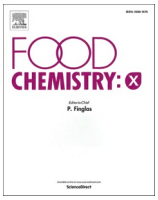
Food Chemistry: X 20 (2023) 100988

Contents lists available at ScienceDirect

Food Chemistry: X

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



Comparative effects of W/O and O/W emulsions on the physicochemical properties of silver carp surimi gels

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ARTICLE INFO

Keywords:
Silver carp surimi
Emulsion
Gel properties
Microstructure
Oil droplet size

ABSTRACT

The comparative effects of water-in-oil (W/O) and oil-in-water (O/W) emulsions on the physicochemical characteristics of silver carp surimi gels were investigated. The breaking force of surimi gels was 188.72 g, which decreased with increasing W/O emulsion but remained constant by adding O/W emulsion. The hardness decreased with increasing W/O emulsion, while the other parameters to TPA maintained constant whether the W/O or O/W emulsion was added. The yellowness value of surimi gels was 1.30, which increased with increasing W/O emulsion while remained constant after adding O/W emulsion. The water-holding capacity of surimi gels was invariant when emulsions increased. After emulsions added to surimi gels, no changes in the surimi protein interactions were found in electrophoretic patterns and Fourier transform infrared spectra. The increasing W/O emulsion enlarged the droplet size of oil and then destroyed the surimi gel network structure, while the oil droplets were evenly dispersed with increasing O/W emulsion.

1. Introduction

The surimi products made from rinsed fish mince have broad market for its nourishing nutrients and simple cooking process (Wu, Li, Li, Yang, Wang, & Zhou, 2022). However, given that the oil from fish meat is removed during the rinsing process, the flavor, taste, and nutrients of surimi-based products are reduced slightly (Choi et al., 2010). Therefore, it is necessary to add exogenous oils to improve the qualities of surimi products. A report indicated that the mouthfeel of fish balls could be improved by adding pork lard (Lin, Chen, & Chen, 2011). Meanwhile, the flavor of silver carp surimi gels could be modified by adding vegetable oils, including peanut oil (Shi, Wang, Chang, Wang, Yang, & Cui, 2014). The reason may be that peanut oil has strong nutty flavor (Dun et al., 2019), which is beneficial to improving the flavor of surimi products.

However, the directly added exogenous oils have adverse impact on the surimi gel structure and reduce the texture properties (Yu, Xiao, Song, Xue, & Xue, 2023). A previous study indicated that large pores and grooves appeared in the grass carp surimi gel network structure when perilla oil was added, which resulted in decreased gel strength (Mi, Zhao, Wang, Yi, Xu, & Li, 2017). After olive oil, peanut oil, or coconut oil was added, the golden threadfin surimi gels showed a loose and rough structure, leading to decreased gel strength and hardness (Song, Lin, Hong, Liu, & Zhou, 2022a). Therefore, some researchers have explored different strategies of adding exogenous oils to reduce the adverse impact, including structured oil, microencapsulated oil, and pre-emulsified oil, to surimi gels (Kang, Xie, Li, Song, & Ma, 2023).

Emulsion is a heterogeneous system formed by continuous and dispersed phase (Guo, Cui, & Meng, 2022). In the case of adding emulsion instead of oil, the oil droplets can be more evenly dispersed in the matrix of surimi products, and alleviated the disruption of protein interactions in the gelation process (Gani & Benjakul, 2018; Xu, Yu, Xue, & Xue, 2023). As previously reported, no obvious changes in the hardness of silver carp surimi gels were found by the addition of fish oil-based oil-in-water (O/W) Pickering emulsion prepared with myofibrillar protein (Zhang, Xie, Liang, Jiang, Zhang, & Shi, 2023). Therefore, the effect of emulsion on surimi gel qualities has attracted widespread interest. Generally, the water is the continuous phase in O/W emulsion, and the oil is the continuous phase in the water-in-oil (W/O) emulsion (Cheon, Haji, Baek, Wang, & Tam, 2023). The stability of W/O and O/W emulsions stabilized by surfactants is significantly lower than that of Pickering emulsion stabilized by solid particles (Ren et al., 2021). At present, the study on the qualities of surimi products prepared with emulsion is mainly focused on O/W emulsion, while surimi gels

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https://doi.org/10.1016/j.fochx.2023.100988
Received 11 August 2023; Received in revised form 14 October 2023; Accepted 6 November 2023
Available online 8 November 2023

prepared by adding W/O emulsion are rarely reported.

Silver carp is likely to replace marine fish to produce surimi in China. A previous study has been conducted to reform the qualities of silver carp surimi products by using emulsion in consideration of their poor gelation capacity (Mi, Li, Wang, Yi, Li, & Li, 2021). Therefore, the objective of this study was to determine the differences in physical properties, including texture, color, and water-holding capacity (WHC), of silver carp surimi gels with the addition of various content of W/O or O/W emulsion. Then, the impact characteristics and mechanism of emulsions on surimi gels were evaluated through confocal laser scanning microscopy (CLSM), scanning electron microscopy (SEM), sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS-PAGE), and attenuated total reflection (ATR)–Fourier transform infrared (FTIR) spectroscopy. This study can reveal the influence mechanism of W/O and O/W emulsions on the physical properties of silver carp surimi gels, providing a suggestion for the production of high-quality surimi products with emulsion.

2. Materials and methods

2.1. Materials and chemicals

Fresh silver carp (*Hypophthalmichthys molitrix*) and peanut oil were bought from local supermarket. Soy protein isolate (SPI) was obtained by Linyi Shansong Biological Products Co., Ltd. (Linyi, China). Sucrose esters (SE-5 and SE-13 with hydrophile-lipophile balance value of 5 and 13, respectively) were supported by Liuzhou Aigefu Food Technology Co., Ltd. (Liuzhou, China). Remaining chemicals were analytical-grade in the experiments.

2.2. Preparation of silver carp surimi

The preparation of silver carp surimi was conducted to a previous report (Weng & Zheng, 2015). After the live fish was transported to the laboratory, the heads, guts and fins of silver carp was detached and then washed by iced-cold water. The obtained fish body was diced into fillets and minced. The mince was rinsed using three fold weight iced-cold water for 3 times. The rinsing process was followed by dewatering with a centrifugal dewatering machine, and then the fish mince was evenly chopped with cryoprotectants including sorbitol (4.0 g/100 g), sucrose (4.0 g/100 g), sodium polyphosphate (0.2 g/100 g), and sodium pyrophosphate (0.2 g/100 g) to obtain surimi. The obtained surimi was preserved at −35 °C before use.

2.3. Preparation of emulsions

The preparation of W/O and O/W emulsions was consulted according to a previous report (Zhao, Ren, Shi, Zhang, & Weng, 2023). The SPI powder (2 g) was dispersed in deionized water (20 g), and SE-5 (1 g) was stirred with peanut oil (80 g) at 70 °C. Both of the solutions were subsequently homogenized together (19,000 rpm) at 70 °C for 3 min to procure W/O emulsion. Meanwhile, the SPI powder (8 g) was dispersed in deionized water (80 g), stirred with SE-13 (1 g) at 70 °C, and then homogenized (19,000 rpm, 3 min) with peanut oil (80 g) at 70 °C to acquire O/W emulsion.

2.4. Preparation of surimi gels

The silver carp surimi gels were prepared following the previous report (Fang, Shi, Ren, Hao, Chen, & Weng, 2021). The defrosted silver carp surimi (1000 g) was ground in a mortar for 3 min and then incorporated and ground with NaCl (30 g) for 15 min. The salted surimi was ground with modified starch (50 g) for 5 min. The obtained mixture was blended with various content W/O or O/W emulsion and ground for 3 min. The final peanut oil content was accounted for 2.5, 5.0 and 10.0 g/100 g of surimi, while the final SPI content was regulated to 4.0 g/100 g of surimi. The resulting paste was filled in the stainless-steel mold. The process of grinding performed with crushed ice to ensure surimi paste lower than 10 °C. The gelation of surimi paste was adopted two-step water bath heating including heated in 45 °C for 60 min and then heated in 90 °C for 15 min. The stainless-steel molds containing surimi gels were placed in crushed ice to cool for at least 60 min. The prepared surimi gels were taken out from the mold, placed in the sealed plastic boxes at 4 °C for the following analysis within 3 days.

2.5. Characterization of surimi gels

2.5.1. Penetration test

The data of breaking force and deformation were collected by a texture analyzer (TA-XT Plus, Stable Micro System, UK) combined with the P/5S globular plunger at ambient temperature. The depression speed, trigger force, and penetration depth were set to 0.5 mm/s, 5.0 g, and 15.0 mm, respectively.

2.5.2. Texture profile analysis (TPA)

The measurement of TPA was conducted on the base of a previous report (Weng & Zheng, 2015). Gels were determined by columnar plunger of P/36R and the compression at strain of 30 % and depression speed of 1 mm/s. The parameters including hardness, springiness, resilience, and cohesiveness were recorded.

2.5.3. Color

The color indexes of brightness (L^*), redness/greenness (a^*), and yellowness/blueness (b^*) values, of silver carp surimi gel samples were recorded with a differential colorimeter (WSC–S, Shanghai, China) at 25 ℃. The colorimeter was corrected using a standard whiteboard (L^*=91.86, a^*=−0.88, b^*=1.42) before the test.

2.5.4. Moisture content and WHC

The moisture content was acquired via recording the weight reduction of silver carp surimi gels after being dried at 105 °C until the weight remained invariant. WHC was evaluated following the process of previous report (Weng & Zheng, 2015). Surimi gels were diced into cubes and accurately weighted. Subsequently, the cubes were encased with filer paper and placed in refrigerated centrifuge and then centrifuged (4 °C, 1000 g) for 15 min. After removing the filter paper, the centrifuged surimi gel cubes were weighted again. The calculating equation was followed by Fang et al. (2021).

2.5.5. CLSM

The images of oil distribution in surimi gels were photographed by the Leica TCS SP8 CLSM system (Leica, Germany), and the selection of staining matters and staining methods were according to the reports (Yang, Gao, & Yang, 2020; Yu, Song, Xiao, Xue, & Xue, 2022a) with modifications. The surimi chips were dripped by 10 μL of ethanol dyeing liquor containing fluorescein isothiocyanate (FITC, 0.9 mg/mL) and Nile red (0.1 mg/mL) for 5 min under the dark. The excitation wavelengths of FITC and Nile red were conducted at 552 and 488 nm.

2.5.6. SEM

The microstructural images of gel samples were collected according to the report (Fang et al., 2021) using a Phenom ProX G6 scanning electron microscope (Thermo Fisher Scientific Inc., USA). After being soaked in phosphate buffer solution (PBS of 0.1 mol/L, pH 7.2) including glutaraldehyde (2.5 mL/100 mL) for 1 d, the surimi gel chips were rinsed in PBS (0.1 mol/L, pH 7.2) to eliminate glutaraldehyde. Subsequently, the rinsed gel chips were dewatered in a serial ethanol solution, freeze-dried, and coated in gold in turn. All microstructure images were visualized at 5000 × magnification.

2.5.7. SDS-PAGE

Evaluation on the electrophoretic profiles of the silver carp surimi

gels was determined by the method of previously report (Hu, Shi, Ren, Hao, Chen, & Weng, 2021). After dissolving in protein-denatured buffer (pH 8.8) containing 20 mM Tris-HCl, 2 g/100 mL SDS, and 8 M urea, the surimi gels were mixed with a loading buffer containing bromophenol blue with or without 2 mL/100 mL β-mercaptoethanol (β-ME). The surimi gels were loaded on 5 % staking gel and 8 % running gel. After being conducted of electrophoresis, the gel was immersed in staining solution including Coomassie Brilliant Blue overnight, and then decolorized with de-staining solution of methanol and acetic acid.

2.5.8. FTIR spectroscopy

FTIR spectra of surimi gels were acquired by the description of Huang, Shi, Ren, Hao, and Weng (2022) using Nicolet iS50 ATR-FTIR spectrometer (Thermo Nicolet Ltd., USA). After being lyophilized, the powder of surimi samples was placed and covered on the ATR probe surface. The scanning wavelength was ranged from 1000 cm^{-1} to 4000 cm^{-1} with scanning rate of 32, and at the resolution of 4 cm^{-1}.

2.6. Statistical analysis

The results of data analysis were demonstrated as means ± standard error, and the software of SPSS statistics 26 (SPSS Inc., Chicago, IL, USA) with one-way ANOVA ($P < 0.05$) was adopted. All data were tested at least 3 times.

3. Results and discussion

3.1. Breaking force and deformation

Table 1 presents the breaking force and deformation of silver carp surimi gels by incorporating with emulsions. The breaking force and deformation of surimi gels were 188.72 g and 10.27 mm, respectively, which were similar with the silver carp surimi gels prepared by Weng and Zheng (2015). With increasing W/O emulsion content, the breaking force and deformation of surimi gels decreased. On the contrary, no significant differences of breaking force and deformation in surimi gels were found after adding O/W emulsion (Table 1). According to the previous study of Pourashouri, Shabanpour, Kordjazi and Jamshidi (2020), the unchanged gel strength of silver carp sausages was found after adding fish oil-based O/W emulsion. At present, the investigations about the addition of W/O emulsion on the characteristics of surimi gels are limited, but it has been clarified the gel strength of silver carp surimi gels decreased with increasing olive oil content (Lu et al., 2022). Moreover, the arrangement of the network structure and gelation capacity of surimi gels can be adjusted by the addition of oil (Han et al., 2021). These findings, including those of this study, suggest that the W/O emulsion might disturb the protein network arrangement and diminish the gelation capacity of surimi gels, similar to oil, thus reducing the gel strength of surimi gels.

Table 1
Effects of emulsions on the breaking force and deformation of silver carp surimi gels.

	Oil (g/100 g)	Breaking force (g)	Deformation (mm)
	0	188.72 ± 11.43^{a}	10.27 ± 0.33^{a}
W/O	2.5	167.56 ± 6.75^{b}	10.42 ± 0.56^{a}
	5.0	164.17 ± 14.77^{b}	9.95 ± 0.80^{a}
	10.0	145.20 ± 9.24^{c}	9.64 ± 0.43^{a}
O/W	2.5	192.64 ± 12.03^{a}	10.18 ± 0.53^{a}
	5.0	193.64 ± 10.25^{a}	10.44 ± 0.57^{a}
	10.0	195.97 ± 13.65^{a}	10.50 ± 0.83^{a}

Each value represents the mean ± standard error.
Different lower-case letters within the same column means significant differences ($P < 0.05$).

3.2. TPA

Table 2 describes the TPA parameters including hardness, springiness, resilience, and cohesiveness of surimi gels by adding emulsions. The hardness of surimi gels decreased with increasing W/O emulsion, while the springiness, resilience, and cohesiveness were not affected. However, no obvious changes in the hardness, springiness, resilience, and cohesiveness of surimi gels were found when O/W emulsion was added. The hardness may represent the initial degree of food structure, while the springiness, resilience, and cohesiveness are related to the changing behavior of food structure during mastication (Wee, Goh, Stieger, & Forde, 2018). Therefore, these results suggested that the formed gel structure was degraded by the W/O emulsion, while it was not affected by the O/W emulsion (Table 2). Meanwhile, the changing behavior of gel structure was not affected by emulsions during mastication process.

3.3. Color properties

Color is an important index for judging the qualities of surimi gel of consumers. Table 3 demonstrates the effects of emulsions on the color parameters of surimi gels. The L^* value of surimi gels was much lower than that of the standard whiteboard, while the a^* and b^* values were close to those of the standard whiteboard, suggesting that the prepared samples were grayish white. The L^* value of silver carp surimi gels was lower than the mackerel surimi gels, which was attributed to the different washing conditions (Chen, 2002). With the increase in W/O emulsion, the L^* value decreased, the a^* value did not change, and the b^* value increased gradually, indicating that the surimi gels changed from being gray to being yellow. A previous study showed that the L^* value of Alaska pollock surimi gels decreased and that the b^* value increased by adding the krill oil (Pietrowski, Tahergorabi, Matak, Tou, & Jaczynski, 2011). The effects on color indexes of surimi gels by adding W/O emulsion in this study were similar to that of krill oil. Meanwhile, the surimi gels with increasing O/W emulsion exhibited an increased L^* value and unchanged a^* and b^* values, indicating that the surimi gels shifted from gray to white color. This could be attributed to that small oil droplets in the gel matrix reflected more light after being added O/W emulsion (Pourashouri et al., 2020).

3.4. Moisture content and WHC

Table 4 presents the effects of emulsions on the moisture content and WHC of surimi gels. The moisture content of surimi gels was 78.98 g/100 g and reduced with the increased content of W/O emulsion. A similar trend was found in the surimi gels with O/W emulsion. This phenomenon could be due to the decreased moisture content, which had also been found in Bologna sausages added with the increased oil content (Carballo, Mota, Barreto, & Colmenero, 1995). The WHC of surimi gels without emulsions was 94.43 g/100 g (Table 4), which was close to the Alaska Pollock surimi gels (Liu, Ji, Zhang, Xue, & Xue, 2019). WHC reflects the capacity of surimi protein to combine water molecules, and higher WHC indicates that more water is constrained by surimi protein (Lakshmanan, Parkinson, & Puggot, 2007; Zhang et al., 2018). A report stated that the WHC of surimi gels could be reduced due to the addition of vegetable oil (Shi et al., 2014). In this study, however, the WHC of surimi gels was maintained invariant after emulsions were added, suggesting that emulsification could reduce the negative impact of oil on the water-binding capacity of surimi proteins. A similar phenomenon has also been noted by Fang et al. (2021) that the WHC remained constant of threadfin bream surimi gels after adding emulsified lard.

3.5. CLSM

The oil droplet size and distribution in the surimi gels are shown in Fig. 1A. The surimi proteins and oil droplets are displayed in green and

Table 2
Effects of emulsions on the TPA parameters of silver carp surimi gels.

	Oil (g/100 g)	Hardness (g)	Springiness	Resilience	Cohesiveness
	0	1467.52 ± 18.15^{a}	0.94 ± 0.01^{a}	0.54 ± 0.01^{a}	0.84 ± 0.01^{a}
W/O	2.5	1290.64 ± 106.49^{b}	0.95 ± 0.01^{a}	0.57 ± 0.04^{a}	0.86 ± 0.03^{a}
	5.0	1208.74 ± 23.52^{bc}	0.91 ± 0.03^{a}	0.56 ± 0.02^{a}	0.85 ± 0.03^{a}
	10.0	1164.17 ± 72.41^{c}	0.94 ± 0.04^{a}	0.58 ± 0.04^{a}	0.88 ± 0.03^{a}
O/W	2.5	1523.18 ± 70.58^{a}	0.93 ± 0.01^{a}	0.54 ± 0.01^{a}	0.84 ± 0.01^{a}
	5.0	1507.80 ± 90.23^{a}	0.94 ± 0.03^{a}	0.57 ± 0.05^{a}	0.87 ± 0.05^{a}
	10.0	1522.90 ± 12.59^{a}	0.92 ± 0.01^{a}	0.57 ± 0.03^{a}	0.86 ± 0.03^{a}

Each value represents the mean ± standard error.
Different lower-case letters within the same column means significant differences ($P < 0.05$).

Table 3
Effects of emulsions on the color parameters of silver carp surimi gels.

	Oil (g/100 g)	L^*	a^*	b^*
	0	48.26 ± 0.40^{c}	−0.80 ± 0.39^{a}	1.30 ± 0.21^{d}
	2.5	48.35 ± 0.23^{c}	−0.78 ± 0.19^{a}	1.86 ± 0.29^{c}
W/O	5.0	47.90 ± 0.31^{d}	−0.87 ± 0.14^{a}	3.55 ± 0.27^{b}
	10.0	47.30 ± 0.23^{e}	−0.68 ± 0.14^{a}	4.99 ± 0.25^{a}
	2.5	48.51 ± 0.24^{b}	−0.75 ± 0.17^{a}	1.45 ± 0.32^{d}
O/W	5.0	48.56 ± 0.33^{b}	−0.73 ± 0.14^{a}	1.50 ± 0.23^{d}
	10.0	48.92 ± 0.49^{a}	−0.78 ± 0.28^{a}	1.47 ± 0.13^{d}

Data are expressed as mean ± standard deviation.
Values with different lower-case letters in the same column indicate significant differences at $P < 0.05$.

Table 4
Moisture content and WHC of silver carp surimi gels.

	Oil (g/100 g)	MC (g/100 g)	WHC (g/100 g)
	0	78.98 ± 0.12^{a}	94.43 ± 0.30^{a}
	2.5	77.97 ± 0.02^{b}	94.50 ± 0.24^{a}
W/O	5.0	76.81 ± 0.04^{c}	95.13 ± 0.49^{a}
	10.0	74.30 ± 0.03^{d}	95.23 ± 0.80^{a}
	2.5	78.02 ± 0.07^{b}	94.79 ± 0.44^{a}
O/W	5.0	76.68 ± 0.33^{c}	94.83 ± 0.43^{a}
	10.0	74.45 ± 0.16^{d}	95.25 ± 0.38^{a}

Data are expressed as mean ± standard deviation.
Values with different lower-case letters in the same column indicate significant differences at $P < 0.05$.

red, respectively. A few small droplets of oil were found and homogeneously dispersed in the compact surimi protein structure, probably due to the remaining fish oil in the surimi. Similar CLSM images were also reported by Yu, Xiao, Xue and Xue (2022b), who prepared surimi gels from Pacific cod. The oil droplet size in surimi gels was enlarged with increasing W/O emulsion, while it was not affected by the addition of O/W emulsion. The enlarged oil droplet weakened the surimi gel structure with the increase in W/O emulsion content, resulting in decreased breaking force (Fig. 1A, Table 1). A similar phenomenon was observed by Yu et al. (2022a), who investigated the texture and microstructure of Pacific cod surimi gels after the addition of peanut protein isolate and fish oil. On the contrary, the oil droplets were uniformly dispersed in the network structure of surimi gels, and the breaking force was not affected with the increase in O/W emulsion content (Fig. 1A, Table 1). The similar phenomenon was observed in croaker gels when the virgin coconut oil nano-emulsion was added (Gani & Benjakul, 2018).

3.6. SEM

The microstructural images of surimi gels with emulsions are observed by SEM (Fig. 1B). The microstructure of silver carp surimi gels was dense with block form, which became rough and glossy, accompanied by some voids, with increasing addition of W/O emulsion. Compared with the W/O emulsion, the addition of O/W emulsion

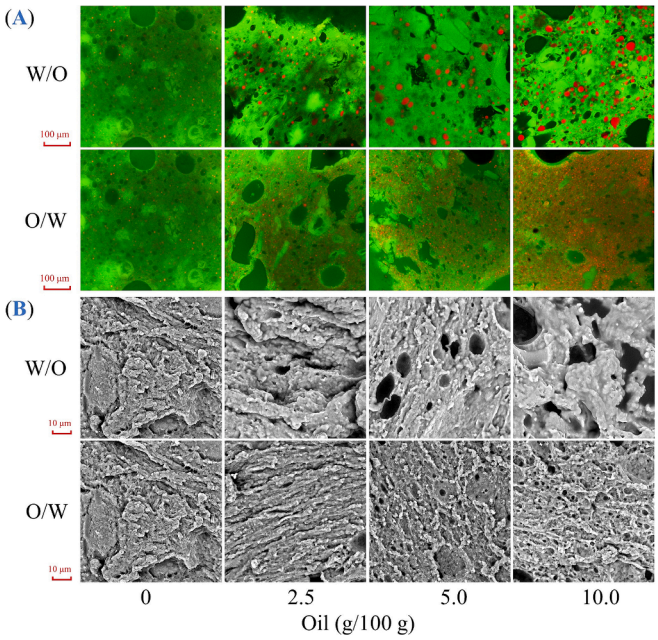

Fig. 1. Oil distribution (A) and microstructure (B) of silver carp surimi gels.

exerted a minimal impact on the gel microstructure. This might be attributed to the destroyed balance between the two interactions of protein–protein and protein–water. Similarly, Yan et al. (2020) revealed that the addition of fish oil showed a negative impact on the microstructure of silver carp surimi gels. Generally, protein gels with fine and ordered networks have excellent gel strength, whereas those with discontinuous networks and large pores have poor gel strength (Fang et al., 2021). The added W/O emulsion to surimi gels was similar to that of oil: The enlarged oil droplets in surimi gels weakened the network structure, leading to the reduction of breaking force (Fig. 1A, Fig. 1B, and Table 1). When O/W emulsion was incorporated in surimi gels, small oil droplets were homogeneously inserted without affecting the ordered gel network and breaking force (Fig. 1A, Fig. 1B, and Table 1).

3.7. SDS-PAGE

The electrophoretic profiles of silver carp surimi gel proteins after adding emulsions are depicted in Fig. 2A and 2B. The main composition of surimi gels included high-molecular-weight fraction (HMWF), myosin heavy chain (MHC), and actin (AC). After being ground with sodium chloride, the myofibrillar proteins of surimi are dissolved into sol, which can form surimi products with good gel strength via non-disulfide covalent bonds between MHCs induced by endogenous or exogenous transglutaminase (TGase). The replacement of sodium chloride by potassium chloride in the gel strength of surimi gels was better than magnesium chloride and calcium chloride, however, the calcium ions was demanded for endogenous TGase activity to enhance the cross-

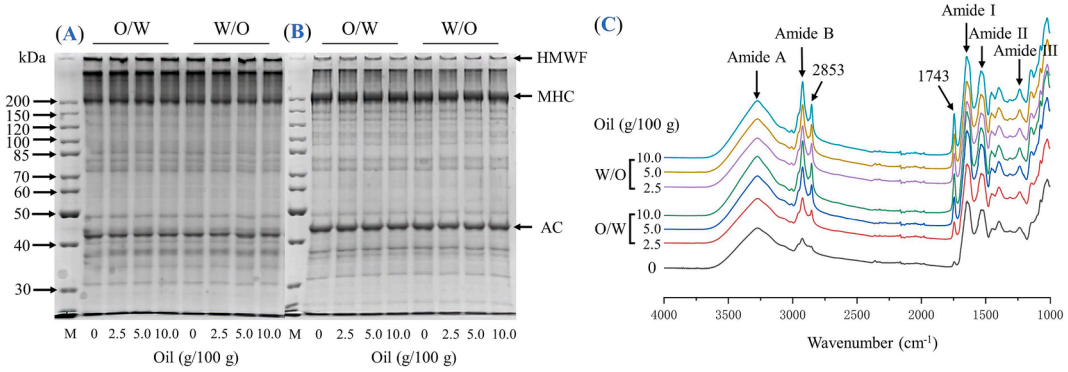

Fig. 2. SDS-PAGE patterns without β-ME (A) and with β-ME (B), and FTIR spectra (C) of silver carp surimi gels treated by various emulsions. M: marker; HMWF: high-molecular-weight fraction; MHC: myosin heavy chain; AC: Actin.

linking of surimi gel proteins (Yingchutrakul et al., 2022). The protein interaction in croaker surimi gels could not be affected by adding virgin coconut oil nano-emulsion (Gani & Benjakul, 2018). Similarly, no changes of the intensities in MHC and AC bands intensities were found when the emulsion content increased when the electrophoretic samples without adding β-ME (Fig. 2A), indicating that the emulsions did not affect the interactions between surimi proteins. Compared to the samples without the addition of β-ME, the HMWF bands was not found in the samples with β-ME, regardless of emulsions, while the intensities of the MHC and AC bands increased, implying that the HMWF in the surimi gels were cross-linked by the MHC and AC via disulfide bonds. However, the addition of emulsions hindered the formation of non-disulfide covalent cross-linking of surimi proteins (Fig. 2B).

3.8. FTIR spectroscopy

The changes of the protein molecular structure were reported by FTIR spectroscopy (Wei et al., 2018), thus, the effects of emulsions on the FTIR spectra of surimi gels were investigated (Fig. 2C). With increasing in emulsion content whether the addition of W/O or O/W emulsion, the peak intensities of 2925, 2853, and 1743 cm^{-1} represented that the characteristic absorption peak of oil was increased (Fang et al., 2021), whereas the other characteristic absorption peaks did not change with the addition of emulsions. The changes in the characteristic peaks could be seen more clearly in the enlarged spectra (Fig. S1). This finding suggested that the interactions between surimi proteins were not affected by the addition of emulsions during surimi gelation. Song, Lin, Hong, Liu and Zhou (2022b) reported a similar phenomenon when they studied the effects of safflower seed oil-based emulsion on the protein conformational changes of *Nemipterus virgatus* surimi gels. Overall, the differences in physical properties of surimi gels between the addition of W/O and O/W emulsions were mainly attributed to the oil droplet size and distribution. The incorporation of W/O emulsion to surimi gels was similar to that of oil, which easily formed large oil droplets and damaged the gel structure, leading to the decreased breaking force and increased b^* values of the gels (Fig. 1A, Table 1, and Table 3). In the case of adding O/W emulsion, the small droplets of oil were uniformly imbedded in the surimi gel structure, and without affecting the breaking force and color parameters of surimi gels (Fig. 1A, Table 1, and Table 3).

4. Conclusion

The effects of W/O and O/W emulsions on the physicochemical characteristics of surimi gels were contrasted. Large oil droplets were found in the matrix of gels with W/O emulsion, resulting in destroyed gel network and decreased gel strength. By contrast, small oil droplets were regularly dispersed in the matrix of surimi gels by adding O/W emulsion, which did not affect the surimi gel network and gel strength. The surimi gels turned yellow when W/O emulsion was incorporated, and turned white after being added with O/W emulsion. However, irrespective of whether W/O or O/W emulsion was added, no obvious changes in the interactions between surimi proteins were found. In conclusion, the O/W emulsion is more suitable than the W/O emulsion for replacing oil in the manufacture of high-quality surimi products. The effects of emulsions on the physicochemical properties of surimi gels during storage would be explored in the future.

CRediT authorship contribution statement

Enhan Zhang: Methodology, Data curation, Conceptualization. **Yuan Zhao:** Supervision. **Zhongyang Ren:** Supervision. **Linfan Shi:** Supervision. **Wuyin Weng:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

The authors do not have permission to share data.

Acknowledgements

This work is sponsored by National Key R&D Program of China (2021YFD2100200/2021YFD2100204), National Natural Science Foundation of China (32272266), and Fujian Science and Technology Project (2021N5013).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2023.100988.

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