



Research Article

Improvement of the quality of surimi gels by high internal-phase emulsions prepared with fish oil and Zein peptide nanoparticles

Jia-Hui Song^{1,†}, Shuang He^{3,†}, Qi-Biao Zhang¹, Bo-Ya Zhang³, Wu-Yin Weng^{1,2}, Lin-Fan Shi^{1,2}, Yue Yu⁴, Wei Yang⁵, Zhan-Ming Li⁴ (✉), Zhong-Yang Ren^{1,2} (✉)

¹ College of Ocean Food and Biological Engineering, Jimei University, Xiamen 361021, China

² Engineering Research Center of the Modern Technology for Eel Industry, Ministry of Education, Xiamen 361021, China

³ National University of Singapore (Singapore) Research Institute, Suzhou 215128, China

⁴ School of Grain Science and Technology, Jiangsu University of Science and Technology, Zhenjiang 212100, China

⁵ Quality and Technology Center, Hainan Xiangtai Fishery Company Limited, Chengmai 571924, China

[†] Jia-Hui Song and Shuang He contributed equally to this work.

Received: 30 August 2024 / Revised: 22 September 2024 / Accepted: 23 September 2024

Abstract: High internal-phase emulsions (HIPEs) could be utilized to improve the surimi quality. However, the effects of Zein peptide nanoparticles (ZPNs) on the stability of HIPEs encapsulating fish oil and HIPEs stabilized by ZPNs (ZPNHIPEs) on surimi gels are still unclear. Therefore, the effect of ZPNs on stabilizing HIPEs and whether ZPNHIPEs could contribute to surimi gelation behaviors were analyzed. The turbidity of ZPNs was smaller than that of corn protein nanoparticles at the same concentration and increased with the rise in ZPN concentrations due to aggregation. Besides, the stability of HIPEs increased with the increase in ZPN concentrations. The addition of ZPNs at 1% could stabilize HIPEs, unlike those at 4% due to peptide aggregation. Moreover, the ZPN interactions in the gel matrix between ZPNHIPEs and surimi were beneficial for improving the texture of surimi gels and the formation of a strong gel structure and elastic behavior, especially at 5% ZPNHIPEs. This work could broaden the potential application of ZPNHIPEs prepared with fish oil to enhance the quality of surimi in the food industry.

Keywords: high internal-phase emulsions; Zein peptide nanoparticles; fish oil; surimi; gelation

Citation: Song J. H., He S., Zhang Q. B., et al. Improvement of the quality of surimi gels by high internal-phase emulsions prepared with fish oil and Zein peptide nanoparticles. *Food & Medicine Homology*, 2027, 4: 9420169. <https://doi.org/10.26599/FMH.2027.9420169>

1 Introduction

Surimi is a high-protein, low-fat food made from marine or freshwater fish. As a nutritious, safe, and healthy low-cost deep-processed marine food, surimi products are popular among consumers for their elasticity, unique flavor, and delicate texture^[1]. Rinsing plays an important role in the removal of blood, myosin, lipids, water-soluble compounds, and other impurities during surimi processing^[2]. However, this process can also lead to varying degrees of nutrient loss in surimi products. Lipids have been reported to confer desirable texture and flavor to foods and play an important role in the creation and enjoyment of a wide variety of foods^[3]. A lack of lipids in meat products can lead to the formation of poorly textured and flavored gels with a rubbery taste, which can cause an unpleasant experience for the consumer^[4].

Fish oil contains high levels of polyunsaturated fatty acids (PUFAs), especially n-3 fatty acids, as well as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are important for human health and physical function^[5]. PUFAs are

effective in preventing cardiovascular disease and inflammatory and autoimmune diseases, as well as reducing neurodevelopmental deficits^[6,7]. It has been noted that vegetable and marine oils are often added to surimi products to improve the color, flavor, and nutritional properties of surimi^[8,9]. However, the direct addition of oils can adversely affect the gelation and textural properties of surimi^[10]. Additionally, fish oil is susceptible to environmental factors such as temperature, oxygen, and light, and affects the sensory properties of surimi during storage^[11]. Therefore, how to add lipids to surimi gels without affecting their quality is an urgent problem^[2]. Meanwhile, preventing the oxidation of fish oil is also the primary challenge in adding fish oil to surimi at present.

Currently, researchers have found that emulsification can improve the oxidative stability of fish oil and mask the unpleasant fishy odor in food products^[12]. High internal-phase emulsions (HIPEs), also known as hyper-concentrated emulsions, are emulsions with a dispersed phase volume fraction of 74% or more. In recent years, HIPEs have attracted considerable interest for various applications due to their tunable flow behavior, large

surface area, good physical stability, as well as the ability to encapsulate large amounts of hydrophobic bioactive substances^[13]. Previous studies have shown that HIPEs can encapsulate fish oils, enhance the stability of fish oils, improve the gelation behavior of surimi, and enhance the whiteness, oxidative stability, and sensory quality of surimi^[14,15]. Conventional HIPEs are mainly stabilized by low-molecular-weight surfactants and biopolymers^[16]. However, due to the kinetic instability of small-molecule surfactants, surfactants with high concentrations are required for the stabilization of HIPEs, which poses potential toxicity risks and biodegradation challenges. Excessive use of non-food-grade emulsifiers can be hazardous to human health. Therefore, researchers have shown great interest in finding safe green solid particles that are ecologically biocompatible and renewable to replace chemical surfactants to produce stable HIPEs^[17].

Zein peptide is a small-molecule peptide obtained by enzymatic decomposition of Zein. Zein peptide is rich in nutrients and possesses biocompatibility, biodegradability, and a variety of physiological activities, including antioxidant, anti-inflammatory, hypotensive, and immune-enhancing properties. The diversity of the Zein peptide structure has led to a significant enhancement of the antioxidant activity^[18,19]. ZP is a potential material to protect fish oil from oxidation. Corn protein-based nanoparticles have been widely used as stabilizers for food-grade HIPEs due to their amphiphilic nature stabilized by hydrogen bonding^[20]. However, the high molecular weight and complex structure of Zein make it difficult to control its surface activity. Some researchers found that peptides have low molecular weight and simple structure with hydrophobic residues and polar groups on the surface compared to proteins, which contributes to their potential as emulsifiers and stabilizers of nanoemulsions^[17,21]. Oil-in-water emulsions using deamidated Zein peptide-polysaccharide conjugates as emulsifiers exhibit good emulsification compared with SDS under acidic conditions^[22]. Most studies have focused on the effect of protein-composite nanoparticles or peptide-composite nanoparticles on HIPEs. Whether Zein peptide nanoparticles (ZPNs) can improve the stability of HIPEs is still unclear.

Therefore, this study aimed to improve the gel behavior of surimi using HIPEs prepared with ZPNs (ZPNHIPEs) as matrix material and fish oil (FO) as filler material. ZPNs were characterized by turbidity, Fourier transform infrared spectroscopy (FTIR), particle size, and zeta potential. The characteristics of ZPNHIPEs were determined using particle size, zeta potential, storage stability, emulsification stability, and rheological properties. The texture properties, rheological properties, and whiteness of the surimi gels after adding ZPNHIPEs were analyzed.

2 Materials and Methods

2.1 Materials

Zein was obtained from Sigma-Aldrich Co., Ltd. (Saint Louis, USA). Trypsin (≥ 10000 U/mg) and fish oil from Menhaden were obtained from Shanghai Macklin Biochemical Technology Co., Ltd. (Shanghai, China). Surimi from silver carp (*Hypophthalmichthys molitrix*) was obtained from Honghu Jingli Aquatic Food Co. (Hubei, China). All reagents were analytical grade, and all solutions were prepared with ultrapure water.

2.2 Fabrication of Zein peptide nanoparticles and Zein nanoparticles

Zein nanoparticle (ZN) suspension with gradients of different

concentrations was obtained by using an anti-solvent method. Zeins were dispersed in 70% ethanol at a concentration of 1.0%, 2.0%, 4.0% and hydrated at 4 °C for 24 h. The Zein alcohol solution was dispersed into the corresponding volume of ultrapure water. Ethanol in the solution was removed by rotary evaporation (XD-3000 A, Xiande, Shanghai, China) under a vacuum to obtain ZNs. The volume of the solution was fixed to the original volume of the alcohol solution to ensure the same concentration.

ZPNs were prepared according to a method with minor modifications^[17]. Zein was dispersed in distilled water at a concentration of 60 mg/mL. Trypsin was added to the suspension at an enzyme and substrate ratio of 1:50 (w/w). The hydrolysis reaction was carried out at 37 °C and pH 8.0 for 3 h. The prepared samples were inactivated in a water bath at 100 °C for 5 min to stop the hydrolysis and then centrifuged at 3500 r/min for 10 min. The supernatant was dialyzed for desalting and lyophilized to obtain ZPNs.

2.3 Preparation of ZPNHIPEs and surimi gels

2.3.1 Preparation of ZPNHIPEs

ZPNHIPEs were prepared according to a previous method^[23]. ZPNs were prepared at different ZPN concentrations of 1%, 2% and 4% (w/v). ZPNs were mixed with FO at an oil-water ratio of 80:20 (v/v). ZPNHIPEs were prepared at 20,000 r/min for 2 min by a high-speed disperser (FSH-2A, Changzhou Yuexin, Changzhou, China) and sonicated for 4 min with 325 W (on 5 s and off 5 s).

2.3.2 Preparation of surimi gels

The surimi gels were prepared according to a method with slight modifications^[24]. Frozen surimi was thawed at 4 °C for 12 h. The minced fish was cut into $2 \times 2 \times 2$ cm pieces and minced for 5 min. After being defrosted in a 4 °C refrigerator for 12 h, surimi was cut into small cubes and then chopped at 3500 r/min for 3 min. Subsequently, NaCl (2.5%) was added and mixed with minced surimi at 4800 r/min for 2 min to dissolve myofibrillar proteins. For the experiment group, 1%, 3%, 5% and 7% of ZPNHIPEs were added and mixed with minced surimi at 4800 r/min for 2 min, respectively. The pastes were filled into the centrifuge tubes to remove air bubbles. The surimi gels were heated at 90 °C for 30 min and cooled to 25 °C with running water and stored in a refrigerator at 4 °C for 12 h for subsequent experiments.

2.4 Fourier transform infrared spectroscopy

FTIR was applied to analyze ZN and ZPNs according to a method with minor modifications^[25]. The spectra of solution samples were taken using a Fourier infrared spectroscopy instrument (Nicolet iS5, Thermo Fisher Scientific, Waltham, MA, USA). The scanning was performed 32 times in the wavenumber range of 500–4000 cm^{-1} with a resolution of 4 cm^{-1} . Images and data were analyzed using OMNIC 8.0 software and Origin software.

2.5 Turbidity, particle size, zeta potential and emulsifying stability of ZPNs

The absorbance of ZPN suspension with different concentrations and Zein nanoparticle suspensions was determined at 25 °C using a multi-mode microplate reader (Synergy HTX S1ALF, BioTek Fisher Scientific, Beijing, China) at 600 nm. The

absorbance was used to indicate trends in turbidity. The ZPN suspension was diluted 100 times before testing. The particle size and zeta potential of the samples were analyzed using a nanoparticle size analyzer (Nano ZS90, Malvern Panalytical, British) at 25 °C.

The bottom layer of ZPNHIEs of 100 μ L was added to 0.1% sodium dodecyl sulfate (SDS) solution of 10 mL. The 0.1% SDS solution was used as a blank. The absorbance was measured at 500 nm (A_{500}). The emulsifying activity index (EAI) and emulsifying stability index (ESI) were determined and calculated according to Eqs. (1) and (2)^[26].

$$\text{Emulsifying activity index} = \frac{2.303 \times 2 \times A_0}{c \times (1 - \phi) \times L \times 10^5} \quad (1)$$

$$\text{Emulsion stability index (\%)} = \frac{A_{10}}{A_0} \times 100 \quad (2)$$

Where EAI, D_t , c , ϕ and L are the emulsified surface area per unit mass of ZPNs (m^2/g), dilution times, protein mass concentration in the sample lysate (g/mL), oil phase fraction, and optical path (1 cm), respectively. A_0 and A_{10} are the EAI values of emulsions after 0 and 10 min, respectively.

2.6 Rheological properties of ZPNHIEs

Rheological properties of emulsions were analyzed using a rheometer (MCR 102E, Anton Paar, Graz, Austria) according to a protocol with slight modifications^[27]. The linear viscoelastic region (LVR) of the sample was obtained by an amplitude scan test at shear strains of 0.01%–10% with a frequency of 1 Hz. Frequency scan tests (0.1–100 rad/s , shear strain within the LVR, 1%) and shear rate scan tests (1–100 s^{-1} , frequency = 1 Hz) were performed for the viscoelastic parameter (storage modulus G' and loss modulus G'') and apparent viscosity measurements, respectively. All measurements were carried out using a 50 mm diameter parallel plate geometry with a gap height of 0.5 mm at room temperature (25 °C).

2.7 Size, zeta potential, microscopic observation and storage stability of ZPNHIEs

The size and zeta potential of ZPNHIEs were determined using a Malvern Zetasizer. Samples were diluted 100 times with deionized water. All tests were carried out at 25 °C. Each sample measurement was repeated three times, and the results were expressed as mean values. The morphology of emulsions was observed under electron microscopy (Panthera U, Motic, Xiamen, China) at 40 $\times$ and 100 $\times$ magnification.

Creaming index (CI) was used to characterize the storage stability of ZPNHIEs by using an approach with some modifications^[28]. ZPNHIEs were stored in flat-bottomed sample bottles, and the total height of the emulsion and the height of the whey layer were measured at regular intervals. CI was calculated using Eq. (3).

$$CI = \frac{H_s}{H_t} \quad (3)$$

Where H_s and H_t are the height of the whey layer measured after a certain time of storage and the total height of the emulsion, respectively.

2.8 Rheological properties of surimi gels

The rheological properties of surimi gels were determined

according to a method with slight modifications^[29], utilizing a rheometer (MCR102E, Anton Paar, Graz, Austria) with a parallel plate (50 mm) and a 1 mm height gap. Three tests were conducted strain sweep, temperature sweep and creep recovery sweep. In the strain sweep test, the linear viscoelastic region (LVE) of samples at 1 Hz was identified by measuring the trends of viscoelastic modulus (G' and G'') with strain in the interval of 0.01%–100% at 25 °C. In the temperature scanning test, the surimi samples were heated at a rate of 5 °C/min from 10 °C to 100 °C. Surimi samples were sealed with dimethyl silicone oil during the heating procedure to prevent water evaporation. The temperature dependency of G' and G'' as well as loss factor ($\tan \delta = G''/G'$) was monitored at a strain of 1% and a frequency of 1 Hz. For the creep recovery sweep, it was performed at 25 °C; the gel samples were subjected to a 100 Pa shear stress (within LVE) for 100 s. The responses of the samples were recorded for 100 s. The creep rate was the inclination of the final stage of the creep curve, and recovery percentage R (%) was calculated using Eq. (4).

$$R(\%) = \frac{(\gamma_T - \gamma_P)}{\gamma_T} \times 100 \quad (4)$$

Where γ_T and γ_P are maximum strain and recovery strain, respectively.

2.9 Texture profile analysis of surimi gels

The TPA of surimi gel samples was evaluated following a protocol using a texture analyzer (Universal TA, Tengba, Shanghai, China) equipped with a 1000 N load cell and a 40 mm panel. In TPA mode, each sample was double-compressed at a speed of 1 mm/s with a trigger force of 0.5 N. Four replicate measurements were performed for each sample to record TPA parameters, including hardness, viscosity, elasticity, cohesiveness, resilience and chewiness.

2.10 Whiteness of surimi gels

The whiteness of surimi gels was measured^[30]. Surimi gels were cut into uniform 2–3 mm slices before testing. The values of lightness (L^*), redness/greenness (a^*), and yellowness/blueness (b^*) were determined using a colorimeter (3NH, Shenzhen, China) at 25 °C. The whiteness of surimi gels was calculated using Eq. (5).

$$\text{Whiteness} = 100 - [(100 - L^*)^2 + a^{*2} + b^{*2}]^{\frac{1}{2}} \quad (5)$$

2.11 Data analysis

All experiments were divided into three parallel groups, and the results were expressed as mean $\pm$ standard deviation (SD). The significant difference was analyzed by Origin 9.0 ($P < 0.05$).

3 Results and Discussion

3.1 Characteristics of Zein peptide nanoparticles

3.1.1 Turbidity

The turbidity of ZPNs and ZNs at different concentrations is presented in Fig. 1A. The turbidity of ZPNs and Zein nanoparticles tended to increase significantly ($P < 0.05$) with increasing concentrations. The turbidity of ZNs was significantly higher than that of ZPNs at the same concentration ($P < 0.05$).

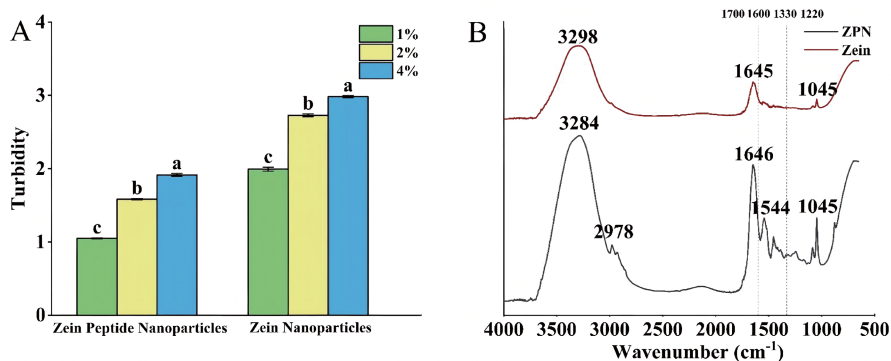


Figure 1 Turbidity (A) and FTIR (B) of Zein peptide nanoparticles (ZPNs) at different concentrations.

Turbidity can be considered a complex process influenced by color, refractive index, particle size, and particle interactions, especially aggregation. The turbidity of macromolecules increases with increasing peptide aggregation^[31]. When the protein solubility increases, the particle size of proteins becomes small, resulting in a decrease in turbidity^[32]. The preparation of ZPNs involves the hydrolysis of proteins, which generates peptides with different molecular weights, and these peptides may form different structures and particle size distributions when self-assembled into nanoparticles, thus affecting the turbidity. In addition, the amino acid sequence and hydrophobicity of the peptides may also affect their assembly behavior and final turbidity.

3.1.2 Fourier transform infrared spectroscopy

FTIR is usually used to analyze the structural information of samples^[17]. The FTIR spectra of ZNs and ZPNs are shown in Fig. 1B. Typical peaks in the range of 3100 to 3400 cm⁻¹ are considered to be hydrogen bonds^[33]. The peak of ZNs corresponding to the hydrogen bond was at 3298 cm⁻¹. The hydrogen bond peaks of ZPNs moved to 3284 cm⁻¹. Meanwhile, the peak intensity of ZPNs increased, indicating the formation of hydrogen bonds after the enzymolysis of ZNs. Hydrogen bonding facilitates the stability of macromolecular structures^[34]. In addition, there were broad absorption peaks of ZPNs at the wavenumbers from 3700 to 3200 cm⁻¹, indicating that enzymatic hydrolysis led to an increase in the number of hydroxyl groups of the protein to cause vibrational absorption. The vibration of ZPNs at 1044 cm⁻¹ with high peaks indicated the increase in the number of C-N after enzymatic hydrolysis.

FTIR spectroscopy can also reflect changes in peptide chain structure that affect the conformational stability of protein molecules^[35]. Compared to ZNs, ZPNs had slight fluctuations and multiple peaks in the range of 2800 to 3000 cm⁻¹, which might be

caused by the -CH₃ group in different modes of stretching vibration^[17]. The amide I band (1600-1700 cm⁻¹) and the amide II band (1500-1600 cm⁻¹) are both essential vibration modes of amide, and the main feature of the protein secondary structure can be estimated in the amide I band^[24]. The bands at 1700 to 1660 cm⁻¹ represent the β-turns, the bands at 1660 to 1650 cm⁻¹ indicate the α-helix, the bands at 1650 to 1640 cm⁻¹ correspond to the random structures, and those at 1640 to 1600 cm⁻¹ indicate the β-sheets^[36]. ZNs had an infrared absorption peak at 1644 cm⁻¹ (Fig. 1B). The absorption peak of ZPNs moved to a high wavenumber of 1646 cm⁻¹ and the vibration intensity became strong in corresponding to the stretching vibration of C=O. The amide III band (1220-1330 cm⁻¹) can distinguish between the α-helix and random coil structures in the protein secondary structure, but its spectral intensity is much weaker than that of the amide I band^[37]. Besides, the appearance of infrared absorption in the amide II band of ZPs at 1543 cm⁻¹ was related to the bending vibration of N-H and the stretching vibration of C-N, indicating the deformation of the N-H bond and the stretching of the C-N bond after enzymatic hydrolysis^[38]. All the above results confirmed that Zein underwent enzymatic hydrolysis to form ZPNs.

3.1.3 Particle size and zeta potential

The size, PDI and zeta potential of Zein nanoparticles and ZPNs are shown in Tables 1 and 2. Zein nanoparticles and their derived peptide nanoparticles had the size of 192.70 ± 3.76 nm and 2854.00 ± 167.20 nm, respectively. Zein with cationic charge had the opposite charge compared to ZPNs. This is consistent with the results of ZPNs obtained after enzymatic hydrolysis by alcalase with the negative charge^[39]. ZNs had an average cationic charge with a smaller PDI than that of ZPNs. In addition, the zeta potential of ZPNs was much low, attributing to the fact that the ZPNs were not well dispersed.

Table 1 Size and zeta potential of 2% Zein and ZP.

Samples	Z-Average diameter (nm)	Polydispersity index (PDI)	Zeta potential (mV)
Zein	192.70 ± 3.76 ^b	0.14 ± 0.04 ^b	35.50 ± 0.67 ^a
ZP	2854.00 ± 167.20 ^a	0.41 ± 0.09 ^a	-8.77 ± 0.48 ^b

*Data represent the mean value ± standard deviation (n = 3).

Table 2 Size and zeta potential of ZPNHIEPs prepared at different ZPN concentrations

Samples	Z-Average diameter (nm)	Polydispersity index (PDI)	Zeta potential (mV)
1%	5380.00 ± 1389.00 ^a	0.34 ± 0.20 ^a	-23.70 ± 1.89 ^b
2%	5350.50 ± 1163.50 ^a	0.18 ± 0.11 ^b	-20.50 ± 1.26 ^a
4%	4767.00 ± 696.70 ^a	0.09 ± 0.09 ^b	-21.20 ± 1.25 ^{ab}

*Upper letters in the same column indicate a significant difference between them ($P < 0.05$).

3.2 Characteristics of ZPNHIEs

3.2.1 Particle size and zeta potential

The size and zeta potential of ZPNHIEs are shown in Table 2. The size and PDI of ZPNHIEs decreased gradually with the increase in ZPN concentrations. On the contrary, the zeta potential of ZPNHIEs gradually increased, the zeta potential at a ZPN concentration of 1% with -23.7 ± 1.89 mV changed to -20.5 ± 1.26 mV and -21.2 ± 1.25 mV at ZPN concentrations of 2% and 4%, respectively. The rise in zeta potential of HIEs is associated with a decrease in surface charge, which minimizes the electrostatic force and leads to the aggregation of particles in the HIEs^[27]. Therefore, these results indicated that ZPNHIEs became stable after the addition of ZPNs as a stabilizer due to the aggregation of peptides.

3.2.2 Emulsion stability

Emulsifying activity and emulsion stability are the main functional properties of HIEs. Fig. 2A shows the emulsifying activity and emulsification stability of HIEs stabilized by different ZPN concentrations. The emulsification activity of ZPNHIEs decreased significantly ($P < 0.05$) with the increase in ZPN concentrations, while the emulsification stability first decreased significantly ($P < 0.05$) and then increased. The emulsification stability of proteins is related to particle size, and the smaller the

particle size, the better the emulsification stability of proteins^[40]. However, the emulsion stability of the 4% group was lower than that of the 1% group, probably because peptides were not fully dispersed and aggregated. A biopolymer can act as a bridge between oil droplets and destabilize the emulsion when the molecular weight of the biopolymer exceeds a certain value^[41]. Besides, *CI* is often used as a parameter to assess the stability of emulsions. The NC group was not counted because demulsification was found in the NC group after 20 min of placement. The *CI* of the other three groups of samples is shown in Fig. 2B. The *CI* values of ZPNHIEs at different ZP concentrations stabilized after 7 days.

3.2.3 Rheological properties

The amplitude sweep, frequency sweep test and shear rate scan test of ZPNHIEs are shown in Fig. 3. Firstly, the linear viscoelastic region (LVER) was established by amplitude sweep, then the frequency sweep was conducted within this region (Fig. 3A). The viscous modulus (G'') of the emulsions is much higher than the elastic modulus (G'), indicating that ZPNHIEs were characteristic of viscous-dominated structures^[42]. For the shear rate scan test, at a low shear rate of 10 s^{-1} , the apparent viscosity of the ZPNHIEs decreased sharply with increasing shear rate. This indicated that ZPNHIEs exhibited near-Newtonian fluid-like rheological properties (Fig. 3B). The

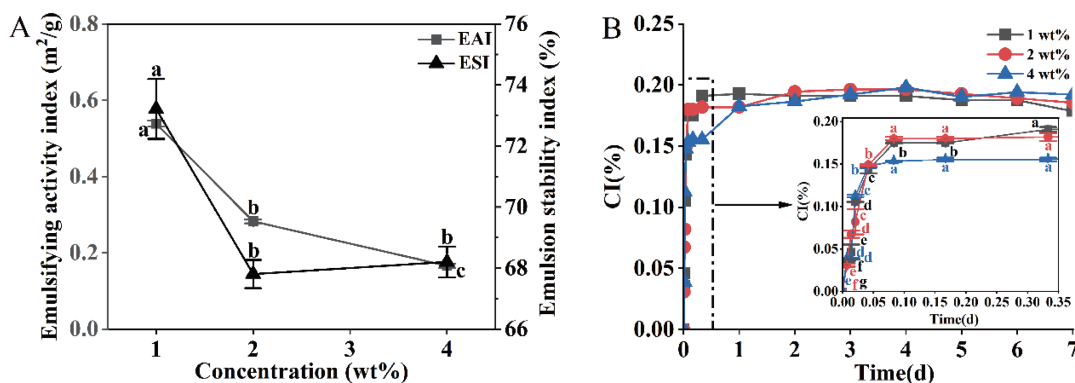


Figure 2 Emulsifying activity and stability (A) and *CI* (B) of ZPNHIEs at different ZPN concentrations.

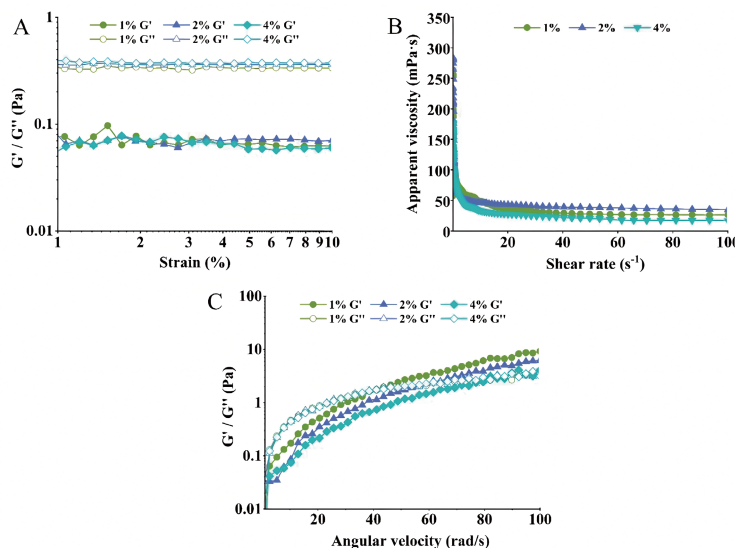


Figure 3 Viscoelastic modulus (G' and G'') during strain sweep (A), apparent viscosity during shear rate scan test (B) and viscoelastic modulus (G' and G'') during frequency sweep curves of HIEs with different addition of ZPNs (C).

apparent viscosity of ZPNHIPEs decreased with the shear rate from 0.1 to 100 s^{-1} and finally reached a stable plateau (Fig. 3B), which could be attributed to the deformation and destruction of the network structure formed by the oil droplets and the stabilizer^[43]. ZPNHIPEs showed shear-thinning behavior, which is a common phenomenon in fluids, due to the reversible shear-induced break-up of flocculated oil droplets, and the deflocculation behavior of oil droplets in nano-emulsions was mainly reflected by the shear-thinning behavior^[44]. With increasing shear rate, the apparent viscosity of ZPNHIPEs became small under this condition. ZPNHIPEs were considered as pseudoplastic fluids. Besides, the apparent viscosities of HIPEs stabilized by ZPNs at 1%, 2%, and 4% were similar.

In the frequency scan of 0.1-100 rad/s, the G' and G'' values kept increasing with the frequency, and the ZPNHIPEs at different ZPN concentrations were similar. When the ZPN concentrations decreased, the G' and G'' values of ZPNHIPEs increased, forming a stable emulsion structure^[42]. This may be attributed to the increase in ZPN concentrations leading to the formation of peptide aggregates. In addition, G'' was always higher than G' before 50 rad/s, while the latter intersection of G' before G''

occurred in the ZPNHIPEs at ZPN concentrations of 1% and 2% compared to that at 4%, indicating that the emulsion changed from solution-like to gel-like.

3.2.4 Microstructure of ZPNHIPEs

Fig. 4 shows the microstructure of ZPNHIPEs. There were few differences in the sizes of the ZPNHIPEs stabilized by different ZPN concentrations. The size of ZPNHIPEs was not uniform enough, and many solid particles aggregated at the oil-water interface of the ZPNHIPEs, which led to an increase in the thickness of the oil-water interface. This indicated that ZPNHIPEs were likely to aggregate with each other. The ZPNHIPEs at a ZPN concentration of 1% showed better properties within the three groups. Therefore, ZPNs at a concentration of 1% were chosen to stabilize HIPEs for the subsequent preparation of surimi gels.

3.3 Properties of surimi gels

3.3.1 Texture properties

Texture properties play a vital role in evaluating surimi products, as they reflect the structural characteristics of the surimi

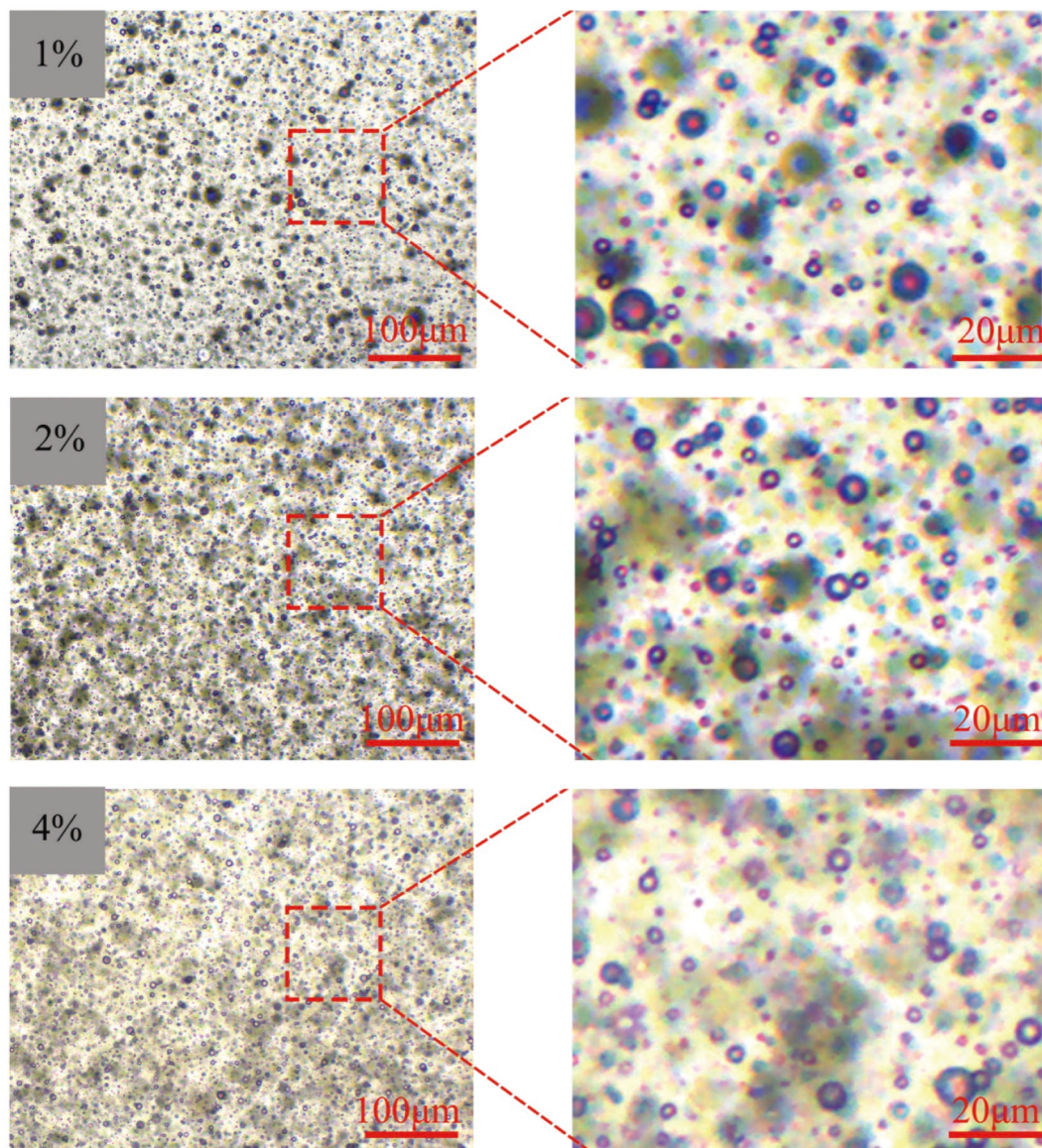


Figure 4 Microscopic observation of ZPNHIPEs prepared with ZPNs at 1%, 2% and 4%.

gels and influence consumer preference and acceptability^[45]. The hardness, viscosity, elasticity, cohesiveness, resilience, and chewiness of surimi gels are shown in Table 3. The hardness of surimi gels decreased with the addition of ZPNHIEs, especially those at a ZPN concentration of 5% higher than those at 3% and 7%. The apparent viscosity of surimi gels with the addition of ZPNHIEs at 1%, 3% and 7% had no difference while ZPNHIEs at 5% were significantly lower ($P < 0.05$) compared with the others. The elasticity, cohesiveness and resilience of surimi gels significantly increased after adding ZPNHIEs ($P < 0.05$). Besides, the chewiness of surimi gels added with ZPNHIEs showed a discontinuous trend between samples. ZPNHIEs could fill the cavity in the surimi gels, leading to the formation of a compact structure and an increase in the elasticity of the surimi gels^[46]. Xu *et al.*^[15] have reported that the addition of emulsion would improve surimi gel texture properties. The ZPN interaction in the gel matrix was also beneficial for improving the surimi gel texture. The surimi gels with the ZPNHIE addition of 5% exhibited better hardness, viscosity, elasticity, cohesiveness, resilience, and chewiness.

3.3.2 Rheological properties

The LVER of surimi gels can be determined using the strain sweep test, which refers to the small deformation region where the

viscoelastic modulus (G' and G'') remains constant despite changes in strain^[11]. The surimi gels with the ZPNHIE addition showed a stable G' and G'' in the strain range from 0.1% to 2.0% (Fig. 5A). Based on these results, a strain of 1% was chosen for the following rheological experiments. Furthermore, the G'' of the surimi gels was much lower than the G' of samples in the strain range from 0.01 to 100%, indicating that the surimi gels had an elastic-dominant structural feature.

The formation of gel networks during the transition from paste to gel of surimi samples can be observed by temperature scanning^[47]. Figs. 5B and C show the trend of G' , G'' and $\tan \delta$ of surimi gels with the change in temperature for surimi gels with different additions of ZPNHIEs. During heating from 10 °C to 100 °C, the G' and G'' of surimi gels showed similar trends for surimi samples with different emulsion concentrations. During the initial heating phase, the G' of surimi gels decreased slowly with increasing temperatures, reaching a minimum peak at around 50 °C. The decrease in G' of samples may be related to breaking hydrogen bonds and dissociating protein aggregates^[48]. Therefore, the dissociation of the peptide aggregates might occur during the heat process if ZPNs were poorly dispersed in the ZPNHIEs induced by peptide aggregation. When surimi gels were heated, the G' of surimi gels increased reaching another peak at about 70 °C to form a stable gel structure. G' and G'' are closely

Table 3 TPA of surimi gels after the addition of ZPNHIEs at different contents

Samples	Hardness (gf)	Viscosity	Elasticity	Cohesiveness	Resilience	Chewiness (gf)
1%	1426.91 ± 43.69 ^{ab}	-12.90 ± 1.49 ^a	0.80 ± 0.02 ^b	0.47 ± 0.03 ^b	0.15 ± 0.01 ^b	533.75 ± 24.04 ^b
3%	1238.54 ± 192.41 ^{bc}	-12.03 ± 1.20 ^a	0.73 ± 0.05 ^b	0.44 ± 0.04 ^b	0.16 ± 0.02 ^b	402.20 ± 56.81 ^c
5%	1411.90 ± 102.77 ^a	-20.42 ± 2.28 ^b	0.85 ± 0.01 ^a	0.63 ± 0.03 ^a	0.22 ± 0.01 ^a	824.99 ± 31.32 ^a
7%	1145.19 ± 65.39 ^c	-15.75 ± 3.82 ^a	0.81 ± 0.03 ^a	0.58 ± 0.03 ^a	0.20 ± 0.01 ^a	542.45 ± 55.21 ^b

*Upper letters in the same column indicate a significant difference between them ($P < 0.05$).

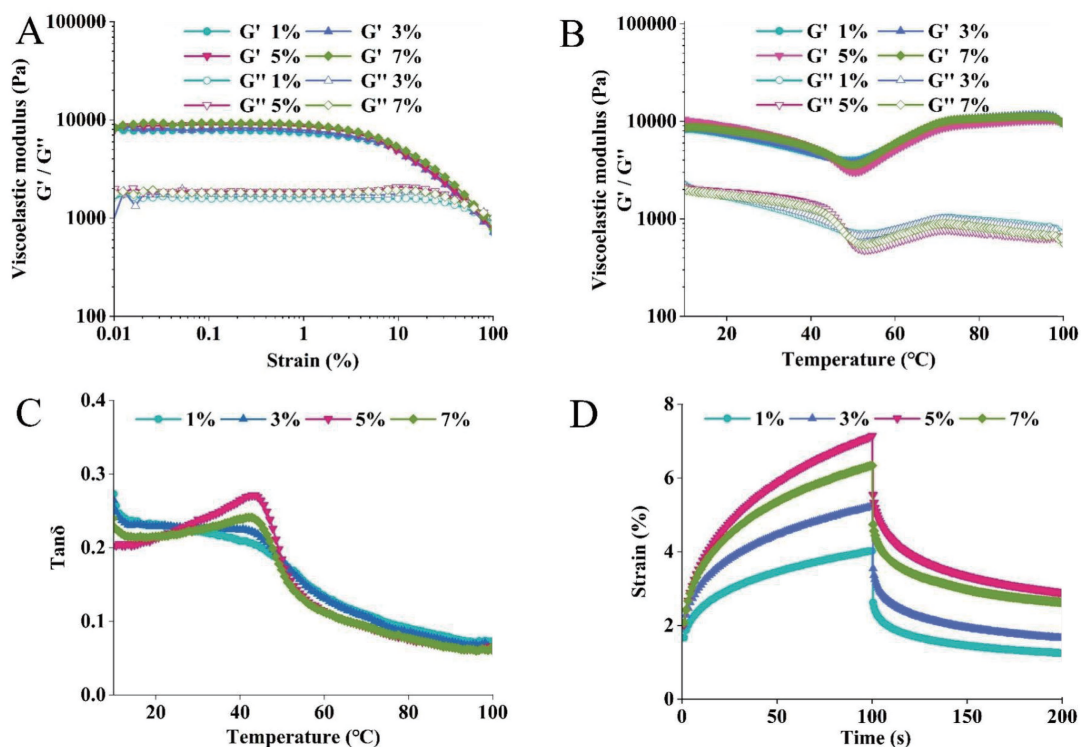


Figure 5 Viscoelastic modulus (G' and G'') during strain sweep (A) and temperature sweep (B), loss factor ($\tan \delta$) during temperature sweep (C) and (D) creep recovery curves of surimi gels added with ZPNHIEs.

related to the elasticity and viscosity of the surimi gels^[49].

Tan δ as the ratio of G' and G'' can reflect the viscoelastic behavior of the surimi gels^[50]. As shown in Fig. 5C, other samples containing ZPNHIEs showed a significant peak at around 40 °C except for those at 1%. This may be related to the depolymerization of peptides. The sharp decrease in tan δ in the temperature range of 40–60 °C implied that this temperature range was crucial for forming a strong gel network as previously reported^[14]. Tan δ decreased as the temperature increased, indicating the formation of a strong gel network and elastic behavior. Tan δ showed a downward and then upward trend before 30 °C (Fig. 5C). At 30–50 °C, the tan δ of surimi gels with the addition of ZPNHIEs at 5% was always highest followed by those at 7%, 3% and 1%. After 50 °C, tan δ returned to the initial trend. These results proved that the increase in ZPNHIE addition was beneficial to forming a strong gel structure and elastic behavior.

Creep tests are temporary experiments performed under continuous stress to determine the cross-linking properties of a gel on a long time scale^[29]. Creep recovery refers to a slow recovery of deformation over time after removing a load to assess a material's resistance to deformation and elasticity^[46]. Fig. 5D shows the creep recovery curves when the surimi gel was mixed with different ZPNHIE additions. The surimi gels with the ZPNHIE addition at 1% possessed the smallest γ_T followed by those at 3%, 7% and 5%. The surimi gels with the addition of emulsions possess creep resistance and deformation recovery ability^[46]. Table 4 summarizes the creep rate and recovery percentage of surimi gels with different ZPNHIE additions. The creep rate increased while the recovery rate decreased with the addition of ZPNHIEs. Surimi gels containing emulsions would have low creep rates and high recovery percentages compared to blank controls, confirming the formation of a protein network with a high degree of cross-linking, thus exhibiting better immediate deformation recovery.

Table 4 Effects of the addition of ZPNHIEs on the creep rate and recovery rate of surimi gels

Samples	Creep rate (s ⁻¹)	Recovery rate (%)
1% ZPNHIEs	0.01	68.90
3% ZPNHIEs	0.01	68.39
5% ZPNHIEs	0.02	59.38
7% ZPNHIEs	0.02	58.52

*Due to the large error in the data resulting from the machine's vacuum problem, only the data with a high degree of overlap were selected.

3.3.3 Whiteness

Color is one of the relevant qualities of surimi products that directly affect consumer acceptance^[51]. The effect of ZPNHIEs on surimi gels can be studied by calculating the whiteness after measuring L^* , a^* , and b^* with a colorimeter. Fig. 6 shows the changes in the whiteness of the surimi gels after the ZPNHIE addition. The whiteness of the surimi gels increased with the increase in the ZPNHIE addition from 1% to 7%. The whiteness of the surimi gels with the ZPNHIE addition at 7% was significantly higher than the others ($P < 0.05$). It has been demonstrated that the increase in whiteness is related to the inherent color and luster of ZPNs, which could be filled into the internal structure to increase the whiteness of the surimi gels^[46]. The higher the concentration of added ZPNHIE, the more ZPNHIEs were filled into the internal structure of surimi, resulting in an increase in the whiteness of surimi with the

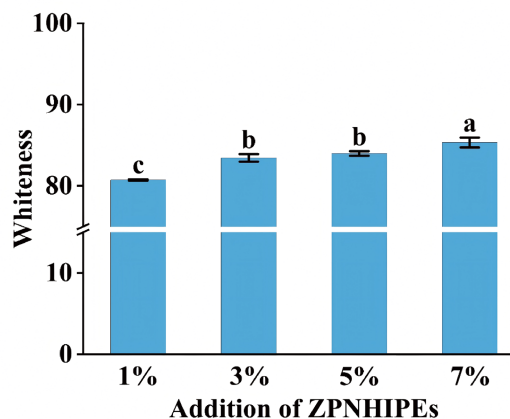


Figure 6 Whiteness of surimi gels with the different addition of ZPNHIEs.

increase in the concentration of added ZPNHIE.

4 Conclusion

ZPNs were fabricated as stabilizers to prepare HIEs. The turbidity of ZPNs increased with increasing concentrations. Subsequently, a HIE containing 80% oil phase stabilized by ZPNs was prepared, and its properties were determined, and it was found that ZPN did have a stabilizing effect on the emulsion. ZPNHIEs were stable at the ZPN concentrations of 1%, 2%, and 4%, showing demulsification at the ZPN concentration of 4% after 7 days. The properties of surimi gels improved with increasing ZPNHIE additions, attributed to the stable network structure of ZPNs and the high oil phase in the ZPNHIEs, especially the ZPNHIE addition at 5%. Novel insights could be provided for researching the role of ZPNs in stabilizing HIEs and broadening the potential application of ZPNHIEs prepared with fish oil in improving the quality of surimi gels.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript. Additional data related to this paper may be requested from the corresponding author upon request.

Conflicts of interest

The authors declare that there are no conflicts of interest in this work.

Acknowledgments

The authors thank the support received from the National University of Singapore (Suzhou) Research Institute.

Funding

This study was funded by the National Natural Science Foundation of China (Nos. 32272266, 32302141), Fund of Engineering Research Center of the Modern Technology for Eel Industry, Ministry of Education, P. R. China (No. RE202409), Natural Science Foundation of Fujian Province in China (No. 2021J01835), Seed Industry Innovation and Industrialization Project of Fujian Province (No. 2021FJSCZY01), Xiamen Science and Technology Plan Project (No. 3502Z20226018) and Key

Research and Development Project of Hainan Province (No. ZDYF2024XDNY204).

Author contribution statement

Jia-Hui Song: Conceptualization and Writing original draft. Shuang He: Project administration and Writing-original draft. Qi-Biao Zhang: Formal analysis and Project administration. Wu-Yin Weng: Investigation and Validation. Lin-Fan Shi, Yue Yu, Wei Yang: Formal analysis and Investigation. Zhan-Ming Li and Zhong-Yang Ren: Funding acquisition and Review & editing.

Informed consent

Not applicable.

Ethics statement

Not applicable.

Use of AI statement

The authors take full responsibility for the content of the publication and confirm that no AI-generated data or figures were included.

References

- [1] Kong, W., Zhang, T., Feng, D., et al. Effects of modified starches on the gel properties of Alaska Pollock surimi subjected to different temperature treatments. *Food Hydrocolloids*, **2016**, 56: 20–28. <https://doi.org/10.1016/j.foodhyd.2015.11.023>
- [2] Mi, H., Su, Q., Chen, J., et al. Starch-fatty acid complexes improve the gel properties and enhance the fatty acid content of *Nemipterus virgatus* surimi under high-temperature treatment. *Food Chemistry*, **2021**, 362: 130253. <https://doi.org/10.1016/j.foodchem.2021.130253>
- [3] Nourbehesht, N., Shekarchizadeh, H., Soltanizadeh, N. Investigation of stability, consistency, and oil oxidation of emulsion filled gel prepared by inulin and rice bran oil using ultrasonic radiation. *Ultrasonics Sonochemistry*, **2018**, 42: 585–593. <https://doi.org/10.1016/j.ultsonch.2017.12.029>
- [4] Choi, Y., Choi, J., Han, D., et al. Optimization of replacing pork back fat with grape seed oil and rice bran fiber for reduced-fat meat emulsion systems. *Meat Science*, **2010**, 84: 212–218. <https://doi.org/10.1016/j.meatsci.2009.08.048>
- [5] Björle, M., Yesiltas, B., García-Moreno, P. J., et al. Bioinformatically predicted emulsifying peptides and potato protein hydrolysate improves the oxidative stability of microencapsulated fish oil. *Food Chemistry Advances*, **2023**, 3: 100441. <https://doi.org/10.1016/j.focha.2023.100441>
- [6] Colussi, G., Catena, C., Novello, M., et al. Impact of omega-3 polyunsaturated fatty acids on vascular function and blood pressure: relevance for cardiovascular outcomes. *Nutrition Metabolism and Cardiovascular Diseases*, **2017**, 27: 191–200. <https://doi.org/10.1016/j.numecd.2016.07.011>
- [7] Salminen, H., Herrmann, K., Weiss, J. Oil-in-water emulsions as a delivery system for n-3 fatty acids in meat products. *Meat Science*, **2013**, 93: 659–667. <https://doi.org/10.1016/j.meatsci.2012.11.035>
- [8] Yan, B., Jiao, X., Zhu, H., et al. Chemical interactions involved in microwave heat-induced surimi gel fortified with fish oil and its formation mechanism. *Food Hydrocolloids*, **2020**, 105: 105779. <https://doi.org/10.1016/j.foodhyd.2020.105779>
- [9] Zhou, X., Jiang, S., Zhao, D., et al. Changes in physicochemical properties and protein structure of surimi enhanced with camellia tea oil. *LWT-Food Science and Technology*, **2017**, 84: 562–571. <https://doi.org/10.1016/j.lwt.2017.03.026>
- [10] Mi, H., Zhao, B., Wang, C., et al. Effect of 6-gingerol on physicochemical properties of grass carp (*Ctenopharyngodon idellus*) surimi fortified with perilla oil during refrigerated storage. *Journal of the Science of Food and Agriculture*, **2017**, 97: 4807–4814. <https://doi.org/10.1002/jsfa.8350>
- [11] Zhang, R., Zhang, T., Hu, M., et al. Effects of oleogels prepared with fish oil and beeswax on the gelation behaviors of protein recovered from Alaska Pollock. *LWT-Food Science and Technology*, **2021**, 137: 110423. <https://doi.org/10.1016/j.lwt.2020.110423>
- [12] Jamshidi, A., Cao, H., Xiao, J., et al. Advantages of techniques to fortify food products with the benefits of fish oil. *Food Research International*, **2020**, 137: 109353. <https://doi.org/10.1016/j.foodres.2020.109353>
- [13] Gao, H., Ma, L., Cheng, C., et al. Review of recent advances in the preparation, properties, and applications of high internal phase emulsions. *Trends in Food Science & Technology*, **2021**, 112: 36–49. <https://doi.org/10.1016/j.tifs.2021.03.041>
- [14] Gani, A., Benjakul, S. Impact of virgin coconut oil nanoemulsion on properties of croaker surimi gel. *Food Hydrocolloids*, **2018**, 82: 34–44. <https://doi.org/10.1016/j.foodhyd.2018.03.037>
- [15] Xu, Y., Lv, Y., Zhao, H., et al. Diacylglycerol pre-emulsion prepared through ultrasound improves the gel properties of golden thread surimi. *Ultrasonics Sonochemistry*, **2022**, 82: 105915. <https://doi.org/10.1016/j.ultsonch.2022.105915>
- [16] Ren, Z., Li, Z., Chen, Z., et al. Characteristics and application of fish oil-in-water pickering emulsions structured with tea water-insoluble proteins/κ-carrageenan complexes. *Food Hydrocolloids*, **2021**, 114: 106562. <https://doi.org/10.1016/j.foodhyd.2020.106562>
- [17] Liu, M., Wang, F., Pu, C., et al. Nanoencapsulation of lutein within lipid-based delivery systems: Characterization and comparison of zein peptide stabilized nano-emulsion, solid lipid nanoparticle, and nano-structured lipid carrier. *Food Chemistry*, **2021**, 358: 129840. <https://doi.org/10.1016/j.foodchem.2021.129840>
- [18] Wang, L., Ding, L., Wang, Y., et al. Isolation and characterisation of *in vitro* and cellular free radical scavenging peptides from corn peptide fractions. *Molecules*, **2015**, 20: 3221–3237. <https://doi.org/10.3390/molecules20023221>
- [19] Shen, Y., Hu, R., Li, Y. Antioxidant and emulsifying activities of corn gluten meal hydrolysates in oil-in-water emulsions. *Journal of the American Oil Chemists Society*, **2020**, 97: 175–185. <https://doi.org/10.1002/aocs.12286>
- [20] Kasaai, M. R. Zein and zein based nano-materials for food and nutrition applications: a review. *Trends in Food Science & Technology*, **2018**, 79: 184–197. <https://doi.org/10.1016/j.tifs.2018.07.015>
- [21] Zhou, L., Xu, G., Zhang, Z., et al. Surface activity and safety of deamidated zein peptides. *Colloids and Surfaces A-Physicochemical and Engineering Aspects*, **2018**, 540: 150–157. <https://doi.org/10.1016/j.colsurfa.2017.12.070>
- [22] Yin, B., Wang, C., Liu, Z., et al. Peptide-polysaccharide conjugates with adjustable hydrophilicity/hydrophobicity as green and pH sensitive emulsifiers. *Food Hydrocolloids*, **2017**, 63: 120–129. <https://doi.org/10.1016/j.foodhyd.2016.08.028>
- [23] Ren, Z., Chen, Z., Zhang, Y., et al. Effect of heat-treated tea water-insoluble protein nanoparticles on the characteristics of Pickering emulsions. *LWT-Food Science and Technology*, **2021**, 149: 111999. <https://doi.org/10.1016/j.lwt.2021.111999>
- [24] Lin, M., Cui, Y., Shi, L., et al. Characteristics of hairtail surimi gels treated with myofibrillar protein-stabilized Pickering emulsions. *Journal of the Science of Food and Agriculture*, **2024**, 104: 4251–4259. <https://doi.org/10.1002/jsfa.13308>
- [25] Sow, L. C., Toh, N. Z. Y., Wong, C. W., et al. Combination of sodium alginate with tilapia fish gelatin for improved texture properties and nanostructure modification. *Food Hydrocolloids*, **2019**, 94: 459–467. <https://doi.org/10.1016/j.foodhyd.2019.03.041>
- [26] Huang, X., Cui, Y., Shi, L., et al. Structural properties and emulsification of myofibrillar proteins from hairtail (*Trichiurus haumela*) at different salt ions. *International Journal of Biological Macromolecules*, **2023**, 253: 127598. <https://doi.org/10.1016/j.ijb.2023.127598>

- ijbiomac.2023.127598
- [27] Jia, Y., Kong, L., Zhang, B., et al. Fabrication and characterization of Pickering high internal phase emulsions stabilized by debranched starch-capric acid complex nanoparticles. *International Journal of Biological Macromolecules*, **2022**, 207: 791–800. <https://doi.org/10.1016/j.ijbiomac.2022.03.142>
 - [28] Ge, S., Xiong, L., Li, M., et al. Characterizations of Pickering emulsions stabilized by starch nanoparticles: Influence of starch variety and particle size. *Food Chemistry*, **2017**, 234: 339–347. <https://doi.org/10.1016/j.foodchem.2017.04.150>
 - [29] Liu, X., Ji, L., Zhang, T., et al. Effects of pre-emulsification by three food-grade emulsifiers on the properties of emulsified surimi sausage. *Journal of Food Engineering*, **2019**, 247: 30–37. <https://doi.org/10.1016/j.jfoodeng.2018.11.018>
 - [30] Buamard, N., Benjakul, S. Improvement of gel properties of sardine (*Sardinella albella*) surimi using coconut husk extracts. *Food Hydrocolloids*, **2015**, 51: 146–155. <https://doi.org/10.1016/j.foodhyd.2015.05.011>
 - [31] Groleau, P. E., Morin, P., Gauthier, S. F., et al. Effect of physicochemical conditions on peptide-peptide interactions in a tryptic hydrolysate of β -lactoglobulin and identification of aggregating peptides. *Journal of Agricultural and Food Chemistry*, **2003**, 51: 4370–4375. <https://doi.org/10.1021/jf0259720>
 - [32] Li, Y., Zhang, X., Lu, F., et al. Effect of sodium bicarbonate and sodium chloride on aggregation and conformation of pork myofibrillar protein. *Food Chemistry*, **2021**, 350: 129233. <https://doi.org/10.1016/j.foodchem.2021.129233>
 - [33] Ghane-Motlagh, B., Javanbakht, T., Shoghi, F., et al. Physicochemical properties of peptide-coated microelectrode arrays and their in vitro effects on neuroblast cells. *Materials Science & Engineering C-Materials for Biological Applications*, **2016**, 68: 642–650. <https://doi.org/10.1016/j.msec.2016.06.045>
 - [34] Tareste, D., Pincet, F., Lebeau, L., et al. Hydrophobic forces and hydrogen bonds in the adhesion between retinoid-coated surfaces. *Langmuir*, **2007**, 23: 3225–3229. <https://doi.org/10.1021/la0629779>
 - [35] Zhou, Y., Yang, H. Effects of calcium ion on gel properties and gelation of tilapia (*Oreochromis niloticus*) protein isolates processed with pH shift method. *Food Chemistry*, **2019**, 277: 327–335. <https://doi.org/10.1016/j.foodchem.2018.10.110>
 - [36] Li, T., Wang, L., Sun, D., et al. Effect of enzymolysis-assisted electron beam irradiation on structural characteristics and antioxidant activity of rice protein. *Journal of Cereal Science*, **2019**, 89: 102789. <https://doi.org/10.1016/j.jcs.2019.102789>
 - [37] Cai, S. W., Singh, B. R. A distinct utility of the amide III infrared band for secondary structure estimation of aqueous protein solutions using partial least squares methods. *Biochemistry*, **2004**, 43: 2541–2549. <https://doi.org/10.1021/bi030149y>
 - [38] Zhao, L., Huang, S., Cai, X., et al. A specific peptide with calcium chelating capacity isolated from whey protein hydrolysate. *Journal of Functional Foods*, **2014**, 10: 46–53. <https://doi.org/10.1016/j.jff.2014.05.013>
 - [39] Jiao, Y., Zheng, X., Chang, Y., et al. Zein-derived peptides as nanocarriers to increase the water solubility and stability of lutein. *Food & Function*, **2018**, 9: 117–123. <https://doi.org/10.1039/c7fo01652b>
 - [40] Zou, X., Kang, Z., Li, Y., et al. Effect of sodium bicarbonate on solubility, conformation and emulsion properties of pale, soft and exudative meat myofibrillar proteins. *LWT-Food Science and Technology*, **2022**, 157: 113097. <https://doi.org/10.1016/j.lwt.2022.113097>
 - [41] Tang, C. H., Yang, X. Q., Chen, Z., et al. Physicochemical and structural characteristics of sodium caseinate biopolymers induced by microbial transglutaminase. *Journal of Food Biochemistry*, **2005**, 29: 402–421. <https://doi.org/10.1111/j.1745-4514.2005.00038.x>
 - [42] Wang, C., Li, X., Sang, S., et al. Preparation, characterization and in vitro digestive behaviors of emulsions synergistically stabilized by γ -cyclodextrin/sodium caseinate/alginate. *Food Research International*, **2022**, 160: 111634. <https://doi.org/10.1016/j.foodres.2022.111634>
 - [43] Qiu, C., Wang, C., Li, X., et al. Preparation of high internal phase Pickering emulsion gels stabilized by glycyrrhizic acid-zein composite nanoparticles: Gelation mechanism and 3D printing performance. *Food Hydrocolloids*, **2023**, 135: 108128. <https://doi.org/10.1016/j.foodhyd.2022.108128>
 - [44] Du Le, H., Loveday, S. M., Singh, H., et al. Pickering emulsions stabilised by hydrophobically modified cellulose nanocrystals: Responsiveness to pH and ionic strength. *Food Hydrocolloids*, **2020**, 99: 105344. <https://doi.org/10.1016/j.foodhyd.2019.105344>
 - [45] Yang, X., Li, A., Li, X., et al. An overview of classifications, properties of food polysaccharides and their links to applications in improving food textures. *Trends in Food Science & Technology*, **2020**, 102: 1–15. <https://doi.org/10.1016/j.tifs.2020.05.020>
 - [46] Yu, J., Song, L., Xiao, H., et al. Structuring emulsion gels with peanut protein isolate and fish oil and analyzing the mechanical and microstructural characteristics of surimi gel. *LWT-Food Science and Technology*, **2022**, 154: 112555. <https://doi.org/10.1016/j.lwt.2021.112555>
 - [47] Zhao, Y., Wang, P., Zou, Y., et al. Effect of pre-emulsification of plant lipid treated by pulsed ultrasound on the functional properties of chicken breast myofibrillar protein composite gel. *Food Research International*, **2014**, 58: 98–104. <https://doi.org/10.1016/j.foodres.2014.01.024>
 - [48] Shi, L., Wang, X., Chang, T., et al. Effects of vegetable oils on gel properties of surimi gels. *LWT-Food Science and Technology*, **2014**, 57: 586–593. <https://doi.org/10.1016/j.lwt.2014.02.003>
 - [49] Moreno, H. M., Dominguez-Timon, F., Diaz, M. T., et al. Evaluation of gels made with different commercial pea protein isolate: Rheological, structural and functional properties. *Food Hydrocolloids*, **2020**, 99: 105375. <https://doi.org/10.1016/j.foodhyd.2019.105375>
 - [50] Nunez-Flores, R., Cando, D., Borderias, A. J., et al. Importance of salt and temperature in myosin polymerization during surimi gelation. *Food Chemistry*, **2018**, 239: 1226–1234. <https://doi.org/10.1016/j.foodchem.2017.07.028>
 - [51] Camara, A. K. F. I., Okuro, P. K., Cunha, R. L. D., et al. Chia (*Salvia hispanica* L.) mucilage as a new fat substitute in emulsified meat products: Technological, physicochemical, and rheological characterization. *LWT-Food Science and Technology*, **2020**, 125: 109193. <https://doi.org/10.1016/j.lwt.2020.109193>