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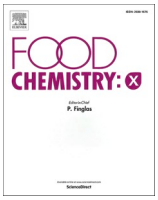

Effects of sturgeon oil and its Pickering emulsion on the quality of sturgeon surimi gel

Li Yuan [a], Xiaomo Guo [a], Zhiyu Xiong [a], Xin Wang [a], Abdul Razak Monto [a], Wengang Jin [b], Jianrong Li [c,**], Ruichang Gao [a,b,*]

[a] School of Food and Biological Engineering, Jiangsu University, Zhenjiang, 212013, China
[b] Bio-resources Key Laboratory of Shaanxi Province, School of Biological Science and Engineering, Shaanxi University of Technology, Hanzhong 723001, China
[c] College of Food Science and Technology, Bohai University, Jinzhou 121013, China

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ABSTRACT

This study aimed to extract sturgeon oil (SO) from the sturgeon head and apply it to sturgeon meat to produce surimi gel. The effects of SO and its Pickering emulsion on the qualities of surimi gel were investigated. The results demonstrated that Pickering emulsions improved the quality deterioration of the gel caused by the direct addition of SO, especially the soy isolate protein (SPI) emulsion and the pea isolate protein (PPI) emulsion. Pickering emulsions contributed to a more uniform and compact network structure of the gel, improved the texture properties, enhanced the freeze-thaw stability, and reduced lipid oxidation. Additionally, compared to the addition of exogenous lipids such as peanut oil and linseed oil, SO and its Pickering emulsion better maintained the characteristic flavor of sturgeon surimi gel. This study provides valuable data and feasible ideas for expanding the utilization of sturgeon by-products and developing new types of surimi gel products.

1. Introduction

Surimi's ability to gel during heating makes it a common intermediate product for preparing surimi gel products, which are popular due to their rich nutrients and unique gelatinous texture (Lv et al., 2023). Currently, the raw materials used for the production of surimi are mainly marine fish such as sardines and pollock, as well as freshwater fish such as silver carp (An, Ruan, Li, Zhang, & Xiong, 2024). China is a major country in sturgeon (*Acipenseridae*) aquaculture, which accounts for about 86% of the global production (Tang et al., 2019). Due to the tough texture of sturgeon meat, it is rarely used in the preparation of surimi gel products. Perennial large sturgeons are mainly used to obtain caviar (Tang et al., 2019), and the rest, such as fish meat and head, become by-products with low availability, which not only causes great waste of resources but even exacerbates environmental pollution. Therefore, improving the quality of surimi gel products prepared from sturgeon meat through various technologies will not only promotes the high-value utilization of sturgeon processing by-products but also facilitates the high-quality development of the surimi processing industry.

Rinsing is a key link in surimi production, which aims to remove water-soluble protein, pigment, odor and lipids from fish, enhance the quality and preservation of surimi gel products (Lv et al., 2023). However, the removal of lipids may lead to a rough taste, reduced flavor and reduced nutritional value of surimi gel products (Xu, Yu, Xue, & Xue, 2023). Adding oil to surimi is one of the effective methods to solve these problems. Nonetheless, the exogenous oils (such as olive oil and lard) to some extent mask the flavor of surimi itself. Sturgeon processing waste, such as fish heads, contains rich oil, with polyunsaturated fatty acids (PUFAs) content comparable to deep-sea fish oil and much higher than other freshwater fish (Chen et al., 2022). However, whether the endogenous oil - sturgeon oil (SO) - can maintain or enhance the flavor of sturgeon surimi gel products remains unclear.

Currently, there are two common methods for adding oil to surimi: direct addition and in the form of emulsion (Liu, Ji, Zhang, Xue, & Xue, 2019). The operation of direct addition is simple, but it is often accompanied by the decline of surimi gel quality, such as softening of texture, decline of water holding capacity and oil precipitation (Song, Lin, Hong, Liu, & Zhou, 2022a; Xu et al., 2023). The emulsion can effectively improve the above problems (Lv et al., 2023). However, the added dose of oil is still relatively low. In recent years, Pickering

* Corresponding author at: School of Food and Biological Engineering, Jiangsu University, 301 Xuefu Road, Zhenjiang, Jiangsu province 212013, China.
** Corresponding author.
E-mail addresses: lijr6491@163.com (J. Li), xiyuan2008@ujs.edu.cn (R. Gao).

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emulsion plays an increasingly important role in food processing. Compared with the traditional emulsion, Pickering emulsion has better stability and biocompatibility, and higher oil holding capacity (Cao et al., 2022; Wang et al., 2023). Numerous studies have consistently demonstrated that Pickering emulsion effectively enhances the aggregation stability, oxidation stability, and bioaccessibility of oil, Consequently, it is widely utilized in various foods, such as meat products, yogurt, and cakes to improve food quality (Cao et al., 2022; Feng et al., 2020; Ren et al., 2021; Zhong, Yang, Cao, Liu, & Qin, 2018). Soybean protein isolate (SPI), pea protein isolate (PPI) and whey protein isolate (WPI) are widely used as emulsifiers in the preparation of Pickering emulsion due to their excellent amphiphilic and film forming ability. In addition, they may also improve the quality of meat products by interacting with matrix proteins (Niu, Li, Han, Liu, & Kong, 2017).

This study aimed to investigate the effect of the direct addition of SO and its Pickering emulsion on the quality of sturgeon surimi gel, encompassing aspects such as gel color, properties, flavor, lipid oxidation, and freeze-thaw stability. The findings offer data reference and feasible ideas for the comprehensive utilization of sturgeon by-products and the development of new surimi gel products. Additionally, they serve as a reference for applying fish oil to improve the quality of other protein gel products.

2. Materials and methods

2.1. Materials

The frozen sturgeon muscle and diced sturgeon head were provided by Quzhou Sturgeon Aquatic Food Technology Development Co., Ltd. (Zhejiang, China), and stored at a temperature of −20 °C. Peanut oil (PO) and linseed oil (LO) were purchased from a local supermarket (Zhenjiang, Jiangsu, China). Soy isolate protein (SPI), pea isolate protein (PPI), and whey isolate protein (WPI) were purchased from Sicongkang Biotechnology Co., Ltd. (Shandong, China), Jinkangtai Biotechnology Co., Ltd. (Shanxi, China), and Qianbo Bioengineering Co., Ltd. (Jiangsu, China), respectively. Linalool, laurene and octanal were purchased from Macklin (Shanghai, China). All other chemicals were of analytical grade.

2.2. Extraction and refining of sturgeon oil (SO)

The method described in the reference by Aitta et al. (2023) with slight modification. Sturgeon heads were completely thawed at 4 °C. Distilled water was added in a 1:1 (*w*/w) ratio, and the pH was adjusted to 7. The mixture was preheated in a water bath at 50 °C for 30 min. Neutral protease and papain were added at a concentration of 1.5% (based on the weight of the fish heads), with a ratio of 1:2 (w/w) for the two enzymes. The enzymatic hydrolysis was carried out for 4 h with intermittent stirring every 30 min. The enzymes were then inactivated by heating at 95 °C for 10 min. The mixture was centrifuged at 10, 000*g* for 15 min, and the upper layer, referred to as crude SO, was collected. The crude SO was degummed using phosphoric acid, deacidified with NaOH, decolorized with activated white clay, and finally deodorized by a rotary evaporator to obtain refined SO.

2.3. Preparation of Pickering emulsions

The method described in the reference by Cao et al. (2022) was followed with slight modifications. SPI, PPI, and WPI (5 g) were dispersed separately in 100 mL of distilled water and refrigerated at 4 °C for 12 h. The NaCl concentration was adjusted to 300 mM, and the mixtures were heated (SPI, 95 °C/15 min; PPI, 95 °C/30 min; WPI, 85 °C/30 min), then promptly cooled in an ice-water bath until they reached room temperature to obtain protein nanodispersions. The pH of the dispersions was adjusted to 7. The dispersions were then homogenized with SO at a ratio of 1:2 (*w*/w) at 11, 000 rpm for 3 min to obtain three corresponding Pickering emulsions, which were named SPE, PPE, and WPE, respectively.

2.4. Preparation of surimi gel

The surimi gel preparation was performed by the method reported by Lv et al. (2023) with slight modification. Sturgeon meat was thawed completely at 4 °C. The white muscle was then cut into small pieces and washed. The washing process was carried out twice using a 5-fold volume of distilled water and a 5-fold volume of salt water solution (2.5 g/L NaCl). Excess water was removed by centrifugation (10, 000*g*, 20 min). Subsequently, 200 g of meat was chopped for 2 min; 3% NaCl was added, and the moisture content was adjusted to 80%. Oil (8%) or Pickering emulsions (12%) were added, and chopping was continued for 5 min. The resulting surimi paste was filled into plastic enteric coatings with a diameter of 3.8 cm. The casings were then subjected to two-step heating in a water bath (40 °C/1 h + 90 °C/30 min). Subsequently, all samples were cooled with iced water for 30 min and stored at 4 °C in a refrigerator. The experiment was divided into 7 groups: control (without oil or emulsion), SO group (directly added SO), three Pickering emulsion groups (SPE group, PPE group and WPE group), PO group (directly added PO) and LO group (directly added LO), with PO group and LO group were specifically used for electronic nose determination and sensory evaluation.

2.5. Whiteness

The measurement of whiteness was based on the method of Wang et al. (2023). A colorimeter (CR-400, Konica Minolta Sensors, Japan) was used to measure the luminance (L*), red/green (a*) and yellow/blue (b*) color values of the gel. Six replicates were set up for each sample. The whiteness of the gel was calculated using eq. (1):

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

2.6. Texture profile analysis (TPA) and gel strength

Follow the method outlined by Xiong et al. (2023). A texture analyzer (TAXT Plus, Stable Micro Systems, UK) equipped with a 5 kg load cell was used. Two probe types were utilized: the cylindrical P/50 probe and the trigger ball probe P/5S (with a diameter of 5 mm). TPA was tested under the following conditions: the trigger force was 5.0 g, each sample was set two compression cycles, the compression level was 40%, and the cycle interval was 5 s. Gel strength was tested under the following conditions: the triggering force was 5.0 g; the distance was 10 mm , and the test speed was 1.00 mm/s. All samples were cut into cylinders with a height of 2 cm.

2.7. Rheological properties

The rheological properties were measured using a rheometer (Discovery HR-1, TA Instruments, USA) equipped with a parallel plate geometry (with a plate diameter of 40 mm and a plate gap of 1 mm) in oscillation mode, following the method described by Chen et al. (2023) with slight modifications. Changes in the constants of G′ and tan δ were recorded to obtain dynamic mechanical variation curves.

2.8. Water holding capacity (WHC) and cooking loss (CL)

The measurement of WHC refers to the method of Zhou et al. (2022) with slight modifications. A gel sample weighing approximately 2 g (M_1) was cut into cubes (2 mm × 2 mm × 2 mm). The cubes were wrapped in double-layered filter paper and placed in centrifuge tubes. The tubes were centrifuged at 10, 000*g* for 15 min at 4 °C. Then the sample was weighed again (M_2), and the WHC% was calculated using eq. (2):

$$WHC(\%) = M_2/M_1 \times 100 \quad (2)$$

The measurement of CL was performed by the method of Lv et al. (2023). The masses of the samples before and after cooking were noted as G_1 and G_2, respectively. The CL% was calculated using eq. (3):

$$CL(\%) = (G_1 - G_2)/G_1 \times 100 \quad (3)$$

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

LF-NMR was conducted according to the method of Xiong et al. (2023). Six replicates were set up for each sample.

2.10. Scanning Electron microscope (SEM)

The samples were prepared with reference to Niu et al. (2017), and the microstructure was observed using a SEM (JSM-7001F, JEOL, Japan) with an amplification of 20, 000×.

2.11. Confocal laser scanning microscope (CLSM)

Referring to the method of Yu, Song, Xiao, Xue, and Xue (2022) with slight modifications. Samples were sectioned to a thickness of 1 mm and stained with a Nile red/ethanol solution (1 mg/mL), protected from light for 10 min, followed by a solid green solution (1 mg/mL) for 30 s. Excess dye was subsequently washed away with distilled water. The excitation wavelengths for Nile red and solid green were 528 nm and 633 nm, respectively.

2.12. Lipid oxidation

Referring to the method of Song, Lin, Hong, Liu, and Zhou (2022b). The measurement wavelength was 532 nm. The TBARS content was expressed as the mass of malondialdehyde (MDA) equivalent per kilogram of gel (mg/kg).

2.13. Electronic nose analysis

Referring to the method of Xu et al. (2022). The sample weighing 3 g was cut into small pieces with side lengths of 2 mm and loaded into a headspace vial. The vial was then placed in a water bath at 40 °C for 15 min. The test parameters were as follows: rinsing time of 150 s, detection time of 120 s, and a flow rate of 300 mL/min.

2.14. Sensory evaluation

The method of sensory evaluation references Zhou et al. (2022) with slight modifications. The sensory properties of the surimi gel were evaluated by 15 assessors experienced in judging surimi gels. This kind of fish is not related to religious beliefs, no prohibitions on such food. Additionally, all the ingredients used to make surimi gels are edible and without any unknown substances, therefore ethical approval is not required. Prior to the analysis, all assessors were informed of the aim of the sensory evaluation, and they provided informed consent to perform it. The color, texture, fish aroma, taste and overall acceptability of the samples were assessed according to the evaluation criteria outlined in Table S1. Cylindrical gel samples measuring 2 cm in height were equilibrated for 1 h at room temperature and then randomly distributed for evaluation.

2.15. Determination of adsorption capacity of flavor substances

The sample treatment was conducted with reference to Xu et al. (2019) with slight modifications. Cylindrical surimi gels measuring 1.5 cm in height were placed in headspace vials and flavor stock solutions (linalool, laurene, and octanal) were added, with a final concentration of 5 ppm for each flavor compound. The headspace vials were then heated in a water bath at 95 °C for 10 min to simulate the cooking process. After equilibration at room temperature for 30 min, the headspace vials were placed in a water bath at 30 °C. A fiber extraction needle was used to adsorb the volatile compounds for 30 min, followed by desorption at 220 °C for 5 min in split-less mode. Blank control headspace vials without surimi gel were included for comparison. Each set of samples was prepared with six replicates.

Gas chromatography (GC) conditions: the capillary column was the Agilent DB-WAX (30 m × 0.25 mm × 0.25 μm). The column temperature was initially maintained at 38 °C for 6 min, then raised to 105 °C at a rate of 6 °C/min, and subsequently increased to 220 °C at 15 °C/min, where it was held for 5 min. The flow rate of the carrier gas (N_2) was 1 mL/min. The peak area of the blank control was recorded as S_1, while the peak area of the sample group was recorded as S_2.

The binding capacity of flavor substances was expressed as the relative adsorption percentage (%), calculated using eq. (4):

$$Binding(\%) = (S_1 - S_2)/S_1 \times 100 \quad (4)$$

2.16. Freeze-thaw (FT) stability

The determination of FT stability was based on Cen et al. (2023) with slight modifications. Samples measuring 2 cm in height were placed in a − 20 °C refrigerator for 2 days and then thawed at 25 °C until the ice crystals were completely melted. This process was defined as 1 FT cycle. Each group of samples underwent 1, 2 and 3 FT cycles. The initial mass of the sample before freezing was denoted as M_1, while the treated samples were wiped with filter paper to remove surface moisture and weighed (M_2). The FT loss rate (TL) was calculated using eq. (5):

$$TL(\%) = (M_1 - M_2)/M_1 \times 100 \quad (5)$$

2.17. Statistical analysis

Statistical analysis was conducted using SPSS 25 (SPSS Inc., Chicago, IL, USA). ANOVA was employed to determine the statistical significance of the data, with a significance level set at $P < 0.05$. The experimental results were analyzed and graphical representations were generated using Origin 2022b (Origin Lab Co., Northampton, MA, USA). All measurements were performed in triplicate, and the results were expressed as mean ± standard deviation (SD).

3. Results and discussion

3.1. Whiteness

Whiteness is a crucial visual indicator of the quality of surimi products and directly impacts consumer satisfaction (Wang et al., 2023). As indicated in Table 1, the whiteness values of the SO, SPE, PPE, and WPE groups were significantly higher than that of the control. Both direct addition and addition in the form of Pickering emulsion can improve the light scattering effect on the surface of surimi gels (Song et al., 2022b). Generally, compared with the direct addition of oil, Pickering emulsion droplets are more evenly distributed in the gel

Table 1
Effect of SO addition on the color of surimi gel.

Sample	L*	a*	b*	Whiteness
Control	82.53 ± 0.45^{d}	3.98 ± 0.11^{d}	8.67 ± 0.12^{b}	80.10 ± 0.33^{e}
SO	84.39 ± 0.26^{b}	4.30 ± 0.06^{c}	8.25 ± 0.17^{c}	81.83 ± 0.23^{c}
SPE	84.86 ± 0.06^{ab}	4.47 ± 0.06^{ab}	7.97 ± 0.17^{d}	82.32 ± 0.04^{b}
PPE	83.61 ± 0.36^{c}	4.51 ± 0.17^{a}	8.70 ± 0.06^{a}	80.90 ± 0.31^{d}
WPE	85.38 ± 0.18^{a}	4.31 ± 0.10^{ab}	7.61 ± 0.03^{e}	82.96 ± 0.14^{a}

Different letters within the same column indicate significant differences ($P < 0.05$).

matrix due to their smaller particle size, which is conducive to enhancing the light scattering effect and thus improving the sample whiteness (Wang et al., 2023). However, in the results of the present study, the whiteness of the PPE group was significantly lower than that of the SO group ($P < 0.05$). This is because the yellow plant pigments contained in PPI have high thermal stability (Zhou et al., 2022), resulting in the sample exhibiting a higher yellowness value (b*) ($P < 0.05$). Therefore, SPI and WPI as emulsifiers are more conducive to the improvement of gel whiteness.

3.2. Texture profile analysis (TPA) and gel strength

As presented in Table 2, compared to the control, the direct addition of SO resulted in a significant reduction ($P < 0.05$) in the textural properties of the surimi gel, including hardness, cohesion, springiness, gumminess, and chewiness. In addition, the gel strength of this sample also showed the lowest (778.17 ± 21.17 g × mm). The reduction in TPA and gel strength can be attributed to the incomplete emulsification of the high dose (8%) of SO in the surimi (Zhang et al., 2023). This resulted in uneven distribution and poor stability of the oil droplets. Consequently, the cross-linking of matrix proteins into a gel was hindered to some extent. Furthermore, the addition of high doses of exogenous substances can reduce the relative content of matrix proteins (Song et al., 2022a), which is further detrimental to the formation of gel networks.

However, as shown in Table 2, the addition of SO in the form of Pickering emulsions mitigated the negative effects on the gel texture caused by SO. Both SPE and PPE demonstrated better improvement, with no significant difference compared to the control ($P > 0.05$). When SO was prepared as Pickering emulsions, the surimi protein is less likely to participate in the emulsification with SO but rather tends to engage in the construction of a three-dimensional gel network (Song et al., 2022b). Additionally, the preheating treatment of protein emulsifiers enhanced the unfolding of the natural protein structure and increased surface hydrophobicity (Wang et al., 2015). This facilitated the interaction between emulsion droplets and matrix proteins during subsequent thermal gelation processes. For instance, upon preheating treatment at 95 °C, the basic subunits of SPI dissociate, they can undergo cross-linking with myosin heavy chains through hydrophobic interactions during thermogelation (Wang et al., 2015). Among the three emulsions, SPE and PPE had the better effect on mitigating the deterioration of gel texture caused by SO. It is reported that legume proteins with large subunit complexes have higher interfacial activity and are more likely to form stable interfacial layers at the oil-water interface (Benjamin, Silcock, Beauchamp, Buettner, & Everett, 2014). Therefore, SPE and PPE may play a more stable filling role in the gel matrix.

3.3. Dynamic rheological properties

The dynamic change of viscoelastic behavior of the sample during its transformation from sol state to gel state could be observed through temperature scanning (Sow, Tan, & Yang, 2019). During thermal gelation, the denaturation and aggregation of myosin are affected by temperature changes and other components in the matrix (Xu et al., 2024; Zhu et al., 2022). As depicted in Fig. 1, both G' and tan δ exhibited similar trends across all groups. The G' values increased with rising

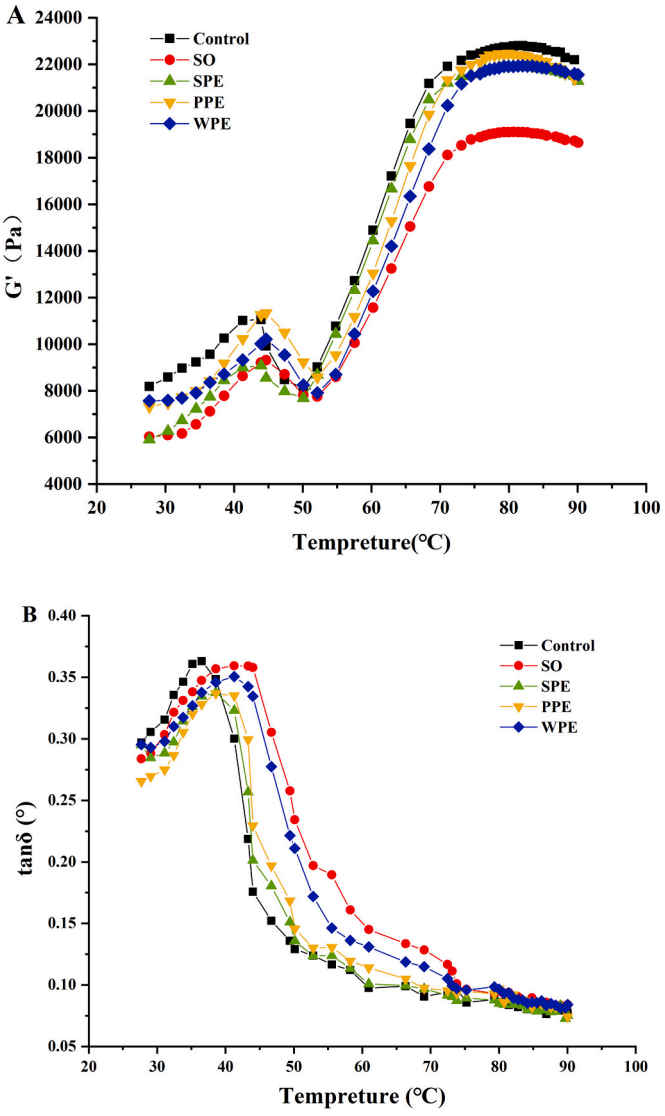

Fig. 1. Effect of SO addition on G '(A) and tan δ (B) of surimi gel.

temperature, reaching an initial peak at approximately 45 °C. This increase can be attributed to aggregation and cross-linking of the myosin head, forming a weak gel network (Xiong et al., 2023). Subsequently, G' started to decrease with further temperature increase and reached a minimum around 50 °C. This decline in G' can be associated with the increased activity of endogenous protein-hydrolyzing enzymes, as well as the unwinding of myosin tails and the breaking of interprotein bonds, leading to an increase in the flowability of myosin (Xu et al., 2023). As the temperature continued to rise, G' increased again, reaching a second peak at approximately 70 °C and then stabilizing. This process is called the "gel strengthening phase". This increase in G' corresponds to the extended protein molecules further crosslinking through chemical forces

Table 2
Effect of SO addition on TPA and gel strength of surimi gel.

Sample	Hardness(Kg)	Cohesion	Springiness	Gumminess(Kg)	Chewiness (Kg)	Gel strength (g × mm)
Control	4.23 ± 0.02^{a}	0.69 ± 0.01^{a}	0.88 ± 0.01^{a}	2.91 ± 0.06^{a}	2.55 ± 0.06^{a}	975.63 ± 35.92^{a}
SO	3.73 ± 0.03^{c}	0.64 ± 0.01^{b}	0.84 ± 0.00^{c}	2.38 ± 0.01^{c}	1.99 ± 0.01^{c}	778.17 ± 21.17^{c}
SPE	4.21 ± 0.03^{a}	0.67 ± 0.04^{a}	0.87 ± 0.01^{ab}	2.84 ± 0.03^{a}	2.48 ± 0.04^{a}	956.52 ± 43.4^{a}
PPE	4.24 ± 0.06^{a}	0.67 ± 0.00^{a}	0.87 ± 0.01^{ab}	2.86 ± 0.05^{a}	2.49 ± 0.04^{a}	948.99 ± 34.85^{a}
WPE	3.99 ± 0.07^{b}	0.66 ± 0.01^{a}	0.86 ± 0.04^{b}	2.64 ± 0.06^{b}	2.28 ± 0.05^{b}	893.04 ± 40.40^{b}

Different letters within the same column indicate significant differences ($P < 0.05$).

such as disulfide bonds and hydrophobic interactions (Somjid, Panpipat, Cheong, & Chaijan, 2022), forming a thermally irreversible gel network. Compared to the SO group, both the control and all emulsion groups exhibited a faster rate of increase and higher values in G' during this process.

The direct addition of SO can induce a portion of myosin to act as emulsifier, thereby occupying some of the hydrophobic sites on the myosin molecule (Shen et al., 2022). Moreover, the incompletely emulsified SO tends to aggregate into large oil droplets. This aggregation leads to an increased spatial distance between matrix proteins, hindering protein crosslinking (Song et al., 2022a), resulting in lower G' values throughout the entire heating process. In contrast, Pickering emulsions not only construct the gel network through the interfacial protein layer (Wang et al., 2023), but also allow the myosin heads to be embedded in the emulsion due to their good hydrophobicity, increasing the stability of myosin and facilitating its gelation function during subsequent heat-induced gelation processes (Liu et al., 2019). In addition, it has been reported that unabsorbed protein nanoparticles dispersed within the gel matrix in Pickering emulsion systems may form aggregates through disulfide bonds or hydrophobic interactions (Yu, Xiao, Xue, & Xue, 2022; Zhang, Xie, et al., 2023; Zhang et al., 2023). These aggregates supported the network structure, further enhancing the stability and strength of the gel system. The tan δ values represent the ratio of viscosity to elasticity, with lower values indicating stronger elastic behavior of the gel (Wang et al., 2023). Fig. 1B demonstrated that the lower tan δ values observed in the emulsion groups aligned with the stronger elasticity observed in the TPA results (Table 2).

3.4. Water holding capacity (WHC) and cooking loss (CL)

WHC and CL are indicators of the gel network's ability to capture and retain water or oil, and they are typically negatively correlated (Shen et al., 2022). As seen in Fig. 2, the SO group exhibited the lowest WHC (~86%) and the highest CL (~5.2%), indicating the poorest gel structure. In comparison to the SO group, all emulsion groups demonstrated higher WHC (> 90%) and lower CL (< 3.8%). This improvement can be attributed to the enhancement of gel network structure by Pickering emulsion, resulting in a stronger water/oil holding capacity. The hydrophilic groups on the surface of the protein layer at the emulsion interface can tightly bind to the water in the matrix through hydrogen bonding (Xu et al., 2023). This conversion of free water into bound water thus improves the WHC of the surimi gel. Additionally, the interfacial protein layer of the emulsions alleviates the repulsion of water molecules by the SO, thus reducing water loss from the system (Shen et al., 2022). Among the three emulsions, SPE and PPE exhibit better enhancement effects on the WHC and CL of the gel.

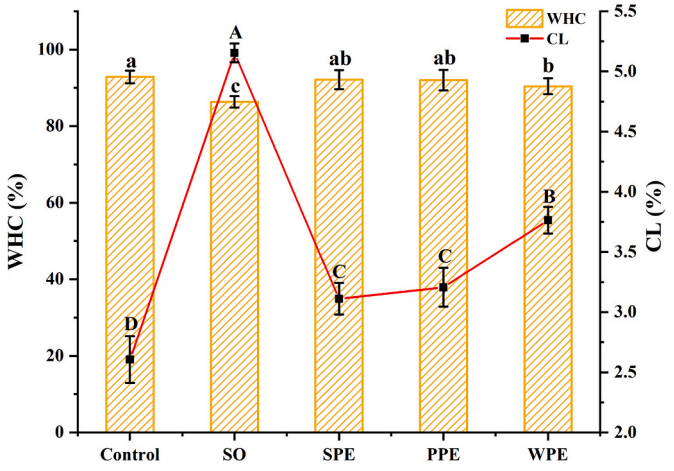

Fig. 2. Effect of SO addition on WHC and CL of surimi gel. Different lowercase letters or uppercase letters indicate significant differences between different samples of the same index ($P < 0.05$).

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

The water distribution of surimi gel directly impacts their WHC, which in turn affects their quality and stability (Song et al., 2022b). As shown in Fig. 3A, compared to the control, the T_{2a} and T_{2b} of the SO group exhibited a significant red shift. The significant increase in free water content (PT_{23}) ($P < 0.05$), indicated that the gel system's ability to retain water was weakened by SO, which was consistent with the observed decrease in WHC (Fig. 2). However, the relaxation times of all emulsion groups did not show significant migration compared to the control. The bound water content ($PT_{2a} + PT_{2b}$) and immobilized water content (PT_{22}) of the emulsion groups were significantly higher than those of the SO group ($P < 0.05$). These findings may relate to the denser network structure of the gel, which improved the water stability. Furthermore, the Pickering emulsion itself has the ability to bind to water molecules and inhibit water migration (Xu et al., 2023).

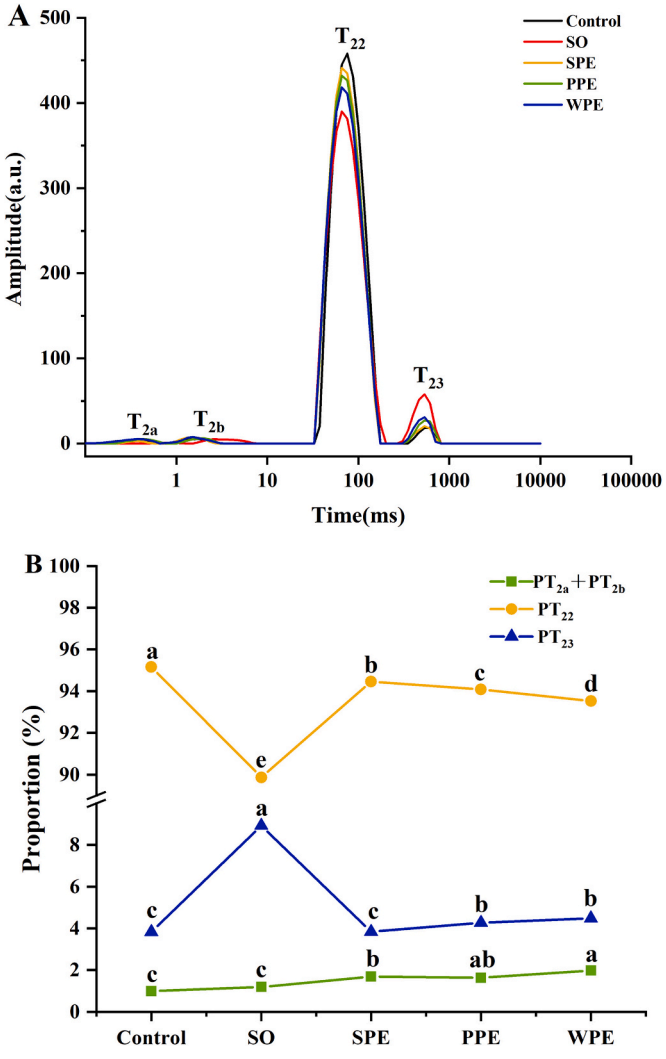

Fig. 3. Effects of SO addition on relaxation time (A) and relative contents of bound water ($PT_{2a} + PT_{2b}$), retained water (PT_{22}) and free water (PT_{23}) (B) of surimi gel. Different lowercase letters indicate significant differences between different samples of the same index ($P < 0.05$).

3.6. Scanning electron microscope (SEM)

The microstructure of surimi gel plays a crucial role in determining its gel properties. As illustrated in Fig. 4A, the control gel exhibited a dense protein network with small and uniform pores. In contrast, the protein network in the SO group appeared coarse and loose, with significantly larger and unevenly distributed pores, leading to lower gel strength (Table 2) and WHC (Fig. 2). This can be attributed to the inadequate emulsification of SO, which resulted in the migration and aggregation of oil droplets within the gel matrix during thermal gelation (Zhang, Xie, et al., 2023; Zhang, Zhao, et al., 2023). Consequently, the dispersion of these large-sized oil droplets hindered proper cross-linking between proteins, leading to a weaker gel structure. In comparison to directly adding SO, the utilization of Pickering emulsion significantly improved the densification and homogeneity of the gel network structure. As a result, this improvement positively influenced the textural properties of the gel, as demonstrated in Table 2.

3.7. Confocal laser scanning microscope (CLSM)

Further investigation of changes in protein network structure and oil droplet distribution was conducted using CLSM. Fig. 4B illustrates the protein network and oil droplets, displayed in red and green, respectively. It can be observed that the protein network structure in the control is dense, with only a small amount of oil distributed within it. In contrast, the SO group exhibited larger irregular oil droplet regions, which disrupt the continuity of the network structure. Compared to the SO group, the Pickering emulsion groups showed smaller and uniformly dispersed spherical oil droplets within the gel matrix. The protein network in the Pickering groups appeared continuous and dense, which aligns with the observations from SEM (Fig. 4A). The results demonstrated that incorporating SO as a Pickering emulsion improved the distribution of oil within the gel matrix. Consequently, this improvement significantly contributed to enhancing the gel network structure and textural properties.

3.8. Lipid oxidation

PUFAs are prone to oxidative degradation due to their high degree of unsaturation (Wang et al., 2023). As shown in Fig. 5A, the TBARS values of both the SO group and the three emulsion groups were significantly higher than those of the control ($P < 0.05$), indicating that a substantial amount of MDA was generated through the oxidation of SO within the gel during the two-stage heating process. However, lipid oxidation was significantly lower in all emulsion groups than in the SO group ($P < 0.05$). In the emulsion system, lipid oxidation mainly occurs at the oil-water interface, where pro-oxidants in the water phase come into contact with the oil wrapped in the emulsion (Keramat, Kheynoor, &

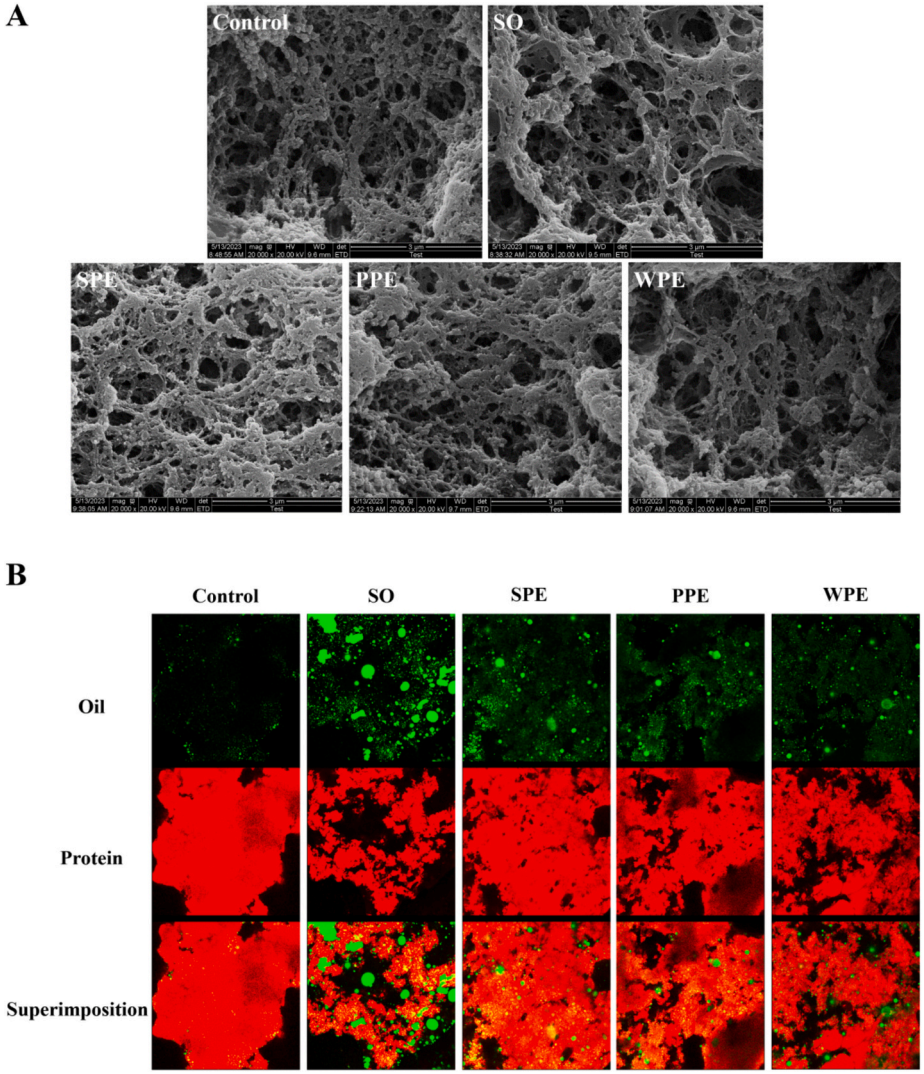

Fig. 4. SEM image (A) and CLSM image (B) of surimi gel.

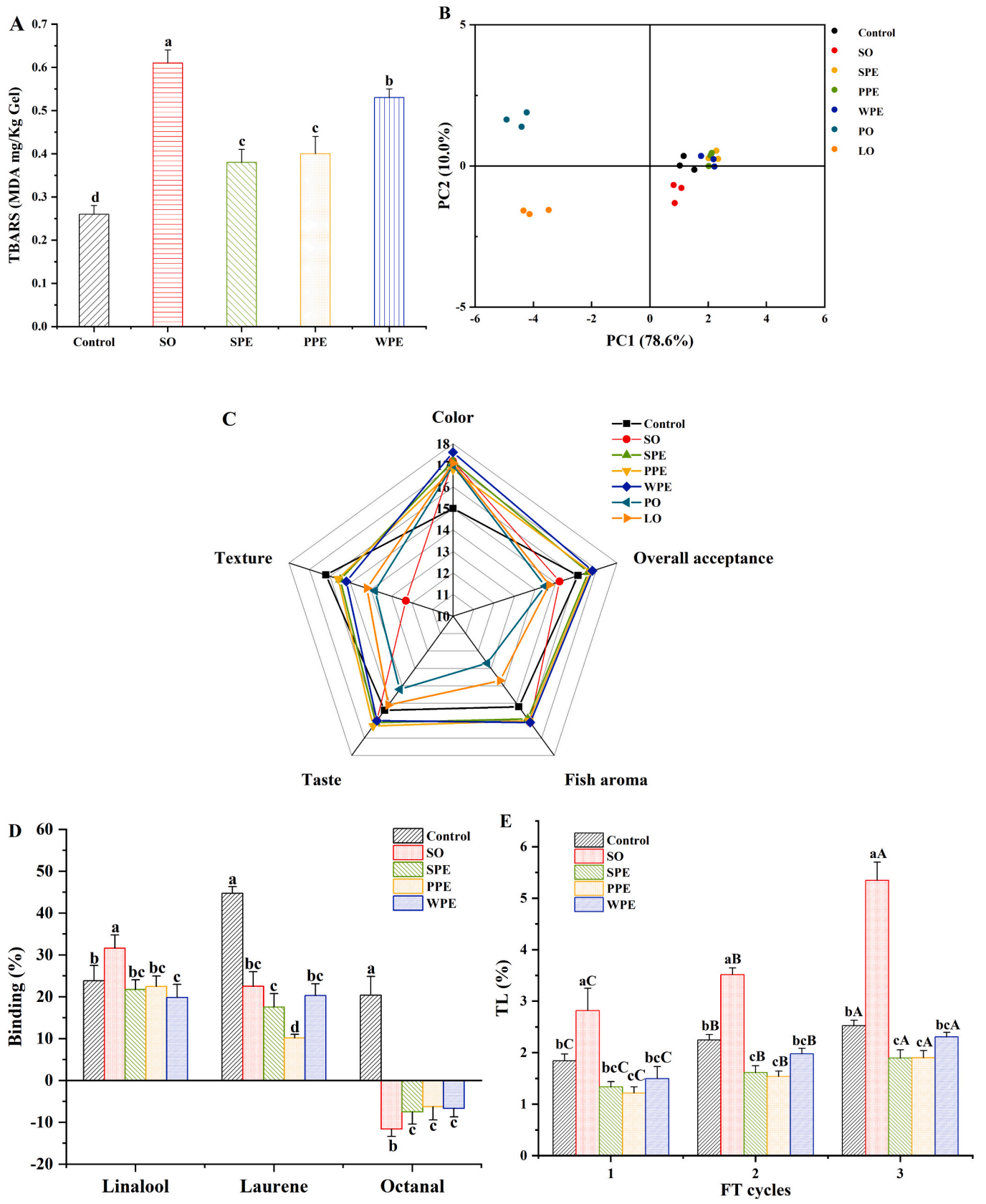

Fig. 5. Effects of SO addition on lipid oxidation (A), electronic nose principal component analysis (B), the adsorption capacity of flavor compounds (C), sensory evaluation (D) and freeze-thaw loss (E) of surimi gel. Different lowercase letters indicate significant differences between different samples of the same index ($P < 0.05$). Different uppercase letters indicate significant differences in the same samples treated by various FT cycles ($P < 0.05$).

Golmakani, 2022). Current studies (Cao et al., 2022; Feng et al., 2020; Li, Zheng, Ge, Zhao, & Sun, 2020) suggested that, compared to traditional emulsion, Pickering emulsions enhance lipid oxidation stability for several reasons: (1) During the preparation of Pickering emulsion, heat treatment induces the exposure of more hydrophobic amino acids on the surface of protein emulsifiers, facilitating their aggregation to form a thicker interfacial protein layer. This enhances the physical barrier effect, effectively isolating pro-oxidants from contacting oil and preventing lipid oxidation; (2) Heat treatment induces the exposure of more antioxidant amino acids on the surface of protein emulsifiers, crucial for enhancing the emulsion's antioxidant performance. Additionally, due to their larger specific surface area, Pickering emulsions allow the interfacial protein layer to more effectively exert antioxidant effects, thereby protecting the oil from oxidation. In this study, the ability of two legumes (SPI and PPI) to protect oil from extensive oxidation was better than that of WPI. This may be attributed to the fact that SPI and PPI form a more stable interfacial protein layer on the surface of SO (Benjamin et al., 2014).

3.9. Electronic nose analysis

Lard is commonly used in surimi gel products (Yu, Song, et al., 2022). However, due to health concerns, there is growing interest in replacing lard, which contains higher levels of saturated fatty acids, with vegetable oils that are richer in unsaturated fats, such as Peanut oil (PO) and Linseed oil (LO) (Chen et al., 2023; Pietrowski, Tahergorabi, & Jaczynski, 2012; Song et al., 2022a). To assess the odor profiles of the surimi gel samples, electronic nose analysis with principal component analysis (PCA) was employed. As shown in Fig. 5B, PC1 and PC2 accounted for a total contribution of 88.6%, indicating that these two principal components contained the majority of the characteristic information of the samples (Zhang, Zhao, et al., 2023). The spatial distribution of the samples revealed that those with SO additions were concentrated near the control, while the groups with PO and LO additions were located farther away from the control. The SO group and emulsion groups were situated on opposite sides of the control, with no overlapping areas, suggesting that the two types of additions imparted distinct flavors to the surimi gel. The proximity of all samples within the emulsion groups indicated their similarity in flavors. These findings indicated that incorporating native oils is more favorable for maintaining the characteristic flavor of the surimi gel, and different methods of incorporation can lead to variations in its flavor profile.

3.10. Sensory evaluation

As depicted in Fig. 5C, there were discernible differences in the sensory scores among the various groups of samples. All groups containing SO showed improvement in color score, with the WPE group achieving the highest score of 17.6. These results were consistent with the increased whiteness of the samples (Table 1). The direct addition of SO resulted in lower texture scores compared to the control, with the emulsion groups being closer to the control. This coincided with the observed changes in gel strength (Table 2). The taste and fish aroma scores of the SO group and emulsion groups were higher than those of the control. Conversely, the samples with added exogenous oils (PO and LO groups) had lower scores than the control. These results had relations with the noticeable presence of exogenous oil odor in the sturgeon surimi products, as indicated by the PCA results (Fig. 5B). The overall acceptability scores ranked as follows: Emulsion groups > Control > SO group > Exogenous oil groups. Therefore, the addition of endogenous oils, particularly in the form of Pickering emulsion, is advantageous in enhancing the quality of sturgeon surimi gel. These results provided direct evidence for the selection of oil in surimi processing.

3.11. Adsorption capacity of flavor substance

Linalool (floral), laurene (fatty), and octanal (fruity) are important volatile flavor substances in spices commonly used in Chinese cuisine (Yu, Song, et al., 2022; Yu, Xiao, et al., 2022). The ability of ingredients to adsorb these flavor substances can directly affect their post-cooking flavor and influence the consumer's perception of the eating experience. As shown in Fig. 5D, the addition of SO altered the adsorption capacity of the surimi gel for the three substances. Specifically, the SO group showed a significant increase in the adsorption of linalool ($P < 0.05$). However, the adsorption capacity of all emulsion groups for the three flavor substances showed varying degrees of decrease, with the adsorption rates of linalool and laurene being lower than those of the SO group. It is noteworthy that the levels of octanal content increased in the headspace vials of all addition groups, with the SO group having the highest content. These findings indicated that the addition of sturgeon oil, particularly through direct addition, enhanced the generation of octanal within the gel.

Proteins, lipids, and carbohydrates are the primary food components that interact with flavor substances, with proteins and lipids playing particularly important roles (Guichard, 2002). The change of conformation of protein (such as myosin) will affect its interaction with flavor substances, and then affect the flavor of food (Xu et al., 2019). External conditions such as heating can transform the secondary structure of myosin from α-helical to β-folded structures, exposing more hydrophobic binding sites (such as serine residues, proline residues, and tryptophan residues) and sulfhydryl groups (Liu et al., 2022), thereby facilitating its binding with hydrophobic flavor compounds. This may contribute to enhancing the adsorption capacity of the control for the three flavor substances investigated in this study. However, the introduction of SO disrupted the spatial distribution of proteins and lipids within the original surimi system, potentially altering the arrangement of hydrophilic and lipophilic groups within the thermogel. This alteration could have resulted in a decrease in the adsorption of flavor substances from the samples. In this experiment, it was observed that among all the groups with different additions, only the SO group demonstrated a higher adsorption capacity specifically for linalool. This increase may be due to the molecular structure of linalool, which consists of a smaller hydroxyl hydrophilic group and a larger hydrophobic region composed of carbon and hydrogen chains. In the SO group, the oil tended to exist in a more dispersed state, as observed in the CLSM results (Fig. 4B), resulting in the exposure of more hydrophilic or hydrophobic ends. This exposure could potentially facilitate the binding of flavor compounds with dual functional groups to some extent. Additionally, in an oil-containing gel, the adsorption capacity for flavor compounds is closely related to the gel's network structure. The larger and more porous pores in the gels of the SO group provided more opportunities for contact between flavor compounds and binding sites, which may be another reason for its stronger adsorption capacity.

The aldehyde group exhibits slightly lower hydrophilicity compared to the hydroxyl group. Based on this observation, it would be expected that the adsorption of octanal would be similar to laurene. However, the experimental results revealed significant differences. It has been reported that the thermal oxidation of linoleic or linolenic acid leads to the generation of a considerable quantity of short-chain aldehydes, including hexanal, heptanal, and octanal (Li et al., 2022). The increased lipid oxidation observed in the SO group and emulsion groups (Fig. 5A), as well as the heating treatment, could potentially contribute to an increase in the content of octanal in the headspace vials. In a study conducted by Li et al. (2022), significant amounts of octanal were detected in steamed sturgeon. Another study by Yarnpakdee, Benjakul, Nalinanon, and Kristinsson (2012) also demonstrated a positive correlation between octanal and fishy odor. Therefore, the utilization of Pickering emulsions may have the potential to reduce the production of octanal in the gel by diminishing the extent of lipid oxidation. This improvement could lead to a more desirable fish flavor in the gel.

3.12. Freeze-thaw (FT) stability

Temperature fluctuations are difficult to avoid during the transportation, storage, and distribution of frozen foods, which may cause repeated thawing of surimi products and impact their quality (Cen et al., 2023). According to Fig. 5E, the TL of all groups exhibited a significant increase ($P < 0.05$) with an increasing number of FT cycles. This phenomenon occurs due to the formation of larger ice crystals within the gel resulting from repeated freezing and thawing, leading to irreversible physical damage to the internal structure of the gel (Wang et al., 2023). Consequently, the water stability of the gel is reduced, resulting in an increase in TL. The SO group exhibited the highest TL. This was attributed to their high content of free water (Fig. 3B) and loose gel network structure (Fig. 4A), which resulted in a larger volume of ice crystals formed during the freeze-thaw process. Thus, the gel structure suffered more damage. The emulsion groups demonstrated significantly lower TL compared to the SO group ($P < 0.05$). Furthermore, both the SPE group and the PPE group had significantly lower TL than the control ($P < 0.05$), indicating that SPE and PPE provided better protection for the gel during freezing. Firstly, the incorporation of Pickering emulsion in the surimi gel contributed to a denser structure and improved texture, making it more resistant to external damage. This enhanced gel structure provided better protection against the detrimental effects of freezing and thawing. Secondly, the addition of Pickering emulsion may enhance the freezing rate of the surimi gels, resulting in the formation of smaller ice crystals during freezing (Cen et al., 2023). This reduction in ice crystal size minimizes the extent of damage caused to the gel network structure by ice crystals. These findings suggested that the inclusion of SO in the form of Pickering emulsion can enhance the freeze-thaw stability of surimi gels.

4. Conclusion

Adding SO (8%) in the form of Pickering emulsion can improve the deteriorating effects on the gel properties of heat-induced sturgeon surimi gels caused by the direct addition of SO. Pickering emulsion also improved the overall acceptability of sturgeon surimi gels, reduced its lipid oxidation level, and enhanced its freeze-thaw stability, which is advantageous for maintaining gel quality during storage, transportation, and consumption. Moreover, the addition of SO helps preserve the inherent characteristic flavor of sturgeon products. This study provides a theoretical basis and reference for the comprehensive utilization of sturgeon processing by-products by preparing a sturgeon surimi gel enriched with PUFAs using sturgeon autogenous oil. The results of this study also provide a reference for using oil to improve the quality of other protein gel products.

CRediT authorship contribution statement

Li Yuan: Writing – original draft, Supervision, Conceptualization. **Xiaomo Guo:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Zhiyu Xiong:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Xin Wang:** Writing – review & editing, Methodology, Data curation. **Abdul Razak Monto:** Writing – review & editing, Methodology. **Wengang Jin:** Writing – review & editing, Formal analysis. **Jianrong Li:** Writing – review & editing, Supervision, Formal analysis. **Ruichang Gao:** Project administration, Funding acquisition.

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

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.101451.

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