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Effects of formulation and processing techniques on physicochemical properties of surimi gel

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Abstract

Surimi is a seafood-based product that is widely consumed around the world, in the form of crab sticks, fish balls, and kamaboko. It is made using white meat from lean saltwater fish, such as Alaska pollock and Pacific whiting, through repeated washing of the fish mince until a mixture primarily made of myofibrillar proteins and cryoprotectants is achieved. Surimi has always been marketed as a source of protein, as a meat or fish replacement and as imitated seafood. The goal of this review is to summarize and compare the recent attempts to produce surimi using other types of fish and fish mince waste, combined with additives and/or emerging processing technologies, and how these have contributed to changes in physicochemical properties.

Keywords: surimi, Alaska pollock, high pressure processing, dietary fibre

Introduction

Surimi is a seafood-based product that is widely enjoyed and used in various dishes around the world, such as crab sticks, fish balls, and kamaboko. It is obtained through the repeated washing of fish mince, resulting in a mixture that is primarily made up of myofibrillar proteins and cryoprotectants (Pietrowski et al., 2011). While surimi has always been significantly marketed as a protein source (as a meat or fish replacement in diets as well as imitation seafood), the production of surimi has always been done using lean saltwater fish with white meat, such as the Alaska Pollock and the Pacific whiting. With the amount of other fish and fish mince waste available in the market, there has been a drive to produce surimi from other types of fish and trying to improve the produced surimi with additives or using new production technologies.

The goal of this review is to summarize and report the results of recent studies that modify the nutritional profile of surimi, particularly focusing on five topics: the use of oils, dietary fibres, salt and additives in surimi production and the process modifications that are implemented to improve the finished product. The focus will be on the physicochemical changes on modified surimi versus the control surimi in each study.

Effect of ingredients on physicochemical properties of surimi

Addition of oils

In order to enhance the polyunsaturated fatty acid content of surimi, several types of oils from plants and aquatic sources have been added to surimi (summarized in Table 1). As a result, physicochemical properties, protein structure, and gelation of surimi changed. Other fish and aquatic sources that are naturally rich in PUFAs have also been trialled instead of Alaska Pollock. The addition of oils into the surimi products mostly occurred during the production of surimi paste. In this case, chilled water used during the processing from surimi blocks to paste was replaced in a 1:1, w/w ratio with the oils added (Anyanwu et al., 2017; Pietrowski et al., 2011; Pietrowski et al., 2012; Sell et al., 2015; Shi et al., 2014; Tolosa et al., 2010; Zhou et al., 2017). This was done during the chopping of surimi blocks to form a surimi paste. During this step, water and salt are added in order to assist in protein solubilisation and to maintain a consistent moisture for the final product. In this case, oil replaces the water leading to a product with lower moisture but higher fat content.

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Table 1. Summary of sources of fish and oil used for improving polyunsaturated fatty acid composition in surimi

Type of fish	Type of oil	References
Alaska pollock	Corn oil Flaxseed oil Algae oil Menhaden oil Krill oil Blended oil (flaxseed:algae:krill, 8:1:1)	Pietrowski et al. (2011)
Alaska pollock	Flaxseed oil Salmon oil Various blended oils (flaxseed:bay leaf, salmon:bay leaf, flaxseed:salmon:bay leaf)	Anyanwu et al. (2017)
Alaska pollock	Algae oil Concentrated fish oil	Tolasa et al. (2010)
Alaska pollock	Flaxseed oil Salmon oil	Sell et al. (2015)
Silver carp	Soybean oil Corn oil Peanut oil Rap oil	Shi et al. (2014)
White croaker	Camellia tea oil	Zhou et al. (2017)

Proximate analysis results of the surimi products showed that there was a general reduction of moisture and increase in the lipid content of the surimi, with protein and ash content remaining constant in surimi with no oil versus oil-enriched surimi. This is expected as the papers reporting proximate analysis followed the method of replacing chilled water with oil during surimi paste production. A roughly 1:1 replacement of moisture with fat content is reported by Pietrowski et al. (2011), Sell et al. (2015) and Zhou et al. (2017). Interestingly, while Anyanwu et al. (2017) reported a similar trend, the 5% to 6% reduction of moisture only resulted in a 0.5% to 1.5% increase in fat content, despite the protein and ash levels remaining consistent. The difference between the moisture and fat content change was not assessed or discussed outside of the fact that the expected results were obtained.

Various oils presented at different concentrations of polyunsaturated fatty acids resulted in different fatty acid profiles of the surimi products. Results were reported in the following ratios: ω-6/ω-3 and UFAs/SFAs. The addition of the oils contributed to an ω-6/ω-3 ratio less than or equal to one for most products except for surimi paste added with corn oil (Pietrowski et al., 2011) and control surimi frank (Sell et al., 2015). The former is due to the corn oil composition while the latter is likely due to the other functional additives used in the creation of the frank, such as binders, fibre, and paste. Both Pietrowski et al. (2011) and Anyanwu et al. (2017) reported that surimi developed with flaxseed oil had the highest total UFA content, driven largely by its ALA content. On the other hand, salmon oil (Anyanwu et al., 2017; Sell et al., 2015) and algae oil (Pietrowski et al., 2011) showed higher DHA content. Salmon oil also showed higher EPA content. However, as there are no conducted studies of fatty acid profile analysis of the oils themselves. Hence, there is no confirmation if the incorporation of the oils in the surimi gel matrix and further processing has an effect on comparative composition.

An expected disadvantage caused by the addition of oils into surimi would be the increased rate of lipid oxidation in the product. This was measured using the thiobarbituric reactive substances (TBARS) assay, which predicts the oxidative stability for seafood-derived food products. There were only three treatments wherein there was no significant increase in the TBARS value, which resulted in increased potential rancidity. These are surimi paste mixed with 10% menhaden oil (Pietrowski et al., 2011), surimi franks with 4% flaxseed oil (Sell et al., 2015) and surimi gel with 0.5% concentrated fish oil (Tolosa et al., 2010). The menhaden oil mixture was only tested immediately after mixture, which is not a clear indication if rancidity really does not increase as storage time increases. The surimi frank with flaxseed oil was only similar (p>0.05) at day 0, which is likely caused by the very low concentration of the actual oil, as the TBARS value did not significantly change until 2 months of storage at both −18℃ and 3℃. All other treatments showed an expected increase in TBARS value and rancidity. Thus, more analysis results during shelf-life studies should be conducted in order to improve to determine which oils have potential for further use if the push is to fortify surimi with oils.

The color analysis results showed that the addition of oils increased the lightness (L*) value for the surimi products. This is a positive effect, seeing as lightness of the surimi will make it easier to be processed further for products such as crab sticks. The only added oil that reduced the lightness value significantly compared to control ($p<0.05$) was krill oil (Pietrowski et al., 2011). This is due to the oil itself naturally having a richer and darker color. As a result, the blended oil in the same experiment also had a lower L* value ($p<0.05$). Anyanwu et al. (2017), Sell et al. (2015), Shi et al. (2014), and Zhou et al. (2017) all observed that the L* value increases as the concentration of oils increased in the surimi for all their formulations. A storage analysis by Anyanwu et al. (2017) and Sell et al. (2015) showed that the L* value decreases gradually ($p>0.05$) at the end of 6 and 21 days, respectively. This natural darkening of the surimi after storage shows that the increased lightness of the oil-enriched surimi can have a positive appeal in terms of perceived freshness of the product.

For over-all acceptability based on consumer palette, sensory analysis was also conducted as the addition of oils is expected to affect taste and color. Anyanwu et al. (2017) concluded that the maximum amount of total oil that can be added to surimi without affecting sensory is 5%. For Shi et al. (2014), who conducted sensory evaluation on fish balls cooked by the surimi, panellists accepted at a 1% addition of oils, which is even lower. Sell et al. (2015), on surimi franks, found that 4% addition of flaxseed and salmon oil had no effect on sensory results for all attributes, but the fact that the surimi is processed at this point could have an effect on masking the taste of the oil. Pietrowski et al. (2011), who conducted tests using six oils, did not conduct any sensory evaluation, which would have helped for further studies to branch out of their research by focusing on one or two oils deemed “acceptable” by sensory standards.

Flaxseed oil is the one source of polyunsaturated fatty acids that can be focused on for further tests. These tests should focus on the issue regarding the increased rate of lipid oxidation. Longer shelf-life tests for various kinds of surimi products at different concentrations of flaxseed oil should be tested in order to create a fortified surimi that is rich with omega-3 that can be stored for a long period of time. Another focus can be the application of flaxseed oil in other fish. While studies have shown that it is effective in improving the properties of Alaska pollock surimi (the most common type), studies using other species of fish for surimi production can benefit from the application and testing of flaxseed oil.

Addition of dietary fibre

Similar to the addition of oils, the addition of dietary fibre in surimi and surimi-based products encompass a large number of fibre sources and a number of fish sources for surimi. This is further summarized in Table 2. The dietary fibre was added in different steps of the surimi processing. The related studies by Cardoso et al. (2009), Cardoso et al. (2011), Cardoso et al. (2012), and Cardoso et al. (2015) all added the fibre during the production of surimi gel from surimi. This was done through mixing a hydrated fibre mixture with the surimi using a refrigerated vacuum homogenizer. Alakhrash et al. (2016), Debusca et al. (2014), and Sánchez-Gonzáles et al. (2009) added dietary fibre along with silicon dioxide (used as an inert filler) during chopping of surimi paste. Tokur and Aksun (2012) added the dietary fibre by adding hydrated fibre mixture onto surimi paste during the production of crab leg paste from surimi.

Proximate analysis results of the modified surimi from Cardoso et al. (2009), Cardoso et al. (2011), and Cardoso et al. (2015) showed a similar pattern where the dietary fibre had a significant effect on the protein level of surimi ($p<0.05$). This was attributed to protein dilution caused by the addition of more water to samples with dietary fibre, in order to keep moisture levels of the control versus the modified product at the same level. Aside from this, dietary fibre having lower protein content also lowered the over-all protein level of the product. In contrast, the addition of fibre from oat bran caused an increase ($p<0.05$) in protein level, which is due to the fact that the oat bran used in the study contained 3.7 g of protein per 100 g (Alakhrash et al., 2016). This result shows the potential in adding oat bran as it increases protein content further, especially since protein level is a nutritional selling point of consuming surimi and seafood products. However, all studies did not conduct tests to analyse directly for dietary fibre levels, which would have shown a better comparison as to how

Table 2. Fish base and source of fibre used for dietary fibre fortification in surimi

Fish base for surimi	Fibre source used	References
Alaska pollock	Wheat	Sánchez-González et al. (2009)
Alaska pollock	Wheat Citrus Carrot	Tokur and Aksun (2012)
Alaska pollock	Wheat	Debusca et al. (2014)
Alaska pollock	Oat bran	Alakhrash et al. (2016)
Atlantic mackerel Chub mackerel	Inner pea Chicory root	Cardoso et al. (2009)
Sea bass	Inner pea Carrageenan Konjac	Cardoso et al. (2011)
Meagre South African hake Sea bass	Inner pea	Cardoso et al. (2012)
Meagre	Inner pea Carrageenan Konjac	Cardoso et al. (2015)

dietary fibre addition affects the results of further tests.

As dietary fibre is an insoluble nutrient that is commonly taken to increase the amount of water in one's gut and faecal matter (thereby relieving constipation), analysis was done on surimi to check if the water holding capacity (WHC) of the product improved with the addition of dietary fibre. Sánchez-González et al. (2009) showed that the addition of wheat dietary fibre can increase WHC by up to 87% (gram moisture per gram of fibre). Cardoso et al. (2011) and Cardoso et al. (2015) showed that various types of fibre had a different effect on WHC, as inner pea fibre decreased WHC while a mixture of carrageenan and konjac had an opposite effect (p<0.05). This was in distinct contrast to an earlier research result by the same group that showed inner pea fibre increasing WHC for mackerel (Cardoso et al., 2009). Alakhrash et al. (2016) confirmed the increase of WHC in Alaska pollock in oat bran. However, the WHC results suddenly decreased from 2% to 4% fibre, but increased again at higher levels. This could have been an analysis error that needed confirmation of results as the discrepancy was not discussed in the study. As WHC is related to the tenderness of meat products, an increase in WHC due to the addition of fibre can be seen as a positive trend.

Unlike the addition of various oils, the addition of dietary fibre did not have a whitening effect on surimi. The various fibre samples used had no significant impact (p>0.05) on the L* value of surimi made from mackerel, sea bass, and meagre (Cardoso et al., 2009; Cardoso et al., 2011; Cardoso et al., 2015). The L* value of Alaska pollock surimi was affected negatively by increased dietary fibre levels with as much as 4 L* units difference (p<0.05). This is likely caused by the fact that Alaska pollock surimi is fish that has very light-colored meat and the additional fibre is of a brownish tinge. However, as there were no further color analyses done after storage, the fact that the surimi with additional oil samples darkened with age means that there could be a perception that the darker surimi with added fibre is less fresh based on appearance.

The texture analysis results also varied with the addition of dietary fibre, though most studies reported an increase in gel strength and hardness with the addition of dietary fibre except for Cardoso et al. (2009), where the values for fibre-fortified surimi were similar (p>0.05). Of importance is a six-time increase in gel strength for meagre surimi (from 9.1 to 57 N·mm) before and after addition of both microbial transglutaminase and inner pea fibre (Cardoso et al., 2012). Kramer shear force and hardness test results for Alaska pollock surimi fortified with oat bran and wheat fibre showed a similar pattern, with continuous increase as the amount of fibre increased (Alakhrash et al., 2016; Debusca et al., 2014). However, the wheat fibre fortified surimi differed in terms of gel strength, which was explained by the authors as simply needing multiple tests in order to completely ascertain over-all texture results.

The biggest drawback in the studies where dietary fibre is added onto surimi is the effect of the additional nutrient on shelf-life and sensory attributes. While shelf-life will not likely be largely affected by the addition of a material that does not directly accelerate lipid oxidation (unlike oils), the effect on sensory could be significant, particularly due to the significant increase in gel strength and hardness, which may result to a tougher and more chewy finished product. Aside from this, as dietary fibre is a largely plant-based product, the acceptability based on potential changes to the taste of the seafood product need to be assessed. Of the papers reviewed, there is great potential in the Alaska pollock surimi fortified with oat bran due to having minimal effect on protein levels and good WHC and texture improvement. The consumer perception of oat as a healthy and hearty cereal will also help potential marketing of surimi product fortified with oats.

Modification of salt levels

Salt is commonly added to surimi to assist in the gelation process through solubilizing and extracting the proteins (Fu et al., 2012). As consumers are getting more conscious of the salt and sodium levels in their diets, there are two sets of studies and modifications being done to address this. The first is the direct reduction of salt (sodium chloride) used in the processing of surimi. The second is through the use of salt substitutes. A summary of these methods can be found in Table 3.

The salt reduction or salt substitution was conducted by all reviewed studies during the homogenization step where surimi is chopped and salt is added to extract the proteins. Proximate analysis results from Cardoso et al. (2010) confirmed a reduction in ash levels from 3.0% to 0.9% as the salt level introduced into the surimi was decreased. Protein levels remained at a similar level ($p>0.05$) with no noticeable trend, as they also tried to maintain the same moisture level for all their samples. As the sea bass used in the study was reported to be of high fat variety, the variations in fat level due to the decrease in ash levels may have also been insignificant. Cando et al. (2017) analysed sodium content directly in surimi and found an 80%–81% reduction, which was qualified as a product possible for a “reduced sodium” regulatory claim. The reduction level is highly significant and will be supported by consumers who are looking to reduce sodium intake in their diets.

To confirm the role of salt in unfolding proteins during processing, several studies conducted differential scanning calorimetry (DSC) to compare the control samples to those with reduced or substituted salt. DSC results from Cando et al. (2015), Cando et al. (2016) and Núñez-Flores et al. (2018) all showed that the samples with lower salt content had higher denaturation temperature and enthalpy, due to the presence of salt unfolding myosin during the washing and chopping steps of surimi processing. Tahergorabi et al. (2012), however, had varied results. The addition of salt and salt substitute actually increased the temperature of the onset of denaturation for surimi. However, DSC results showed larger peaks for surimi with salt, which means the rate of denaturation was higher (or faster). KCl, the salt substitute, did not show any increase in peak size. In fact, surimi with 0.17 M KCl added had a smaller peak than surimi with no NaCl or KCl at all. The mechanism of KCl potentially inhibiting myosin unfolding greatly at this concentration was not discussed by the authors.

Another property largely tested in these studies is the water holding capacity of the surimi. Cando et al. (2015), Cando et al. (2016), and Fu et al. (2012) all reported that the WHC of

Table 3. Types of fish base and modification of salt level for surimi

Fish base for surimi	Method used	References
Alaska pollock	Salt level reduction (0.3% vs 3%)	Cando et al. (2015)
Alaska pollock	Salt level reduction (0% vs 3%)	Núñez-Flores et al. (2018)
Silver carp	Salt level reduction (0%, 1%, 2%)	Fu et al. (2012)
Sea bass	Salt level reduction (0%, 0.25%, 0.5%, 1%, 2.5%)	Cardoso et al. (2010)
Alaska pollock	Salt substitute (KCl)	Tahergorabi et al. (2012)
Alaska pollock	Salt substitute (KCl)	Tahergorabi and Jaczynski (2012)
Alaska pollock	Salt substitute (KCl)	Debusca et al. (2013)

surimi increased as the amount of salt also increases. Again, this relates to the fact that surimi with salt resulted in easier unfolding of proteins that makes it react easily with water during processing. To compound this issue, WHC was measured over a period of 28 days in surimi with reduced sodium chloride content and it showed a significant reduction ($p<0.05$) at the 28-day mark (Cando et al., 2017). There were no WHC analyses conducted for salt substituted surimi, so the performance of KCl versus NaCl in relation to this property cannot be concluded.

Color analysis conducted in the studies showed that the reduction of salt in surimi either did not cause any significant changes ($p>0.05$) in the L* value of the surimi (Cardoso et al., 2010) or it resulted in increased lightness values ($p<0.05$) for the surimi products (Cando et al., 2015; Tahergorabi et al., 2012). Storage of surimi with reduced salt levels also showed that the L* value was not significantly impacted ($p<0.05$) over time. This is a positive finding as lightness of seafood is commonly equated by consumers to its freshness. Salt substitute, however, affected color to varying degrees. At lower quantities of addition (0.17 mol/L and 0.34 mol/L), salt substitute affected L* at the same level as salt ($p>0.05$). However, when added at the maximum level of addition, the L* value for salt substitute was significantly lower ($p<0.05$) than for its equivalent level in salt (Tahergorabi et al., 2012). This raises another potential stumbling block in the use of KCl-based salt substitute when it comes to consumer perception of the product.

Similar to the studies conducted on fibre, sensory and shelf-life tests were lacking for surimi with reduced salt or surimi processed with salt substitute. Cando et al. (2015) conducted sensory tests, but only on the firmness and elasticity of the surimi gel, which showed that reduced salt product had lower scores in firmness ($p<0.05$) with comparable scores in elasticity. Other properties were not tested. As the reduction of salt largely affects surimi processing itself due to the unfolding of the proteins, studies have been focused on additional treatments in order to mitigate the effect of reducing salt. This includes the application of high pressure (Cando et al., 2015), using additives such as cysteine and lysine (Cando et al., 2016), and microwave heating (Fu et al., 2017). Meanwhile, other salt substitutes outside of KCl can be explored alongside the above mentioned mitigating factors to see if there is a true possibility of eliminating the addition of salt to relieve the consumer base's perception of the harmful consumption of too much sodium.

Use of process additives

With the improvement of food technology over the years, there have been several efforts to improve surimi through the addition of ingredients that were not normally used outside of the original surimi production process. The additives were used mainly to improve the texture and gel properties of surimi, thus the comparisons will largely focus on the effects of the various additives on these properties. A summary of the additives and the fish based used for the improvement of surimi is available in the Table 4. Additives are normally added at very low concentrations to act as process aids or for product improvement (such as fortification). Thus, proximate analysis results from surimi with additives resulted in only minor changes to the nutritional profile of the product, with the addition of 0.5% to 2% of the most additives listed. Protein levels in surimi with 0.5% microbial transglutaminase (MTGase) showed a reduction that was not significant (Cardoso et al., 2015). The difference in protein levels, in fact, could be more attributed to the difference in actual fish mince used in these experiments: 77.3% vs. 75.1% meagre mince (Cardoso et al., 2015), 86.0% vs. 84.2% sea bass mince (Cardoso et al., 2012) and 62.8% vs. 61.1% sea bass mince (Cardoso et al., 2011). The difference in mince used was due to the studies targeting a specific level of moisture for the final product, so water was added into the surimi until the moisture levels were the same, resulting in protein dilution. On the other hand, Cardoso et al. (2009) showed an inverse result, with protein levels increasing despite the addition of MTGase and more water to the experimental sample, but with no statistical analysis available to determine if the increase is significant.

Texture analysis was widely analyzed in these studies, with various tests such as TPA and puncture test being employed to see if the additives had an effect. As a known protein cross-linker used in the food industry, MTGase had a significantly positive ($p<0.05$) effect on texture, with 0.5% MTGase being able to almost double gel strength in sea bass surimi (Cardoso et al., 2009; Cardoso et al., 2011; Cardoso et al., 2012). For amino acid addition, cystine shows a significant increase in breaking force and breaking deformation levels but not lysine (Cando et al., 2016; Cando et al., 2017), which the authors attributed to cystine being a weaker oxidant that maximizes cross-linking compared to lysine. Young apple polyphenols (YAP) were added more for the antioxidants and shelf-life stability and, as such, did not significantly contribute ($p>0.05$)

Table 4. Surimi fish base and process additives used for product improvement

Fish base for surimi	Additive used	References
Alaska pollock	Cystine Tetra-sodium polyphosphate Lysine	Cando et al. (2016)
Alaska pollock	Lysine Cystine	Cando et al. (2017)
Alaska pollock	Konjac glucomannan	Zhang et al. (2016)
Grass carp	Rice starch	Yang et al. (2014)
Grass carp	Thinned young apple polyphenols	Sun et al. (2017)
Grass carp	6-Gingerol	Mi et al. (2017)
Atlantic mackerel Chub mackerel	Microbial transglutaminase	Cardoso et al. (2009)
Meagre	Microbial transglutaminase	Cardoso et al. (2015)
Meagre Gilthead seabream Hake Sea bass	Microbial transglutaminase	Cardoso et al. (2012)
Sea bass	Microbial transglutaminase	Cardoso et al. (2011)
Sea bass	Microbial transglutaminase	Cardoso et al. (2010)
Dolphin-fish (mahi-mahi)	Bacterial cellulose (nata)	Lin et al. (2011)
Japanese Spanish mackerel (*S. niphonius*)	Pullulan	Wu (2016)
Pacific whiting	Salmon plasma protein	Fowler and Park (2015)

to an increase in in gel strength (Sun et al., 2017). However, the surimi with higher YAP content retained higher gel strength at the end of a seven-day shelf-life study, with significant differences ($p<0.05$) between 0.10% YAP, 0.05% YAP, and control. The addition of 6-gingerol, another antioxidant, produced surimi with much better gel strength compared to control ($p<0.05$) during shelf-life study (Mi et al., 2017). While the increase of gel strength and texture properties are welcomed with additives, these are always best paired with sensory analysis to determine if the increase (particularly with MTGase doubling gel strength) results in a product that is still easy to masticate. TPA results on chewiness (Cardoso et al., 2009) showed a seven-time increase in force (0.9 N vs. 7.0 N) with just a 0.5% addition of MTGase, which only strengthens the need for actual consumer tests through sensory analysis.

To confirm the changes in gelation leading to a change in gel strength, sample microstructures were assessed with a scanning electron microscope (SEM). The microstructure of MTGase- added surimi showed a more homogeneous microstructure with more evenly distributed pores, exhibiting a more rigid structure (Cardoso et al., 2009; Cardoso et al., 2011). A similar more rigid microstructure also characterized surimi with added 6-gingerol (Mi et al., 2017), pullulan (Wu, 2016), salmon plasma protein (Fowler and Park, 2015), and rice starch (Yang et al., 2014). While the microstructure of surimi with added nata was not directly assessed with SEM, the raw materials were. The study showed that alkaline-treated (AT) nata had a more fibrous microstructure compared to native nata, resulting in AT nata being able to provide better crosslinking when applied to surimi. Thus, surimi with AT nata had better gel strength results than surimi with native nata ($p<0.05$) when added at the same concentration levels.

As a high moisture product, the ability of surimi to retain moisture during heating is an important property as it highly affects texture and mouthfeel of the product during consumption was tested via water holding capacity (WHC) analysis. WHC results showed that MTGase (Cardoso et al., 2011; Cardoso et al., 2015), cystine and lysine (Cando et al., 2017) and 6-gingerol (Mi et al., 2017) generally had no significant effect ($p>0.05$) on WHC. The addition of 6-gingerol would slightly affect water loss during the twelve-day shelf-life study, but would have a similar value with control surimi ($p>0.05$) at the end of storage. Cystine and lysine-added surimi samples retained more water ($p<0.05$) than control at the end of 28 days shelf-life study. Pullulan addition increased WHC of surimi as pullulan addition concentration also increased (Wu, 2016). On the other hand, nata produced the opposite effect: an increase in nata addition resulted in a decrease in WHC (Lin et al., 2011). This shows that most of the additives used, aside from nata, resulted in similar or increased WHC, which can be considered a positive in the use of these additives. The studies on MTGase and pullulan could have used a similar shelf-life study to determine if WHC levels are similar or better than control after storage, as that would be a better test of the structure and texture of surimi once it has already reached consumers.

Surimi is most commonly made of white-meat fish such as Alaska pollock and its use as a cheaper replacement for more expensive seafood such as crab and lobster put premium on the whiteness of the product. The addition of 6-gingerol (Mi et al., 2017) had a significant increase ($p<0.05$) on whiteness, as it is commonly used as a yellow oil that helps with the scattering of light once added onto products. Color analysis after twelve days of storage also consistently showed that surimi with the additive had higher whiteness value. On the other hand, MTGase (Cardoso et al., 2009; Cardoso et al., 2015) and salmon plasma protein (Fowler and Park, 2015) had the opposite effect, with a significant decrease ($p<0.05$) on the whiteness value. Rice starch (Yang et al., 2014) and young apple polyphenols (Sun et al., 2017) showed no significant effect of the additives on color ($p>0.05$). Color degradation was significantly reduced for 0.10% YAP surimi versus control after seven days in storage. The addition of cystine and lysine had different effects on surimi, with cystine increasing lightness significantly ($p<0.05$) while lysine had no effect ($p>0.05$). This was supported with sensory analysis results with panellists rating color on a scale from 1 (white) to 10 (gray), and product with cystine having lower scores, though results were not significantly different ($p>0.05$). Sensory analysis for preference could support this result, though the gradual decrease in color after storage puts premium on whiteness as a visual trigger for freshness of surimi.

The continued research on the use of additives to improve the functional properties of surimi shows promise, as some studies are pairing up additives with nutritional modifications to produce an over-all better surimi product for consumers. These studies include MTGase and dietary fibre (Cardoso et al., 2009; Cardoso et al., 2011; Cardoso et al., 2012), MTGase and salt reduction (Cardoso et al., 2010; Cardoso et al., 2015), amino acids and salt reduction (Cando et al., 2016; Cando et al., 2017), and 6-gingerol with perilla oil (Mi et al., 2017). 6-gingerol has shown to be an additive that improves texture, color, and shelf-life stability, and it will be interesting to see if these improvements can offset potential salt level modifications that have showed to adversely affect surimi texture due to salt's role in protein solubility. Otherwise, it would also be beneficial if more studies would consider conducting sensory and shelf-life studies pertaining to additive usage in surimi. While consumers would appreciate the improvement of the texture or the color of a food product, the current market trend is going towards products that are "natural" or "organic" and the use of additives in processing goes against that trend. This can be offset with a product that is better in terms of sensory and taste. Of the reviewed papers, only two studies conducted sensory evaluation, with YAP showing improvement in over-all sensory score during shelf- life study due to antioxidant performance (Wu, 2016) and cystine-added surimi reporting a significantly lower score for flavour due to the smell of "cooked eggs" (Cando et al., 2017). This highlights the disadvantage of using additives and not conducting sensory. The improvement will not be noticeable if the consumer will not eat the improved food product.

Process modifications

The traditional surimi gel cooking method involves stuffing chopped surimi paste into small 3 cm diameter casings and heating for 20 to 30 minutes at around 90℃. This method is known as "water bath heating" (Tadpitchayangkoon et al., 2012). But with the advent of new food processing techniques to make food processing easier and make food with better properties and safer to eat, such techniques have already made their way into surimi processing as well. A summary can be found in Table 5.

Of the methods listed above, electron irradiation and high pressure processing (HPP) are used to assess their effect on the conformation of surimi proteins that can potentially lead to initial protein denaturation before the actual cooking and heating process (Cando et al., 2015; Deng et al., 2017). Surimi will then need to undergo less stress and need less energy to transform it to a finished product. On the other hand, ohmic and microwave heating are simply alternative cooking methods using electric current and electromagnetic radiation, respectively, in transferring heat to a food product. Both techniques do not require a solid-liquid interface to induce temperature changes

Table 5. Surimi fish base and process modifications used for product improvement

Fish base for surimi	Processing method used	References
Threadfin beam Bigeye snapper Goatfish Lizardfish	Ohmic heating	Tadpitchayangkoon et al. (2012)
Pacific whiting	Ohmic heating	Fowler and Park (2015)
Alaska pollock	High pressure processing	Cando et al. (2015)
Alaska pollock	High pressure processing	Cando et al. (2017)
Alaska pollock	Microwave heating	Ji et al. (2017)
Silver carp	Microwave heating	Fu et al. (2012)
Silver carp	Microwave heating	Feng et al. (2016)
Grass carp	Microwave heating Electron irradiation	Zhang et al. (2017)
Hairtail	Electron irradiation	Lin et al. (2015)
Hairtail	Electron irradiation	Lin et al. (2015)
Collicthys lucidus	Electron irradiation	Deng et al. (2017)

and are noted as methods that achieve faster heating rates in shorter periods of time, with this shorter cooking time being comparable to commercial crabstick production, where surimi paste is extruded on a thin sheet and directly heated by steam, gas, or electricity (Tadpitchayangkoon et al., 2012). With this, there can be a potential in combining one of the pre-heating methods with one of the cooking methods, which was done with the study conducted by Zhang et al. (2017). Unfortunately, this one study that combined a pre-treatment and alternative treatment method did not conduct the basic tests of color, texture, and water binding capacity with the combination of treatments.

Like most studies concerned with the gelation properties of surimi, one of the main attributes assessed with the use of alternative processing methods was texture analysis, primarily due to the perceived effect of these methods with the protein conformation in the samples. The addition of 5 kGy and 7 kGy of electron irradiation showed significant increase ($p<0.05$) in gel strength and breaking force in *C. lucidus* surimi, with smaller doses (1 to 3 kGy) having no significant effect and 9 kGy resulting in a significant decrease (Deng et al., 2017). Hairtail surimi showed a similar trend, with texture results peaking at 7 kGy and going down at 9 kGy (Lin et al., 2015). HPP treatment had similar results, with 150 MPa showing an increase in breaking force but 300 MPa having a similar result ($p>0.05$) compared to control (Cando et al., 2015). Ohmic heating treatments at 6.7 and 16.7 V-cm^{-1} increased breaking force significantly ($p<0.05$) for threadfin beam, bigeye snapper, goatfish, and lizardfish surimi samples tested by Tadpitchayangkoon et al. (2012) compared to water bath heating treatments. Considering different fish samples had varied results in control (30 N for threadfin beam versus 4 N for goatfish), ohmic heating showed potential application in improving the texture of fish with vastly different protein properties. Microwave heating at 300 W significantly increased ($p<0.05$) breaking force at 5 and 10 minutes compared to water bath heating for 30 minutes (Ji et al., 2017). Of these tests, however, only the ones with HPP treatment were subjected to sensory evaluation to confirm the changes in texture. HPP-treated surimi had higher scores in hardness and chewiness, but lower scores in juiciness (Cando et al., 2017). Unfortunately, these sensory results were not presented with statistical analysis to assess if the changes in these scores would be significant and, if they were significant, to see if these changes would still be acceptable to consumers.

Water holding capacity of surimi followed similar patterns to gel strength results, with WHC showing significant increase ($p<0.05$) at 5 kGy for electron beam irradiation (Deng et al., 2017) and 150 MPa for HPP (Cando et al., 2015). Similar patterns were also found with ohmic heating at 6.7 and 16.7 V-cm^{-1} (Tadpitchayangkoon et al., 2012) and microwave heating at 300 W for 5 and 10 minutes (Ji et al., 2017). This result lends credence to the fact that bonding between proteins and water in the matrix leads to increased gelation and texture of the surimi product. However, the results from Ji et al. (2017) showed that microwave heating at 300 W for a shorter period (1 and 2 minutes) was not able to increase WHC, and instead had a significant decrease ($p<0.05$). This was largely different from the results of Fu et al. (2012) where WHC increased significantly ($p<0.05$) at microwave treatment for 40 seconds. This result may have been caused by the fact that the studies used two different types of fish (Alaska pollock vs. silver carp) or a different microwave wattage. But the latter issue could not be confirmed as Fu et al. (2012) only specified microwave power settings at 15 W/g, and did not provide the weight of the surimi they treated, thus the total microwave heat setting could not be checked against 300 W from Ji et al. (2017).

SEM results showed that electron irradiation at 5 kGy (Deng et al., 2017; Lin et al., 2015) and HPP at 150 MPa (Cando et al., 2015) resulted in more compact and homogeneous microstructure compared to untreated surimi samples, which translates to the over-all stronger structure of the product. At lower levels of irradiation (1 and 3 kGy), there was no visible difference in the loose and coarse structure of surimi as compared with samples that were not irradiated at all. For microwave heating, samples heated for 20, 40, 60, and 80 seconds at 15 W/g showed the formation of a network-like microstructure (Fu et al., 2012). However, at 80 seconds, the networks began to break and the structures becoming coarse, showing that the additional heating time led to degradation of proteins in the sample. This structure was the same as the surimi heated with a water bath in their study. Ohmic heating had a similar result, with a surimi product ohmic-heated at 60℃ for 30 minutes prior to ohmic heating to 90℃ showing the least compact microstructure with the most number of voids, compared to a sample that was simply just ohmic-heated directly to 90℃, or one that was treated in a water bath (Fowler and Park, 2015). This shows that while microwave and ohmic heating are technically more efficient heating and cooking methods, there is an easier tendency for the product to be over-cooked and for surimi proteins to degrade due to the faster heat transfer. Hence the study of the application of such technologies in surimi production should take time into account.

The potential application of these various technologies has opened more possibilities in terms of the improvement of surimi processing. To provide one example, HPP can be used to improve protein solubilization in surimi that is produced with less salt. Salt is an important part of surimi gel production as the presence of NaCl allows for protein solubilization and unfolding during the chopping process. Reducing salt will cause a drastic negative effect in surimi modification as the resulting paste will require more energy to produce an appropriate gel, leading to the possibility of over-cooking and the production of surimi gel without the required sensory properties in terms of color and texture (Cando et al., 2017). With electron irradiation resulting in similar trends on texture and WHC, a combination with low-salt surimi gel would be possible to explore. Aside from this, the earlier mentioned mixture of a pre-treatment (HPP or electron radiation) and a modified heat treatment (microwave or ohmic heating) can be explored to see if the methods will be able to produce a compounded improvement on the physicochemical properties. The advantage with modifying the process is that it is more “invisible” to consumer perception and negative appeal, especially when compared to the use of additives. In fact, the only process that would have negative perception would be irradiation. For the others, consumers would likely not mind if high pressure is applied or heating methods modified.

Conclusion

Advancement of food processing and formulation to produce surimi that is safe, nutritious and easier to produce is evident in the literature. Addition of oil increased omega 3 content, lightness (L*) of the color and rate of lipid oxidation, dependent on the source of oil and the amount of oil being added. With the addition of fibre, improvement in water holding capacity, surimi gel strength and hardness were observed. With reduction of salt, decrease in water holding capacity and firmness detected by sensorial testing was observed. And use of additives such as MTGase improved surimi gel strength and produced homogeneous microstructure. With the use of eletron irradiation, high pressure processing, ohmic heating and microwave heating, improvement in breaking force of surimi gel and water holding capacity were observed compared to the traditional processing method using water bath heating. Retaining the familiarity or authentic properties of the surimi that the consumers are familiar with remains to be a weakness in the reviewed studies on surimi processing, as sensory evaluation is rarely reported. There is potential in further studies on the production of surimi and a combination of these factors: nutritional additives, process additives, and manufacturing options, could be the direction for surimi in the future.

Conflicts of Interest

The authors declare no potential conflict of interest.

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Ethics Approval

This article does not require IRB/IACUC approval because there are no human and animal participants

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