, in which the WHC of the corresponding treated GTB surimi gels increased by 24.3% and 22.9%, respectively (Fig. 2B). Similarly, Han *et al.*[26] and Yu *et al.*[12] demonstrated that the addition of XG was able to generate a hydrophilic polymer to combine with *Oviductus Ranae* proteins and sturgeon paste due to its good water binding ability, thus enhancing the WHC of the composite systems. Indeed, the WHC of surimi gels would typically increase with the participation of polysaccharides, which could be ascribed to the combination of water-soluble proteins with hydrophilic groups in surimi and water molecules to form electrostatic intermolecular repulsion.[27,28] Therefore, it is suggested that the addition of GM and XG could decrease the CLR and correspondingly increase WHC of GTB surimi gels mainly based on their ability to immobilize water within the network, while GA and PC have a negative effect on the water retention of GTB surimi gels. Based on the above results, representative polysaccharides of GM and XG were selected to modify GTB surimi gels in the following experiments.

3.3. The whiteness of GTB surimi gels affected by GM and XG

The effect of GM and XG on the whiteness of GTB surimi gels is shown in Table 2. The whiteness of composite gel systems was reduced by 0.8–7.1% when GM and XG were added, as compared to the control (Table 2), while the difference among various composite samples was not significant enough to be distinguished by the naked eye (Fig. 1). Indeed, as a quality evaluation parameter of surimi-based gel products, system whiteness is related to the type and color of additives.[29] As reported by Sharma *et al.*,[29] the whiteness of silver carp surimi gels decreased due to the dark brown color of pineapple peel. In this case, an overall decrease in the whiteness of the GTB surimi gel was due to the coloration of GM and XG. In addition, the variation in the whiteness value was also related to the degree of molecular binding of the composite surimi gels.[30] XG addition could reduce the whiteness of the egg white gel during the heating process due to the weaker molecular binding reflected by the looser structure and higher light transmittance.[31] Therefore, it is demonstrated that GM and XG decreased the whiteness of GTB surimi gels mainly based on the coloration of polysaccharides and weaker molecular binding.

Table 2 Influence of various polysaccharides (GA, GM, PC, and XG) on the color values of GTB surimi gels

Sample	L^*	a^*	b^*	Whiteness
Control	81.45 ± 0.58^{a}	-2.45 ± 0.07^{b}	8.83 ± 0.40^{a}	79.31 ± 0.85^{a}
GA	80.33 ± 0.64^{a}	-2.31 ± 0.22^{b}	9.71 ± 0.60^{a}	77.93 ± 0.42^{a}
GM	75.37 ± 0.92^{b}	-2.60 ± 0.19^{b}	8.79 ± 0.49^{b}	73.71 ± 0.87^{c}
PC	80.07 ± 0.44^{a}	0.44 ± 0.14^{a}	12.41 ± 0.34^{a}	76.52 ± 0.67^{b}
XG	81.22 ± 0.80^{a}	-2.22 ± 0.14^{b}	9.75 ± 0.23^{b}	78.71 ± 0.76^{a}

Note: data are reported as the mean ± SD of the three measurements. Different superscripts (a–c) in the same column indicate significant differences at $p < 0.05$.

3.4. IDDSI analysis of GTB surimi gels affected by GM and XG

In terms of the spoon tilt test, as shown in Fig. 3A, the GTB surimi gels with or without polysaccharides exhibited sufficient cohesion to maintain their shape on the spoon. Moreover, when the spoon was flipped over, these foods fell off the spoon smoothly without leaving any food on it. This kind of food is ideal for those with dysphagia because its texture reduces the probability of sticking to the pharynx.[31] With regard to the fork pressure test (Fig. 3B), the GTB surimi gels could be cut into small pieces under the pressure of nails turning white. This indicated that GTB surimi gels complied with level 7 of the IDDSI, suggesting that oral processing of food (including biting and chewing) is necessary for the formation of a tender, swallowable food bolus.[32] In this case, GM and XG were introduced to soften the GTB surimi gels and the mixed gels could be easily squashed and divided apart. This was possible by applying pressure to the area where the thumbnail blanched to white, while the shape did not change after removing the pressure. These behaviors indicated that the GM group and XG group could be classified as level 6 food, suggesting that food needs to be swallowed through chewing and the control of tongue force. The GA group and PC group, which have a negative effect on the

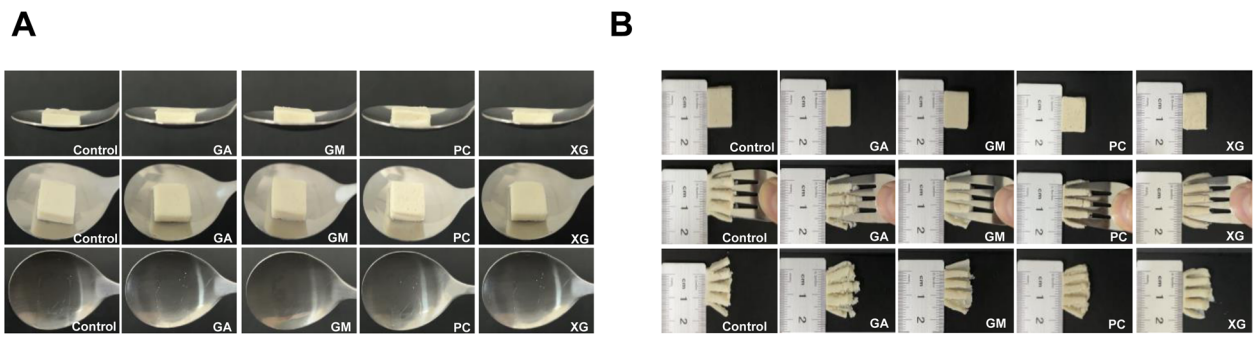

Fig. 3 Influence of various polysaccharides (GA, GM, PC, and XG) on the IDDSI tests including (A) spoon tilt tests; (B) fork pressure tests of GTB surimi gels.

water retention of GTB surimi gels, were classified as level 6 (soft and bite-sized) dysphagia food according to IDDSI testing (Fig. 3). Based on the test combining spoon tilt and fork pressure, sodium alginate/shrimp surimi gels,[9] inulin and konjac glucomannan/golden pompano (*Trachinotus ovatus*) MP emulsion gels,[33] XG/pork pastes[34] and GM/pork pastes[34] were classified as level 6 (soft and bite-sized) food. These samples could whiten the thumb nail with light pressure, and no shape recovery was observed when the pressure was removed.

The IDDSI framework is based on the visual scale and could not provide numerical values.[18] A texture profile analyser with a fork attachment was used for the quantitative verification of the IDDSI test, which could avoid the subjectivity associated with individuals conducting the tests and give more precision in the IDDSI test, thus providing reliable data for the level of dysphagia-specific foods.[18] As presented in Table 3, two key parameters were assessed named peak positive distance and negative area. According to Pematilleke *et al.*,[35] the peak positive distance indicated the hardness of the food. The peak positive distance of GTB surimi gels with the addition of polysaccharides was reduced by 12.3–36.9% (Table 3), suggesting that polysaccharides could soften the GTB surimi gels. This was consistent with the visual observation in the IDDSI test, the gel strength and the rheological results, indicating that the samples as level 6 food could be easily squashed and divided apart under the pressure of nails turning white. Similarly, the negative area represented the stickiness of the GTB surimi gels. The obtained negative areas had low values as various GTB surimi gels could be detached from the fork, indicating that these GTB surimi gels were non-sticky.[18] These results were consistent with the spoon tilt test, in which various GTB surimi gels could fall off the spoon smoothly without leaving any food on it, indicating that they were easy to swallow without sticking to the tongue and pharynx. Meanwhile, Qin *et al.*[18] utilized IDDSI instrumental evaluation to detect custard gels with the addition of soy protein and found that the peak positive distance of custard gels decreased when 8.9% soy protein was added, which corresponded to the IDDSI test results as level 6 food of the IDDSI framework. Therefore, GM and XG could reduce the difficulty of oral chewing and swallowing of GTB surimi gels from level 7 to level 6 according to the IDDSI and the peak positive distance reduced, indicating their potential feasibility as alternative foods for patients with dysphagia.

Table 3 Influence of various polysaccharides (GA, GM, PC, and XG) on the instrumental IDDSI test of GTB surimi gels

Sample	Peak positive distance (mm)	Negative area (N s^{-1})
Control	4.147 ± 0.395^{a}	-0.104 ± 0.058^{c}
GA	3.224 ± 0.115^{bc}	-0.003 ± 0.001^{a}
GM	2.811 ± 0.174^{cd}	-0.003 ± 0.003^{a}
PC	3.636 ± 0.448^{b}	-0.053 ± 0.011^{b}
XG	2.616 ± 0.067^{d}	-0.001 ± 0.001^{a}

Note: data are reported as the mean ± SD of the three measurements. Different superscripts (a–c) in the same column indicate significant differences at $p < 0.05$.

3.5. Rheological properties of GTB surimi gels affected by GM and XG

Changes in the storage modulus (G') of the GM group and XG group as a function of temperature from 20 °C to 90 °C are shown in Fig. 4 indicating the transition from sol to gel. The G' of GTB surimi experienced an initial decrease followed by an increase during the heating process. The dissociation of MPs upon heating would also enhance the fluidity of the gel solution, resulting in a decreasing G' value.[33] In addition, hydrogen bonds in the gel system were first weakened by thermal induction, destroying the initial weak viscoelastic structure of the polysaccharide-protein gel systems and subsequently being reconstructed to form new gel networks reflected by increasing G'.[36] The XG group exhibited the lowest G', indicating weak cross-linking between XG and GTB surimi. When heated to 55 °C, the structure of MPs in GTB surimi formed a three-dimensional network structure under thermal induction, resulting in an increase in G'. Moreover, from 20 °C to 90 °C, the G' values of the GM and XG groups were reduced by 12.2% and 29.3% compared with the control (Fig. 4), suggesting that GM and XG weakened the ability of GTB surimi to form gels, leading to soft food being desirable for people with dysphagia.[37] Moreover, the G' values of the GA and PC groups were reduced by 6.4% and 37.8% compared with the control at 90 °C, indicating that the GTB surimi system exhibited a weaker gelation behavior when GA and PC were added (Fig. 4). Liu *et al.*[11] and Tan *et al.*[9] found that the G' of *Meretrix meretrix* gels and shrimp surimi gels supplemented with polysaccharides significantly decreased at 85 °C. Indeed, the decrease in G' could be due to an increase in electrostatic repulsive force and spatial sites, thus affecting the aggregation of proteins after adding polysaccharides.[9] The electrostatic repulsive forces may play a pivotal role in maintaining the gel structure, such as viscoelasticity and stiffness, resulting in less covalent cross-linking.[38] During the heating process, this unstable combination led to the formation of a loose network structure, resulting in softening of gel quality.[39] The G' results were aligned with the gel strength results (Fig. 1),

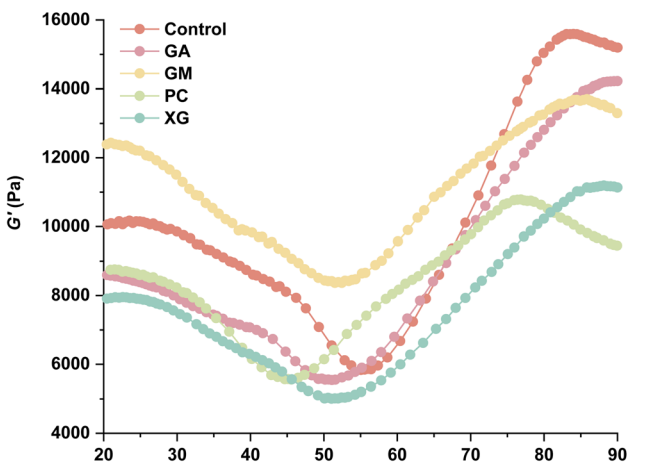

Fig. 4 Influence of various polysaccharides (GA, GM, PC, and XG) on rheological properties of GTB surimi gels.

affirming that GM and XG could soften the texture properties of the GTB surimi gels. Therefore, it is suggested that GM and XG could soften the gel properties of GTB surimi gels due to increased electrostatic repulsive force and spatial site resistance.

3.6. Water migration and distribution of GTB surimi gels affected by GM and XG

All gels exhibited three peaks, in which T_{21} represented tightly bound water within the MP structures, T_{22} indicated not readily available mobile water, and T_{23} represented free water outside the protein lattice.[40] According to Yasui *et al.*,[41] the water was found to be more loosely bound to the macromolecules when it had a longer relaxation time, reflecting a trend of lower gel strength in GTB surimi gels. As shown in Fig. 5, T_{21} showed a migration to higher values from 1.5 ms to 2.4 ms and 2.3 ms with the addition of GM and XG, reflecting the increased degree of freedom of the water. Moreover, T_{22} significantly shifted toward higher relaxation times from 54.8 ms to 77.5 ms and 58.7 ms in the GM group and XG group, in comparison to the control, indicating the decreased binding of immobile water by MPs and proton mobility and freedom.[9] Yang *et al.*[42] also reported that the T_{22} of squid surimi gels supplemented with laver powder increases. To some extent, GM would increase water mobility by weakening the binding of the gel network structure with water molecules, thus affecting the gel strength.[43] Therefore, it is suggested that GM would cause weakened interactions between water molecules and macromolecules and decrease the binding of immobile water with MPs.

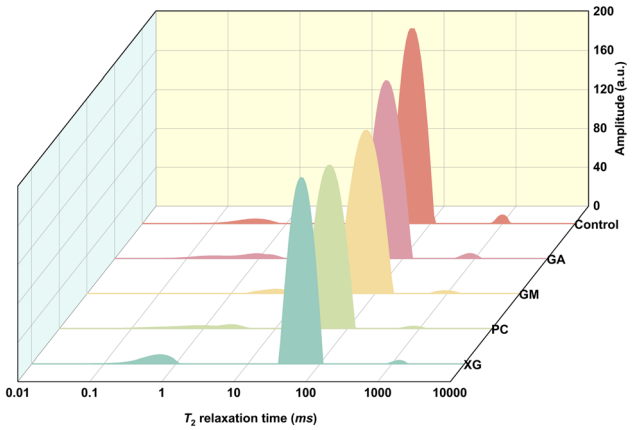

Fig. 5 Influence of various polysaccharides (GA, GM, PC, and XG) on LF-NMR of GTB surimi gels.

3.7. Intermolecular forces of GTB surimi gels affected by GM and XG

As shown in Fig. 6A, the ionic bonds in the GTB surimi gel were increased when XG was added. In addition, the main intermolecular forces of GTB surimi gels were hydrophobic interactions and disulfide bonds, which were 0.5 mg ml^{-1} and 0.3 mg ml^{-1}, respectively. The addition of XG and GM enhanced the contents of hydrophobic interactions and disulfide bonds by 12.3–22.3% and 21.4–28.6%, respectively. In addition, the main intermolecular forces of GTB surimi gels were hydrophobic interactions and ionic bonds when GA and PC were added (Fig. 6A). Chen *et al.*[10] and Yu *et al.*[12] found that the addition of XG into silver carp surimi gels resulted in an increase of ionic bonds in sturgeon pastes. Lei *et al.*[21] demonstrated that the addition of polysaccharides increased hydrophobic interactions and disulfide bonds. When XG was added, the ionic linkage increased, possibly due to the combination of Na^+ in sodium chloride and the negative charges of XG, leading to enhanced electrostatic interactions of the system.[12] In addition, heating could induce protein denaturation and expose myosin hydrophobic groups, which promotes the aggregation and cross-linking of proteins.[27] Indeed, the hydrophobic interactions of the GTB surimi gels increased with polysaccharide addition, proving that polysaccharides would aggregate with MPs in GTB surimi. Furthermore, an increase in disulfide bonds in GTB surimi gels might be attributed to the heating process, which leads to the

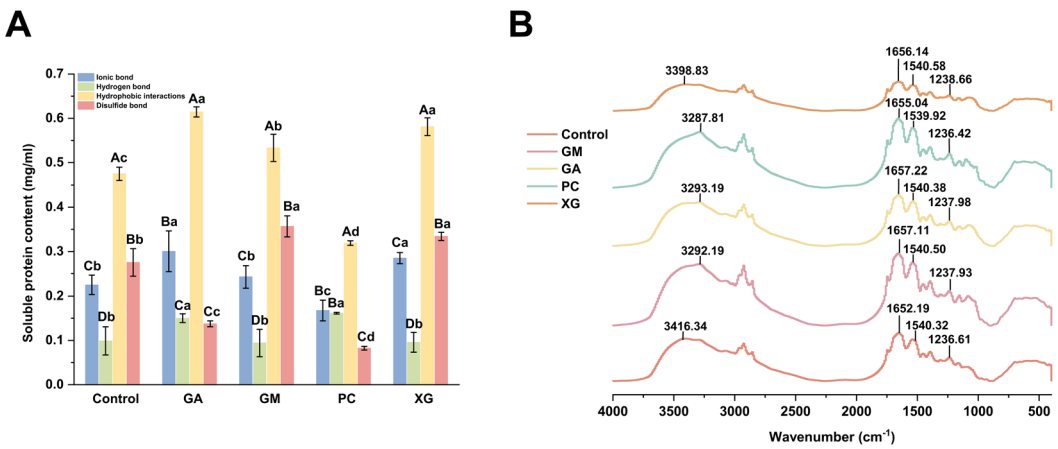

Fig. 6 Influence of various polysaccharides (GA, GM, PC, and XG) on (A) intermolecular forces; (B) FTIR spectroscopy of GTB surimi gels. Different uppercase letters within the same intermolecular forces indicate significant differences ($p < 0.05$), $n = 3$. Different lowercase letters within the same sample indicate significant differences ($p < 0.05$), $n = 3$.

unfolding of peptide chains in proteins and breaking of the internal disulfide bonds, thus leading to the formation of an inhomogeneous gel network contributing to soft texture.[42] Therefore, it is suggested that the addition of GM and XG could enhance hydrophobic interactions and disulfide bonds due to the exposure of hydrophobic groups and the breaking of internal disulfide bonds.

3.8. Conformation changes of GTB surimi gels affected by GM and XG

FTIR spectroscopy could detect the chemical changes induced by protein–polysaccharide interactions in gels.[27] Fig. 6B shows the FTIR spectra of the GM group and XG group. The peak at 3200–3400 cm^{-1} is the extension of hydroxyl hydration, indicating the existence of hydrogen bond interactions.[21,44] When compared with the control, the absorption peaks of hydroxyl groups showed a blueshift from 3416.3 cm^{-1} to 3292.2 cm^{-1} and 3293.2 cm^{-1} in GM and XG spectra, respectively. The 1652 cm^{-1} absorption band represented the amide I band, which could be associated with the stretching vibration of the C=O.[27] The amide I band of the GM group and XG group showed a redshift to the peak at 1652.2 cm^{-1}, demonstrating weaker electrostatic interactions in the system and a transition from an ordered to a disordered structure. Furthermore, the addition of GM and XG did not affect the amide II and amide III regions in the FTIR spectra of the GTB surimi gel. Moreover, when GA and PC were added the absorption peaks of hydroxyl groups showed a blueshift from 3416.3 cm^{-1} to 3293.2 cm^{-1} and 3287.8 cm^{-1} and the amide I band showed a redshift from 1652.2 cm^{-1} to 1657.2 cm^{-1} and 1655 cm^{-1}, respectively (Fig. 6B). Lei *et al.*[21] reported that with the addition of GM, a shift in the phycocyanin gel hydroxyl hydration extension from 3337 cm^{-1} to 3309 cm^{-1} was observed, suggesting an enhancement in hydrogen bonds. Basyigit *et al.*[1] demonstrated that the amide I band showed a higher wavelength in the soy protein gel system with the addition of polysaccharides. Therefore, it is suggested that hydrogen bonds and electrostatic forces participate in the interactions between polysaccharides (GM and XG) and GTB surimi gels.

3.9. Cryo-SEM of GTB surimi gels affected by GM and XG

Cryo-SEM images of GTB surimi gels contained GM and XG and the relevant quantitative network analysis parameters are shown in Fig. 7A and B. Specifically, the GTB surimi gel network structure had minimal porosity, a dense microstructure and uniform cavity distribution (Fig. 6A). With the addition of GM and XG, a relatively loose structure and heterogeneous cavity-size distribution were observed (Fig. 7A). Similarly, GA and PC

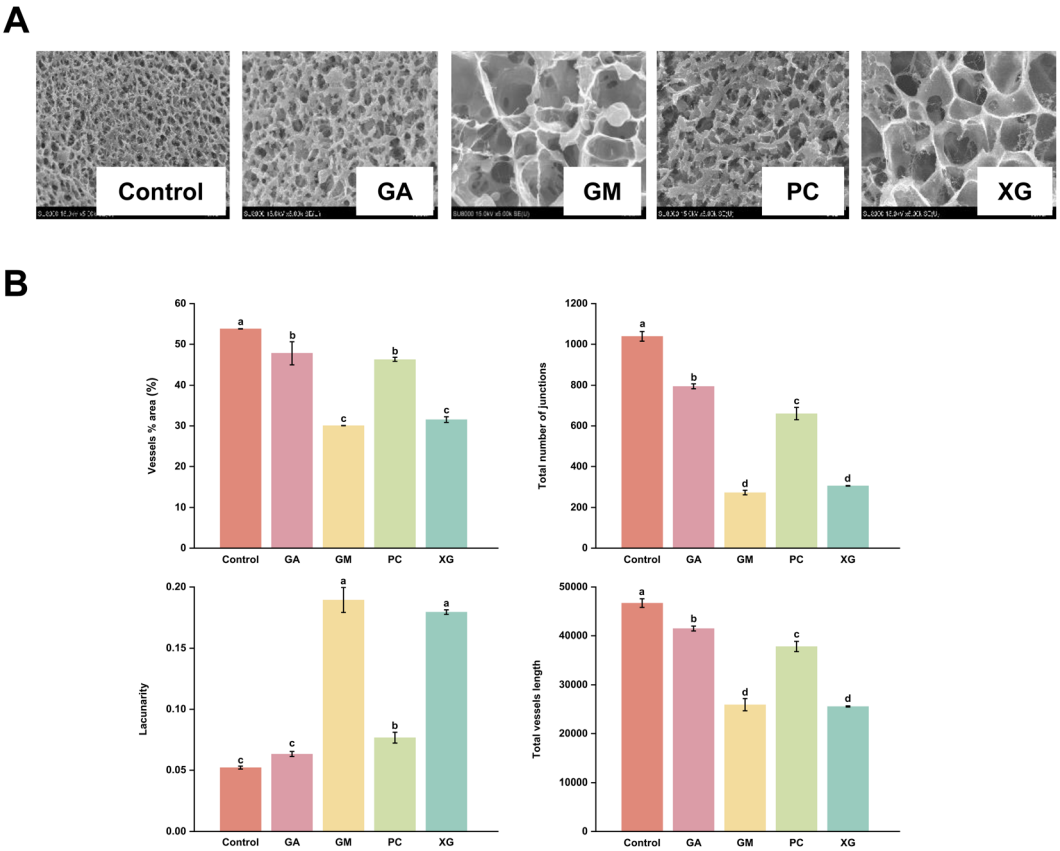

Fig. 7 Influence of various polysaccharides (GA, GM, PC, and XG) on microstructure properties of GTB surimi gels. (A): Cryo-SEM images; (B): quantitative network analysis including vessel percentage area; the total number of junctions; lacunarity; total vessel length. The various letters (a–d) indicate significant differences ($p < 0.05$) among each group, $n = 3$.

also promoted a weaker microstructure of GTB surimi gels with large holes and a weakly cross-linked structure (Fig. 7A). The increased pore diameter of the GM group and XG group suggested the formation of an incompact microstructure cross-linked between MPs and XG molecules, leading to a desirable softened gel structure. The cryo-SEM results of GTB surimi gel showed similar trends to gel strength (Fig. 1). Quantitative network analysis was further applied to analyze the microstructure of the GM group and XG group (Fig. 7B). The vessel percentage area, total number of junctions, and total vessel length of GTB surimi gels were decreased by 41.5–73.8%, while the corresponding lacunarity increased by 70.9–72.5% compared with the control group (Fig. 7B), suggesting the loose network and soften gel formation. Similarly, previous research reported that pea protein isolate/XG gel,[31] sturgeon paste/XG[12] and mutton goshtaba/GM[45] system structures were observed in large pores and more empty spaces, which could be ascribed to the increased electrostatic repulsive forces between polysaccharides and proteins, preventing interconnected structure formation. Zhou *et al.*[24] reported that antagonistic effects between pea protein isolate and grass carp protein isolate led to a loose gel structure with many large holes. The above phenomena were consistent with our research results. Therefore, it is suggested that the addition of GM and XG could promote the loose microstructure of GTB surimi gels with large voids and uneven distribution, thus exhibiting softened textural properties being favorable as dysphagia food.

4 Conclusions

The combination of GTB surimi and various polysaccharides (GM, GA, PC, and XG) was used to develop soft-type surimi gels with reduced gel strength due to antagonistic interaction and excessive aggregation of proteins. The polysaccharides (GM and XG) enhanced WHC and reduced the CLR of the GTB surimi gels representing well gel quality mainly based on their ability to immobilize water within the network. The GM group and XG group could be categorized into level 6 (soft and bite-sized) according to IDDSI testing. Indeed, hydrogen bonds and electrostatic forces were dominant interactions between polysaccharides (GM and XG) and GTB surimi gels, and polysaccharide (GM and XG) addition further led to enhanced hydrophobic interactions and disulfide bonds. Moreover, GM and XG participation led to a looser and less homogeneous microstructure of GTB surimi gels with easier chewing and swallowing potential. The results provided a theoretical foundation for the effect of polysaccharides on GTB surimi gels, which has potential applications in the development of soft-gel foods with rich proteins as dysphagia food.

Author contributions

Jia-Ni Zhou: writing – original draft, validation, methodology, investigation, formal analysis, data curation, conceptualization. Zhu-Jun Zhang: validation, methodology, investigation, formal analysis, data curation, conceptualization. Yin–Yin Lv: investigation. Bin Lai: investigation. Ce Wang: investigation. Jia-Nan Yan: writing – review & editing, supervision, funding acquisition. Hai-Tao Wu: writing – review & editing, supervision, project administration, funding acquisition.

Conflicts of 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.

Abbreviations

GTB	golden threadfin bream
GM	guar gum
GA	gum arabic
PC	pectin
XG	xanthan gum
MPs	myofibrillar proteins
TPA	texture profile analysis
WHC	water holding capacity
Cryo-SEM	cryo-scanning electron microscopy
LF-NMR	low-field nuclear magnetic resonance
MRI	magnetic resonance imaging

Data availability

All the data obtained from the analysis in the present study are given in the form of figures and tables, attached as separate files in the manuscript.

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