Effects of wheat fiber addition on emulsion and lipid/protein stabilities of an omega-3 fatty acid–fortified chicken surimi product

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ABSTRACT Meat, except marine sources, is a highly nutritious food but generally lacks some healthy ingredients, such as omega-3 fatty acids (**ω-3 FA**) and dietary fiber. However, ω-3 FA and dietary fiber could be incorporated during the manufacture of surimi-like products. In our previous study, chicken surimi was successfully developed from spent-hen breast. Although there was no ($P > 0.05$) difference in water-holding capacity between wheat fiber and carrageenan, an increased ($P < 0.05$) flaxseed oil–holding capacity was observed in wheat fiber samples. Furthermore, an addition of 5% wheat fiber resulted in optimal emulsification capacity and less cooking loss at 4°C for 14 d and at −20°C for 60 d ($P < 0.05$). Because of the lower ($P < 0.05$) purge and centrifugation losses, thiol group content, and thiobarbituric acid reactive substance value than those formulated with more flaxseed oil, 12% flaxseed oil was an optimal level in chicken surimi with 5% wheat fiber. Scanning electron microscopy results also showed better emulsification of surimi batters with wheat fiber compared with those without wheat fiber, and meanwhile, the formulation with 5% wheat fiber could hold up to 12% flaxseed oil as well. To enhance flaxseed-oil addition, semi-manufactured chicken surimi batter was successfully fortified with a combination of 12% flaxseed oil and 5% wheat fiber. This surimi-like product with dietary fiber and ω-3 FA would fit the need in the current market regarding consumers' demands for high nutritional value and improved processing characteristics.

Key words: chicken surimi, emulsion stability, lipid/protein oxidation, omega-3 fatty acid, wheat fiber

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INTRODUCTION

In comparison with official recommendations, most people consume insufficient omega-3 fatty acids (**ω-3 FA**). Meat products other than marine sources are considered as highly nutritious and versatile but lack ω-3 FA (Marsh et al., 2004). However, it is possible to incorporate functional ingredients in surimi owing to its high variability in formula and composition (Giri et al., 2011). Hence, an ω-3 FA–enriched surimi was developed (Wang et al., 2016). Surimi was first developed at an industrial level in Hokkaido, Japan (Park, 2013). Surimi is an edible processed paste made from fish or meat and an excellent protein resource. The quality of products can be improved by surimi processing through the removal of unpleasant compounds, such as lipids, blood, odors, and natural enzymes.

Both protein and ω-3 FA are necessary for human health. Flaxseed oil has the highest ratio of ω-3 to omega-6 (**ω-6**) FA among plant sources (National Research Council, 1993). In comparison with fish oil, the incorporation of flaxseed oil in meat products can improve the nutrition quality with less adverse influence on the product's palatability (Wang et al., 2016). Besides, it has been reported that dietary fiber could improve the emulsion stability, cooking loss, shelf-life prolongation, and textural properties in emulsion-type sausage and other meat products (Mehta et al., 2015). Fortification of a fish-based product with dietary fiber or ω-3 rich oil either alone or in combination could

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improve its rheological and textural characteristics (Debusca et al., 2013). Carrageenan contributes to gel formation and water retention in the meat products; hence, it is well applied in the meat industry (Trius et al., 1996). However, owing to the health concern of carrageenan on inflammatory bowel disease (Tobacman, 2001), it is worth to look for a substitute in meat products. Dietary fiber has excellent water- and oil-binding capacities as well as gel-forming ability (Talukder, 2015). Meanwhile, it has been reported that dietary fiber is a potential ingredient that could be used in a low-fat beef sausage formulation (Ktari et al., 2014).

Although global seafood production (including freshwater areas) increased from 166.8 to 199.74 million tons from 2010 to 2015, the production of capture fisheries remained unchanged owing to environmental changes (Ritchie and Roser, 2019a). Furthermore, the fish consumption per capita has been declining in most developed countries within the past decade, particularly in Japan (Ritchie and Roser, 2019a). In contrast, poultry production has continuously increased worldwide, and the poultry meat consumption per capita has elevated rapidly since 2000 (Ritchie and Roser, 2019b). Consumers are pursuing healthier ingredients rather than a sense of satisfaction; thus, they crave meat products with healthier composition or functional claims (Jiménez-Colmenero et al., 2001; Arihara, 2006). Although the negative impacts of meat intake on health are still disputed, it is still meaningful to develop better-quality, more nutritional, and healthier chicken-sourced meat products. The trends indicate a potential for a development of functional chicken product. The aim of this study is to investigate a possibility of wheat fiber on the increased addition of flaxseed oil into the recipe of a semimanufactured chicken surimi product.

MATERIALS AND METHODS

Materials

Broiler breast meat was purchased from a local meat packer (Ding Yao Food Co. Ltd., New Taipei City, Taiwan), packaged in vacuum bags, and transported to our laboratory at −20°C. All other chemicals used in this study were of analytical or food grade. Carrageenan (Genu Texturizer Type MB-101F) and wheat fiber (VITACEL Wheat Fiber WF 200) were purchased from Gemfont Co., Ltd. (Taipei, Taiwan).

In Vitro Water- and Oil-Binding Capacities of Dietary Fiber

Carrageenan and wheat fiber, as well as distilled water/flaxseed oil (Gut & Gerne, Stubenberg, Germany), were mixed at a ratio of 1:100 (w/w) in a 50-mL centrifuge tube. The tubes were shaken on a rotator stirrer (LWS 2100-A; Diytrade Inc., New Taipei City, Taiwan) at 150 rpm (∼3 × g) overnight and then centrifuged at 2,500 × *g* for 30 min at 4°C (Centrifuge 3700; Kubota Corp., Osaka, Japan). The unabsorbed water/flaxseed oil was poured out, and the water/oil–binding capacity (%) was calculated as follows: weight $_{\text{absorbed water/oil}}$ (g)/weight $_{\text{sample}}$ (g) × 100%.

Preparation of Raw Chicken Surimi

A suitable amount of broiler breast was minced in a homogenizer (Model: RC-Blixer 4, 4.5L S/S bowl; Robot Couple, South Melbourne, Australia). Based on a previous study, a washing solution containing 0.1% (w/v) NaCl can reduce the loss of myofibrillar proteins in the extraction of proteins from the spent-hen breast effectively (Wang et al., 2016). There were 3 washing steps. During each step, the minced broiler breast was blended with a washing solution at 4°C at a ratio of 1:4 (w/w). In this experiment, 0.1% (w/w) NaCl solution (Taiyen Co., Tainan, Taiwan) was used in only the third washing step and centrifugation was carried out at 8,000 × *g* (Centrifuge 6500 and AG-5600A, Kubota Corp., Osaka, Japan) for 15 min at 4°C in each washing step. Samples of chicken surimi batter were obtained by mixing the recovered chicken-breast protein with 2.0% (w/w) salt, 0.3% (w/w) polyphosphate (Chien-Yuan Inc., Taipei, Taiwan), and a cryoprotectant mixture containing 4.0% (w/w) trehalose (Hayashibara Shoji Inc., Okayama, Japan) and 4.0% (w/w) sorbitol (Roquette, Lestrem, France). The chicken surimi batter was stored at −20°C and thawed overnight at 4°C before the experiment started. Furthermore, it was divided into 4 parts, which were shown as follows: 1) a combination of 5% wheat fiber with 10% flaxseed oil; 2) a combination of 5% wheat fiber with 12% flaxseed oil; 3) a combination of 5% wheat fiber with 14% flaxseed oil; and 4) 10% flaxseed oil without wheat fiber. Meanwhile, the recipes of different formulated chicken surimi batters are shown in Supplementary Table 2. SiO_2 was used as an inert filler in the recipe of chicken surimi batters in place of wheat fiber and partial amount of flaxseed oil in this study. Flaxseed oil, wheat fiber, and SiO_2 were added to the chicken surimi batter in 4 combinations to a total final concentration of 19 g/100 g. Tahergorabi et al. (2012) reported that SiO_2 does not contribute to texture development. Moreover, during the manufacture of chicken surimi, dry ice was added at a ratio of 1:10 (w/w) into chicken surimi batter to retard the lipid peroxidation (Wang et al., 2019). The chicken surimi obtained from each treatment was stored at 4°C or −20°C. At the same time, after various storage periods, some of the samples were heated in a circulating water bath (GDB160; GenePure Technology Co., Ltd., Taichung, Taiwan) at 100°C for 15 min (core temperature > 80°C), and the heat-set (cooked) chicken surimi batters were collected for subsequent analyses.

Texture Profile Analysis of Heat-Set Chicken Surimi

Texture profile analysis was performed with 3 replicates of each independent-batch sample. The chicken

surimi obtained from different treatments was cooked at 100°C for 15 min (core temperature > 80°C) and cooled for approximately 1 h (core temperature: approximately 25°C). Then, cubic-centimeter cooked samples of cooked chicken surimi were prepared (Wang et al., 2016). The textural properties of each cooked sample were measured using a P/50 cylinder probe (50-mm-diameter aluminum cylinder; Stable Micro System Ltd., Godalming, UK) and a texture analyzer (TA.XTplus; Stable Micro System Ltd., Godalming, UK). The samples were compressed to 60% strain, and the test speed was 5 mm/s (Supplementary Table 1). The hardness (N), springiness, cohesiveness, gumminess (N), chewiness (N), and resilience were measured for further analyses.

Color Parameter of Heat-Set Chicken Surimi

The color parameters of the cooled heat-set chicken surimi obtained from different treatments were determined using a color checker (Model NR-11; Nippon Denshoku, Bunkyo, Tokyo, Japan). The L*, a*, and b* values indicated the lightness, redness, and yellowness, respectively. The heat-set samples (core temperature > 80°C) were equilibrated to room temperature (25°C), and then, color parameters (CIE L*, a*, and b*) were measured on the sample surface.

Cooking Loss of Heat-Set Chicken Surimi

One hundred grams of raw chicken surimi obtained from different treatments were heated at 100°C for 15 min (core temperature > 80°C) and cooled (core temperature: app. 25°C) as previously described. The cool heat-set chicken surimi was wiped and weighed, and the weight loss percentage was calculated using the following equation: cooking loss (%) = (weight $_{\text{before}}$–weight $_{\text{after}}$)/weight $_{\text{before}}$ × 100%.

Emulsion Stability of Raw Chicken Surimi

The emulsion stability was measured as per a previous method with a slight modification (Choi et al., 2009). After the heat-set chicken surimi obtained from different treatments was cooled to a core temperature of approximately 25°C, water and oil layers were isolated. The portions of water and oil layers (g/100 g surimi) were calculated as follows: weight (g)$_{\text{water layer}}$/weight (g)$_{\text{raw chicken surimi batter}}$ x 100% and weight (g)$_{\text{oil layer}}$/weight (g)$_{\text{raw chicken surimi batter}}$ × 100%, respectively.

Scanning Electron Microscopy of Raw Chicken Surimi

The microstructure of the raw chicken surimi was observed using a scanning electron microscope (**SEM**). First, the raw chicken surimi obtained from different treatments was placed in 2-mL tubes, cooked at 100°C for 15 min, and sliced into cylindrical gels (diameter: 1 cm, height: 0.2 cm). Each sample of gel was soaked in protein-fixing solvent (2.5% [w/v] glutaraldehyde in PBS solution) for 1 h, washed with PBS, and soaked in lipid-fixing solvent (4% [w/v] osmium tetroxide [Sigma-Aldrich Co., LLC., St Louis, MO] in PBS solution). After fixing the protein and lipids, a dehydration process was conducted. The dehydration process included alcohol dehydration (35, 50, 70, 85, 90, 95, and 100% [v/v] ethanol; Merck, Taipei, Taiwan) and critical point drying (Samdri-PVT-3B; Tousimis Co., Inc., Rockville, MD). Finally, the samples of gel were covered with gold using an ion sputter (SPI, West Chester, PA) and observed using an SEM (JSM 6510 LV, JEOL, Tokyo, Japan) at magnifications of 200X and 2,000X.

Centrifugation Loss of Raw Chicken Surimi after Storage

The centrifugation loss was measured using a previous method with slight modification (Ding et al., 2018). Briefly, the centrifugation loss of raw chicken surimi obtained from different treatments was measured after 0, 7, and 14 d of storage at 4°C, as well as after 30 and 60 d of storage at −20°C. Approximately 0.2 g of raw chicken surimi was weighed and placed into 1.5-mL centrifugation tubes with filter papers (No.1 55 mm diam. Advantec). The raw chicken surimi was then centrifuged at 4°C at low speed (100 × *g*) for 1 h (Centrifuge 3700; Kubota Corp., Osaka, Japan). The centrifugation loss was calculated as the fluid loss and expressed as the percentage of the weight of liquid release using the following equation: centrifugation loss (%) = (weight $_{\text{before}}$–weight $_{\text{after}}$)/weight $_{\text{before}}$ × 100%.

Purge Loss of Raw Chicken Surimi

The purge loss of raw chicken surimi obtained from different treatments was measured using a previous method with slight modifications (Ding et al., 2018). The purge loss was measured after 0, 7, and 14 d of storage at 4°C, as well as after 30 and 60 d of storage at −20°C. Approximately 2 g of raw chicken surimi was wiped with Kimwipes (Kinberly-Clark Global Sales, Inc., Roswell, GA) to remove excess surface moisture before storage, weighed to record the initial weight, and vacuum packed. After a precise storage period, the samples were dried with Kimwipes and weighed again. The purge loss was calculated as the weight loss and expressed as the percentage of weight loss with the following equation: purge loss (%) = (weight $_{\text{before}}$–weight $_{\text{after}}$)/weight $_{\text{before}}$ × 100%

Lipid and Protein Oxidation of Raw Chicken Surimi on Storage

Raw chicken surimi obtained from different treatments stored at 4°C and 20°C was separated and packed for assigning the day 0, 7, and 14 and on day 30 and 60. Next, 7.5 mL of PBS (pH 7.0) was added to the raw chicken surimi (2.5 g) on ice, and then, they were centrifuged at 1,400 × *g* for 15 min at 4°C (Centrifuge 3700;

Kubota Corp., Osaka, Japan). The supernatant was collected and stored at −80°C for further analyses of the lipid and protein oxidation. The amount of thiobarbituric acid reactive substance (**TBARS**) was used as an index for the lipid oxidation of the raw batters (Wang et al., 2016, 2019). Typically, 60 μL of 10% homogenates was reacted with 90 μL of 2-thiobarbituric acid solution (Sigma-Aldrich Co., LLC., St Louis, MO) and 510 μL of trichloroacetic acid-hydrochloride solution (Sigma-Aldrich Co., LLC., St Louis, MO). The mixture was vortexed and then incubated in a boiling water bath at 100°C for 30 min. The sample was cooled, vortexed again, and centrifuged at 9,000 × *g* for 3 min at 4°C (Centrifuge 3700; Kubota Corp., Osaka, Japan). The absorbance of the resulting supernatant was read at 535 nm against a blank (PBS solution, pH 7.0) with an ELISA reader (Hybrid Reader, Synergy H1; BioTek Inc., Winooski, VT). The TBARS values in the raw chicken surimi were calculated by using a molar extinction coefficient of 156,000 M^{-1} cm^{-1} and demonstrated as mg MDA eq./kg raw chicken surimi.

The protein oxidation level of the chicken surimi obtained from different treatments was evaluated by the total sulfhydryl (**-SH**) content using a method from previous reports with slight modification (Wang et al., 2019). First, the 10% (w/w) homogenate of raw chicken surimi was prepared. Then, 60 μL of 10% homogenates was reacted with 480 μL of EDTA solution (0.086 M Tris, 0.09 M glycine, 4 mM EDTA, pH 8.0) and centrifuged at 9,000 × *g* for 15 min at 4°C. An aliquot of 450 μL of the supernatant was added to 50 μL of 5,5′-dithiobis-(2-nitrobenzoic acid) (10 mM DTNB; Alfa Aesar, MA). The mixture was vortexed and then incubated at room temperature in darkness for 30 min. The absorbance of the resulting supernatant was read at 412 nm with an ELISA reader. The SH concentration was expressed in μmole/g surimi batter and calculated using a molar extinction coefficient of 13,600 M^{-1} cm^{-1}. The total sulfhydryl content in raw chicken-surimi were calculated by using a molar extinction coefficient of 156,000 M^{-1} cm^{-1} and demonstrated as μmole/g raw chicken-surimi batter.

Fatty Acid Composition in Raw or Cooked Chicken Surimi

Raw chicken surimi obtained from different treatments stored at 4°C and 20°C was separated and packed for assigning the day 0, 7, and 14 and on day 30 and 60. The fatty acid (**FA**) profile in raw or cooked chicken surimi (core temperature > 80°C) obtained from each treatment was assayed as per previous reports (Wang et al., 2016, 2019). The lipid was extracted from raw or cooked batters using Folch solution (chloroform:methanol = 2:1, v/v). Fatty acids were transmethylated by the addition of 4 mL of 4% (w/v) methanolic sulfuric acid (Sigma-Aldrich Co., LLC., St. Louis, MO). The mixture was saponified by transferring it through a glass Pasteur pipette filled with sodium sulfate (Sigma-Aldrich Co.) and then dried. The FA methyl esters were resuspended in filtered isooctane. The FA methyl esters were analyzed using a gas chromatograph (Model#: 6890 N; Agilent, Santa Clara, CA) and a flame ionization detector fitted with a highly polar stationary phase (100-m length, 0.25-mm inside diameter, 0.20-μm film thickness; SP-2560 column Supelco Inc., Bellefonte, PA). The injector and detector temperatures were maintained at 250°C and 300°C, respectively, while the column temperature had an initial temperature of 170°C and final temperature of 200°C with increases at 3°C/min and then maintained at 200°C for 50 min. The stationary phase was CP-Silica 88 (Varian Analytical Instruments, Walnut Creek, CA). Helium was the carrier gas (0.75 mL/min), and a split ratio of 40:1 was used. The FA were identified by comparing their retention times with known standards (Sigma-Aldrich Co.). Peak areas and the amounts of each FA (Sigma-Aldrich Co.) were computed by integration using Star GC Workstation, version 6, software (Varian Analytical Instruments). The total saturated FA, monounsaturated FA, polyunsaturated FA (**PUFA**), ω-3 FA (Σ ω-3 FA), ω-6 FA (Σ ω-6 FA), and the ratio of total ω-3 FA and ω-6 FA (Σ ω-3 FA/ Σ ω-6 FA) were summarized based on each category of identified FA.

Statistical Analysis

All analytical parameters were determined in 3 independent batches (replications, n = 3). The in vitro water-holding capacity (**WHC**) and oil-holding capacity (**OHC**) between carrageenan and wheat fiber were differentiated by Student *t* test ($P < 0.05$). The other testing parameters were measured 3 times (at least triplicates for each replication) in each batch and subjected to 1-way ANOVA. When a difference ($P < 0.05$) among groups was detected, differences between treatments were further distinguished using the least significant difference test. All statistical analyses of data were conducted by using SAS (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

In vitro WHC and OHC Between Carrageenan and Wheat Fiber

Figure 1 shows the results of the in vitro WHC and OHC between carrageenan and wheat fiber. There was no ($P > 0.05$) difference on WHC between carrageenan and wheat fiber, but there was a higher ($P < 0.05$) OHC in wheat fiber than carrageenan. Carrageenan is a common food additive in meat products because of its proper gel formation and water retention. (Bater et al., 1993; Trius et al., 1996). It has been reported that carrageenan can improve the emulsion stability, WHC, textural parameters, and sensory properties of formulated turkey sausages (Ayadi et al., 2009). However, it is suspected that undigested carrageenan could induce intestinal inflammation or even promote cancer

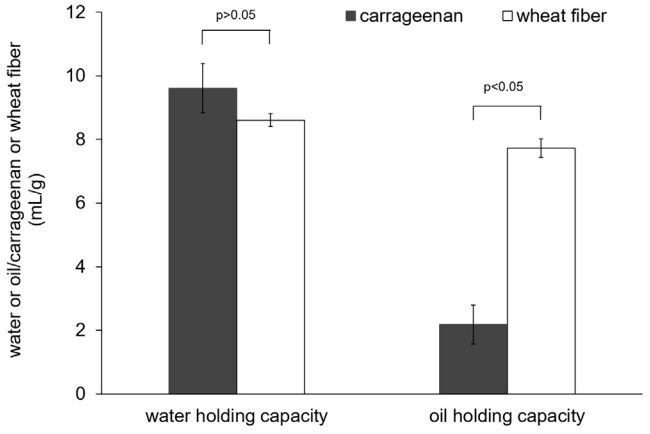

Figure 1. In vitro water- and oil-holding capacities of carrageenan and wheat fiber. The data are given as mean ± SEM (n = 3).

occurrence (Tobacman, 2001; Martino et al., 2017). Owing to absence of definitive reports regarding the varying degrees of human susceptibility to inflammation effects of carrageenan, Joint FAO/WHO Expert Committee on Food Additives (57th Meeting) (2002) reported that the acceptable daily intake for carrageenan is regarded as "not specified", meaning that the total dietary intake of carrageenan when used as a food additive does not harm human health. Hence, the substitution of carrageenan on the meat product could be interesting and practical. Talukder (2015) indicated that the certain dietary fiber can be a binder, extender, and filler when they are incorporated in the processed meat products thus improving not only nutritional components but also processing characteristics, that is WHC, emulsion stability, shear press value, and sensory characters of finished products. It was reported that wheat fiber could reduce cooking loss and enhance the emulsion stability and viscosity of frankfurter sausages (Choe et al., 2013). Besbes et al. (2008) also indicated that wheat fiber can improve the stabilization of fat emulsions in beef burger. Based on the results of in vitro WHC and OHC, wheat fiber is a potential ingredient in chicken surimi products because its good WHC and OHC could enhance the nutritional value (higher ω-3 FA content) and allows the batters to hold more lipids during storage.

Quality and Textural Changes of Cooked Chicken Surimi With 5% Wheat Fiber and Different Flaxseed Oil Levels

Figure 2 shows the effects of wheat fiber addition on cooking loss, emulsion stability, and microstructural observation for chicken surimi products with different added amount of flaxseed oil. In comparison with the batter with only 10% flaxseed oil added (Figure 1A), the ones that contain wheat fiber had the lower cooking loss and higher emulsion stability ($P < 0.05$). Among the chicken surimi with 5% wheat fiber, there were no ($P > 0.05$) differences in the cooking loss and the emulsion stability between ones containing 10 and 12% flaxseed oil. However, 14% flaxseed oil addition resulted in higher cooking loss ($P < 0.05$) and a greater fat layer ($P < 0.05$) than with the other levels of flaxseed oil addition. Table 1 shows the texture profiles and color properties of a combination of 5% wheat fiber and chicken surimi batters with different flaxseed oil levels. There were no ($P > 0.05$) differences on springiness, cohesiveness, and resilience among chicken surimi with the 3 different flaxseed oil levels. However, the hardness,

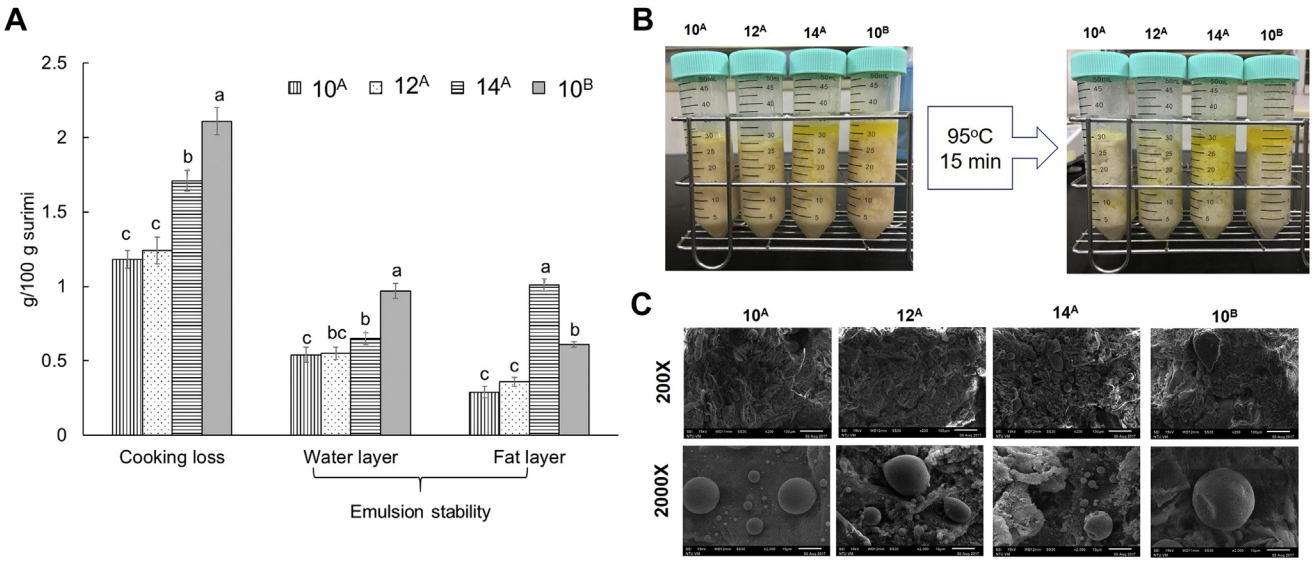

Figure 2. Cooking loss, emulsion stability, appearances, and scanning electron micrographs of chicken surimi. (A) Cooking loss and emulsion stability of chicken surimi. Data are given as mean ± SEM (n = 3). [a–c]Mean values without the common letter in each testing parameter are significantly different ($P < 0.05$). (B) Appearances of all chicken surimi obtained from different treatments in tubes before and after heating at 100°C for 15 min. (C) Scanning electron micrographs taken with 200X and 2,000X magnifications. Scale bars indicate 100 μm and 10 μm, respectively. Abbreviations: 10^A, chicken surimi batter with both 10% flaxseed oil and 5% wheat fiber; 10^B, chicken surimi with 10% flaxseed oil but without 5% wheat fiber; 12^A, chicken surimi batter with both 12% flaxseed oil and 5% wheat fiber; 14^A, chicken surimi with both 14% flaxseed oil and 5% wheat fiber.

Table 1. Effects of different levels of flaxseed oil addition on texture profile and color properties of raw chicken surimi with 5% wheat fiber.

Flaxseed-oil level (%)	10	12	14
	Texture profile analyses		
Hardness (N)	0.90 ± 0.07[a]	0.65 ± 0.03[b]	0.48 ± 0.03[c]
Springiness	0.80 ± 0.01[a]	0.81 ± 0.00[a]	0.81 ± 0.03[a]
Cohesiveness	0.53 ± 0.01[a]	0.52 ± 0.02[a]	0.54 ± 0.01[a]
Gumminess (N)	0.48 ± 0.05[a]	0.34 ± 0.02[b]	0.26 ± 0.02[b]
Chewiness (N)	0.39 ± 0.05[a]	0.27 ± 0.02[b]	0.21 ± 0.02[b]
Resilience	0.20 ± 0.00[a]	0.18 ± 0.01[a]	0.17 ± 0.00[a]
	Color properties		
L*	83.55 ± 0.25[a]	82.63 ± 0.18[a,b]	81.34 ± 0.59[b]
a*	1.23 ± 0.05[a]	1.44 ± 0.08[a]	1.26 ± 0.09[a]
b*	19.84 ± 0.64[b]	23.90 ± 1.34[a,b]	23.63 ± 1.29[a]
Whiteness	74.20 ± 0.60[a]	70.40 ± 1.13[b]	69.86 ± 1.38[b]

[a–c]Mean values without the common letter in each testing parameter are significantly different ($P < 0.05$).

Data are given as mean ± SEM (n = 3).

Whiteness = $100-.\sqrt{(100-L)^2+a^2+b^2)}$

gumminess, and chewiness were decreased ($P < 0.05$) with increased flaxseed oil addition, especially with 14% flaxseed oil. Regarding the color properties, the lightness (L*) and whiteness of the surimi products were decreased ($P < 0.05$) as the flaxseed oil levels increased, but the yellowness (b*) was increased ($P < 0.05$). The redness/greenness (a*) of chicken surimi with 5% wheat fiber was not influenced by the different flaxseed oil contents ($P > 0.05$). Figure 2B shows images of the raw flaxseed oil–fortified chicken surimi. More liquid was expelled in chicken surimi with higher flaxseed oil added levels after they were heated at 100°C for 15 min, but wheat fiber addition decreased the volume of expelled liquid from heat-set chicken surimi (Figure 2B). The topography of chicken surimi was observed by a SEM as well (Figure 2C). Generally, there were more oil droplets in the 12 and 14% flaxseed oil formulations, and oil droplets were uniformly distributed in chicken surimi with the wheat fiber addition. The SEM results illustrated the better emulsification of chicken surimi with wheat fiber than those without fiber (10^A group vs. 10^B group, Figure 2). Overall, these results clearly indicated that the surimi containing 5% wheat fiber could hold up to 12% flaxseed oil.

Flaxseed oil has several health benefits. Upper limit of 10% vegetable oil has been added to surimi products in many studies owing to the characteristics of flaxseed oil, which is high in unsaturated FA (Debusca et al., 2013; Shi et al., 2014; Wang et al., 2016). Hence, the emulsion stability and the cooking loss of chicken surimi with different flaxseed oil levels (10, 12, and 14%) were studied to determine the maximum flaxseed oil addition (Figure 2A). The results of the cooking loss and the emulsion stability in this study were consistent with the results of a previous study, which reported that the cooking loss was lower when 3 or 6% wheat fiber was added to minced fish products (Sánchez-Alonso et al., 2007). Theoretically, cooking loss is closely related to the taste, appearance, juiciness, and other features of a meat product (Aaslyng et al., 2003). Previous studies reported that 2% oat fiber addition in hamburger meat (without extra water addition) could reduce cooking losses by 20 to 40% and enhanced the WHC and emulsion stability of the meat products (Alakhras et al., 2016). During the production of comminuted meat products, the mincing process could destroy the tissue structure that holds water, so the WHC of this meat product is decreased (Schmidt et al., 2013). Controlling cooking loss and the emulsion stability is essential to maintain proper juiciness of meat products (Choi et al., 2009). In emulsification-type food products, the interaction of fat or lipid and protein plays a crucial role. An increased vegetable oil addition in meat products results in tender texture because oil alters the network formation and the physicochemical properties of the protein (Shi et al., 2014). A similar result was also observed in this study (Table 1), and the wheat fiber (5%, w/w) in our ω-3 FA–fortified chicken surimi products is recommended based on the appearance of the heat-set surimi (Figure 2B). Our data on the color properties fully agreed with that of the study by Shi et al., who reported that the addition of vegetable oil was considered as an effective way to improve the color of surimi gels (Shi et al., 2014). The color of chicken surimi with 14% flaxseed oil added showed the highest yellowness ($P < 0.05$) because of the yellow color of flaxseed oil, which is from the carotenoid content (Wang et al., 2016). Similar to the results from Shi et al., higher whiteness also resulted from vegetable oil addition (Shi et al., 2014). The topography in the SEM observation indicated the texture of chicken surimi and their structural details. It has been reported that added oil plays a "filler" role by filling in the void spaces in the matrix of gels and restraining the matrix from movement. Oil-added chicken surimi had lower hardness and gumminess owing to reduced protein concentrations in the network structure (Wang et al., 2016). Therefore, more flaxseed oil addition reduces the hardness and gumminess of chicken surimi.

Physicochemical Properties and FA Profiles of Raw Chicken Surimi With 5% Wheat Fiber and Different Flaxseed Oil Levels During Storage at 4°C and −20°C

Both the centrifugation and purge losses were used to evaluate the WHC of chicken surimi with 5% wheat fiber and different flaxseed oil levels after storage (Table 2). After storage at either 4 or −20°C, the centrifugation loss (%) and purge loss (%) were increased ($P < 0.05$) in the chicken surimi with both 5% wheat fiber and 14% flaxseed oil, but there were no ($P > 0.05$) differences on surimi with 10 and 12% flaxseed oil added. Moreover, raw chicken surimi with 5% wheat fiber and 14% flaxseed oil had the highest TBARS values after storing at either 4 or −20°C ($P < 0.05$; Table 2). Besides, the lowest thiol group content was measured in chicken surimi stored at 4°C for 14 d and −20°C for 30 and 60 d ($P < 0.05$; Table 2). After storage at 4 or −20°C, no differences were detected in TBARS values and thiol group contents in chicken surimi with either 10 or 12%

Table 2. Effects of different levels of flaxseed oil addition on centrifugation loss, purge loss, and lipid and protein oxidation levels of raw chicken surimi with 5% wheat fiber on 14-d storage at 4°C or 60-d storage at −20°C.

		Storage period (d)				
		0	7	14	30	60
	Flaxseed oil level (%)	4°C			−20°C	
Centrifugation loss (%)	10	23.95 ± 0.97^{b}	38.14 ± 0.59^{b}	42.42 ± 0.58^{b}	22.14 ± 0.80^{b}	26.60 ± 0.29^{a}
	12	24.98 ± 0.47^{b}	39.13 ± 0.51^{b}	44.71 ± 0.99^{b}	23.94 ± 0.51^{b}	27.78 ± 1.25^{a}
	14	27.60 ± 0.70^{a}	43.29 ± 1.07^{a}	47.91 ± 0.90^{a}	27.72 ± 0.79^{a}	32.73 ± 0.82^{a}
Purge loss (%)	10		7.46 ± 0.20^{b}	8.87 ± 0.14^{c}	5.08 ± 0.30^{b}	5.92 ± 0.26^{b}
	12		7.99 ± 0.21^{b}	9.68 ± 0.12^{b}	5.37 ± 0.38^{b}	6.32 ± 0.45^{b}
	14		9.64 ± 0.11^{a}	10.08 ± 0.31^{a}	8.60 ± 0.09^{a}	9.12 ± 0.57^{a}
TBARS values (mg MDA eq./kg surimi^{-1})	10	0.42 ± 0.02^{b}	0.56 ± 0.02^{c}	0.92 ± 0.03^{b}	0.49 ± 0.04^{b}	0.63 ± 0.05^{b}
	12	0.43 ± 0.02^{b}	0.63 ± 0.02^{b}	1.02 ± 0.00^{b}	0.59 ± 0.03^{b}	0.75 ± 0.07^{b}
	14	0.88 ± 0.02^{a}	1.04 ± 0.02^{a}	1.56 ± 0.04^{a}	0.72 ± 0.02^{a}	1.04 ± 0.03^{a}
Thiol group contents (μ mole/g surimi)<	10	7.75 ± 0.06^{a}	6.24 ± 0.14^{a}	5.52 ± 0.06^{a}	6.51 ± 0.13^{a}	5.63 ± 0.11^{a}
	12	7.72 ± 0.15^{a}	6.18 ± 0.05^{a}	5.50 ± 0.10^{a}	6.33 ± 0.05^{a}	5.56 ± 0.06^{a}
	14	7.67 ± 0.20^{a}	6.24 ± 0.10^{a}	4.91 ± 0.18^{b}	5.46 ± 0.07^{b}	4.83 ± 0.16^{b}

Data are given as mean ± SEM (n = 3).
^{a,b}Mean values without the common letter in each testing parameter within the same storage period are significantly different ($P < 0.05$).
Abbreviation: TBARS, thiobarbituric acid reactive substance.

flaxseed oil ($P > 0.05$), except lower TBARS in the one containing 10% flaxseed oil than 12% flaxseed oil stored at 4°C for 7 d. Regarding the FA profile, surimi with 12 and 14% flaxseed oil addition stored at 4°C had higher saturated FA, monounsaturated FA, PUFA, Σ ω-3 FA, and Σ ω-6 FA levels than those with 10% flaxseed oil addition in 0- and 4-d storage ($P < 0.05$; Table 3). However, 14% flaxseed oil addition resulted in the lowest ($P < 0.05$) PUFA, Σ ω-3 FA, Σ ω-6 FA, and Σ ω-3 FA/Σ ω-6 FA levels in raw chicken surimi stored at 4°C for 14 d, followed by 10 and 12% flaxseed oil additions. The similar trend in FA profile of raw chicken surimi stored at −20°C which lower saturated FA, monounsaturated FA, PUFA, Σ ω-3 FA, and Σ ω-6 FA levels was analyzed, but there was a tendency toward lower Σ ω-3 FA in 14% flaxseed oil addition than 12% added one, thus leading to lower ($P < 0.05$) Σ ω-3 FA/Σ ω-6 FA levels (Table 3).

The TBARS values and thiol group contents were characterized as lipid and protein oxidation levels in meat products, respectively (Ding et al., 2018). Owing to oxygen contact or temperature changes on storage, lipid oxidation occurred in flaxseed oil–fortified chicken surimi. As per a previous study (Pikul et al., 1989), the TBARS values of fresh chicken breast meat should fall within the range of 0.33–0.58 mg MDA e.q./kg. Ke et al. (1984) proposed a correlation between TBARS and freshness/rancidity of fish tissues: TBARS lower

Table 3. Changes of fatty acid profiles in raw chicken surimi batters with 5% wheat fiber and different levels of flaxseed oil after storage at 4°C and −20°C.

Flaxseed oil level (%)	SFA	MUFA	PUFA	Σ ω-3 FA	Σ ω-6 FA	Σ ω-3 FA/Σ ω-6 FA
			g/100 g raw chicken surimi batter			
			4°C, 0 d			
10	0.88 ± 0.01^{b}	1.85 ± 0.05^{b}	6.05 ± 0.07^{b}	4.68 ± 0.05^{b}	1.37 ± 0.02^{b}	3.43 ± 0.01^{a}
12	1.00 ± 0.02^{a}	2.11 ± 0.03^{a,b}	6.84 ± 0.09^{a,b}	5.28 ± 0.07^{a}	1.55 ± 0.02^{a}	3.40 ± 0.00^{a}
14	1.08 ± 0.06^{a}	2.32 ± 0.06^{a}	7.33 ± 0.34^{a}	5.66 ± 0.26^{a}	1.67 ± 0.08^{a}	3.38 ± 0.01^{a}
			4°C, 7 d			
10	0.88 ± 0.01^{b}	1.84 ± 0.02^{b}	6.05 ± 0.07^{b}	4.68 ± 0.06^{b}	1.37 ± 0.02^{b}	3.43 ± 0.01^{a}
12	1.01 ± 0.01^{a}	2.18 ± 0.06^{a}	6.77 ± 0.06^{a}	5.23 ± 0.05^{a}	1.54 ± 0.02^{a}	3.40 ± 0.01^{a}
14	1.02 ± 0.02^{a}	2.13 ± 0.08^{a}	6.80 ± 0.23^{a}	5.06 ± 0.17^{a}	1.57 ± 0.05^{a}	3.22 ± 0.02^{b}
			4°C, 14 d			
10	0.88 ± 0.02^{b}	1.96 ± 0.02^{b}	6.12 ± 0.09^{b}	4.86 ± 0.02^{b}	1.49 ± 0.00^{b}	3.26 ± 0.01^{b}
12	1.01 ± 0.02^{a}	2.22 ± 0.02^{a}	6.76 ± 0.02^{a}	5.22 ± 0.09^{a}	1.54 ± 0.02^{a}	3.38 ± 0.01^{a}
14	1.02 ± 0.02^{a}	2.11 ± 0.01^{a,b}	5.57 ± 0.12^{c}	4.05 ± 0.03^{c}	1.42 ± 0.03^{b}	2.86 ± 0.05^{c}
			−20°C, 30 d			
10	0.89 ± 0.01^{b}	1.91 ± 0.05^{b}	5.98 ± 0.13^{b}	4.62 ± 0.11^{b}	1.36 ± 0.02^{b}	3.39 ± 0.03^{a}
12	1.01 ± 0.02^{a}	2.17 ± 0.07^{a}	6.76 ± 0.05^{a}	5.22 ± 0.10^{a,b}	1.54 ± 0.02^{a}	3.38 ± 0.02^{a}
14	1.07 ± 0.02^{a}	2.25 ± 0.07^{a}	7.18 ± 0.28^{a}	5.53 ± 0.18^{a}	1.65 ± 0.05^{a}	3.34 ± 0.05^{a}
			−20°C, 60 d			
10	0.88 ± 0.01^{b}	1.92 ± 0.03^{b}	6.04 ± 0.08^{b}	4.68 ± 0.06^{b}	1.36 ± 0.02^{b}	3.45 ± 0.03^{a}
12	0.99 ± 0.01^{a}	2.16 ± 0.10^{a}	6.79 ± 0.03^{a}	5.25 ± 0.02^{a}	1.54 ± 0.01^{a}	3.40 ± 0.02^{a}
14	1.02 ± 0.02^{a}	2.20 ± 0.06^{a}	6.58 ± 0.10^{a}	5.05 ± 0.04^{a,b}	1.53 ± 0.03^{a}	3.31 ± 0.01^{b}

Data are given as mean ± SEM (n = 3).
^{a,b}Mean values without the common letter in each testing parameter within the same storage period are significantly different ($P < 0.05$).
Abbreviations: MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; SFA, saturated fatty acid; ω-3 FA, omega-3 fatty acid; ω-6 FA, omega-6 fatty acid.

Table 4. Changes of fatty acid profiles in cooked chicken surimi products with 5% wheat fiber and 12% flaxseed oil during different storage periods at 4°C.

Storage period (d)	SFA	MUFA	PUFA	Σ ω-3 FA	Σ ω-6 FA	Σ ω-3 FA/Σ ω-6 FA
	g/100 g cooked chicken surimi					
0	0.90 ± 0.02[a]	1.80 ± 0.02[a]	5.90 ± 0.06[a]	4.57 ± 0.05[a]	1.33 ± 0.02[a]	3.43 ± 0.02[a]
7	0.85 ± 0.01[a,b]	1.82 ± 0.02[a]	5.87 ± 0.06[a]	4.55 ± 0.04[a]	1.32 ± 0.02[a]	3.44 ± 0.01[a]
14	0.75 ± 0.02[b]	1.72 ± 0.00[b]	5.54 ± 0.02[b]	4.29 ± 0.02[b]	1.25 ± 0.00[b]	3.42 ± 0.00[a]

Data are given as mean ± SEM (n = 3).
[a,b]Mean values without the common letter in each testing parameter are significantly different ($P < 0.05$).
Abbreviations: MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; SFA, saturated fatty acid; ω-3 FA, omega-3 fatty acid; ω-6 FA, omega-6 fatty acid.

than 0.58 mg MDA/kg were perceived as freshness, 0.58–1.51 mg MDA/kg slight rancidity but acceptable, and higher than 1.51 mg MDA/kg were perceived as rancidity. Based on our results, our raw chicken surimi fortified with less than 12% flaxseed oil addition are still perceived as acceptable until 4°C storage for 14 d, but 14% flaxseed oil added chicken surimi stored at 4°C for 14 d are considered as rancidity. Regarding the chicken surimi stored at −20°C for 60 d, all levels of flaxseed oil addition are acceptable. Protein oxidation is associated with a decrease in thiol groups, which are converted into disulfides (Choi et al., 2009; Wang et al., 2019). Visual deterioration under extended storage was also observed via a SEM, such as pores, cracks, or rupture of linseed oil microcapsules (Gallardo et al., 2013). The surface of the oil droplets in chicken surimi with 14% flaxseed oil became rougher (with more contact area) than those with other flaxseed oil levels (Figure 2C), which may result from the higher probability of oxidation in the chicken surimi (Table 2). The higher protein oxidation in meat products probably results from increased lipid oxidation in chicken meat (Soyer et al., 2010; Ding et al., 2018). Disulfide bonds are formed if the protein is oxidized, so the thiol group contents of protein are reduced. Moreover, a correlation between decreased WHC of meat products and increased protein oxidation was revealed in previous reports (Delles and Xiong, 2014). A similar observation was also made in this study (Table 2). In addition, the decreased trends of PUFA, Σ ω-3 FA, Σ ω-6 FA, and Σ ω-3 FA/Σ ω-6 FA levels in chicken surimi with 14% flaxseed oil could be highly corresponding to the changes of TBARS values in the chicken surimi during the storage (Tables 2 and 3).

The FA Profile in Cooked Chicken Surimi With 5% Wheat Fiber and 12% Flaxseed Oil During 4°C Storage at 4°C

Cooked chicken surimi was stored at 4°C for 14 d to evaluate the change in FA profile. The FA profiles were analyzed at 7-d intervals over 14 d (Table 4). All categories of FA were decreased ($P < 0.05$) in the 14 d of storage, while only the Σ ω-3 FA/Σ ω-6 FA levels were not influenced ($P > 0.05$) among 3 different flaxseed oil level–added surimi. Herein, the total ω-3 and ω-6 FA in the cooked chicken surimi were α-linolenic and linoleic acids (data not shown). Omega-3 FA are relatively rare in meat foods sourced from domesticated animals but are usually rich in flaxseeds, walnuts, and canola oil. Omega-6 FA (mainly α-linolenic acid) are often present in plant-sourced oils, such as soybean oil and corn oil. Owing to the modern diet, there is often an imbalanced intake ratio of Σ ω-3 FA/Σ ω-6 FA, which is as high as 15:1 or even 30:1. This easily leads to chronic inflammation in the body and might cause several chronic diseases or even cancer. Simopoulos (2002) indicated that the optimal ratio of ω-3 FA to ω-6 FA in foods should be lower at 1:1 or at least not exceeding 1:10. Hence, it can be concluded that 5% wheat fiber can keep a better ratio of Σ ω-3 FA/Σ ω-6 FA (∼3:1) for human consumption in flaxseed oil–fortified surimi with 12% flaxseed oil.

CONCLUSION

Wheat fiber was chosen because of its good WHC and OHC in vitro. The OHC and WHC may contribute to keep the higher ω-3 FA content and improve the stability of chicken surimi batters during storage. The incorporation of wheat fiber in ω-3 FA–fortified chicken surimi can allow for a higher amount of flaxseed oil addition to as high as 12%, which does not influence the textural properties, color parameters, lipid/protein oxidation, and FA profile under refrigeration and frozen storage. Thus, based on nutritional concerns (dietary fiber, ω-3 FAs, and ratio of Σ ω-3 FA/Σ ω-6 FA) and physicochemical properties during the storage, semimanufactured chicken surimi with a higher nutritive value can be successfully obtained by formulating it with 12% flaxseed oil and 5% wheat fiber.

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DISCLOSURES

The authors declare no conflicts of interest.

SUPPLEMENTARY DATA

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