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Bio-based edible coatings for the preservation of fishery products: A review

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Abstract

The popularity of preprocessed fresh fishery products such as fillets and peeled shrimps is growing in today's market due to their convenience for subsequent processing and cooking. However, fishery products are highly perishable because of the combined actions of biochemical reactions and microbial metabolism. Various methods have been proposed to address this problem. Among these methods, bio-based edible coating has been highlighted as a promising solution. This review updates and summarizes the recent literature on the application of coatings for the preservation of fishery products including the aspects of coating carriers, composite natural preservatives and coating methods, and a discussion of the protective effects based on

microbial, physicochemical and sensorial evaluations. Moreover, some challenges and future research directions regarding optimization of formulas and exploration of mechanisms of coating are also discussed. Given consumer demand for fresh fishery products with long shelf life, edible coatings that are environmentally friendly and effective alternative will be used to extend the shelf life of fishery products.

Keywords

Fishery products; Edible coatings; Natural preservatives; Shelf life; Quality retention

Abbreviations

ATP, Adenosine triphosphate; CFU, Colony forming units; CMC, Carboxyl methyl cellulose; EU, European Union; FAO, Food and Agriculture Organization; HHP, High-hydrostatic pressure; Hx, Hypoxanthine; HxR, Hypoxanthine ribonucleoside; IMP, Inosine monophosphate; LAB, Lactic acid bacteria; LPO, Lactoperoxidase; MAP, Modified-atmosphere packaging; QIM, Quality index method; SSO, Specific spoilage organisms; TBARS, Thiobarbituric acid reactive substances; TBP, Tartary buckwheat polysaccharides; TMA, Trimethylamine; TP, Tea polyphenols; TPC, Total psychrophilic count; TVB-N, Total volatile base nitrogen; TVC, Total viable count.

Introduction

Fishery products are important nutritionally in daily life as they are high in protein, unsaturated fatty acids, vitamins and minerals. In addition, the fishing industry is often important to the national economy of many coastal countries and regions. According to reports from the Food and Agriculture Organization (FAO) and related conference proceedings, the global production of aquatic products was estimated to be nearly 170 million tonnes in 2014, with ~19.7 kg per capita as the average global consumption, accounting for approximately 15% of animal protein intake for 4.3 billion people worldwide (FAO, 2016). Traditionally, local distribution of live aquatic products has the problems of high cost and poor efficiency. With the advances in available and reliable cold-chains and online shopping, and the changes in consumption concepts, fresh preprocessed products such as refrigerated fillets and peeled shrimps are more popular with consumers, especially the younger generation (Ge et al., 2016a). However, compared with terrestrial animal, aquatic products are more vulnerable to spoilage after post-mortem storage because of their large amounts of endogenous enzymes, and small molecules that can serve as nutrients for spoilage organisms, and a more neutral pH than most other meats (Abdollahi, Rezaei, and Farzi, 2014; Liu et al., 2013). The changes caused by biochemical, physicochemical and microbial activity result in the accumulation of deleterious substances and unpleasant off-odors, and eventually lead to economic or health-related problems (López de Lacey, López-Caballero, and Montero, 2014). Therefore, research on how to effectively maintain the high quality of fresh fishery products while still "fresh" (i.e., not frozen) for longer times is potentially valuable.

At present, many studies concerning preservation technologies for fishery products have been done and are being implemented, e.g., low-temperature storage, irradiation, modified-atmosphere packaging (MAP) and high hydrostatic pressure (HHP) (Liu et al., 2013; Mace et al., 2012; Mahmoud et al., 2016; Qiu, Xia, and Jiang, 2013). Although irradiation is an effective measure to inactivate foodborne pathogens and spoilage bacteria in fishery products (Oraei et al., 2012), consumers are still worried about its safety. In addition, MAP and HHP need more expensive and more specific packaging materials and processing equipment, leading to increased production costs. Based on the storage temperature, low-temperature preservation can be traditionally divided into refrigerated storage, iced storage, partial freezing storage and frozen storage. Currently, low-temperature preservation, especially refrigeration, is extensively used for fishery products in supermarkets and homes because of its convenience. Nevertheless, low-temperature condition cannot completely inhibit microbial growth, lipid oxidation or endogenous enzyme activities (Ge et al., 2016b; Wang et al., 2014). To solve these problems and provide fishery products with premium quality, new methods, either independent of current systems or working with them, need to be developed.

Edible coating has been widely studied and confirmed as an effective and environmentally friendly process to ensure the quality and safety of food during refrigerated storage (Guo et al., 2015). Edible films formed on the surface of foods contribute to the control of moisture movement, lipid oxidation, microbial contamination and enzyme activity, which are viewed as the dominant detrimental contributors to food spoilage (Atarés and Chiralt, 2016; Kerch, 2015; Yu et al., 2017c). In the past decade, several edible materials, including chitosan, gelatin, whey protein and alginate, have been shown to have positive effects on prolonging the shelf life of fishery products when they are used alone or with natural preservatives (Hosseoni et al., 2016; Mohan et al., 2012; Neetoo, Ye, and Chen, 2010; Yildiz and Yangilar, 2016). Species studies included sea bass (*Lateolabrax japonicas*) (Cai et al., 2015a), rainbow trout (*Oncorhynchus mykiss*) (Andevari and Rezaei, 2011; Shokri, Ehsani, and Jasour, 2015), whiteleg shrimp (*Litopenaeus vannamei*) (Wang et al., 2015), silver pomfret (*Pampus argentus*) (Wu et al., 2016b), grass carp (*Ctenopharyngodon idellus*) (Yu et al., 2017a), salmon (*Salmo salar*) (Souza et al., 2010) and olive flounder (*Paralichthys olivaceus*) (Li et al., 2017b). However, reviews on the application of edible coatings for aquatic product preservation are limited. The early reviews mainly focused on the applications of chitosan to many food products (including aquatic product) or generally introduced chitosan-based edible films and coatings (Aider, 2010; Elsabee and Abdou, 2013; Kerch, 2015). In addition to chitosan, other natural materials have also been shown to benefit fishery products. In particular, natural preservatives are being combined with coating solutions. These bio-based active coatings often have better antioxidant and/or antibacterial capacities. However, no review has comprehensively focused on the application of bio-based edible coatings for the preservation of post-mortem fishery products to date. This review will focus on current work on bio-based edible coatings for low-temperature stored fishery products with an emphasis on the effect on freshness retention, and the future outlook and trends will also be discussed.

Coating carriers

Chitosan

Chitosan is a deacetylated derivative of chitin, a linear polysaccharide composed of β-(1–4)-2-acetamido-D-glucose and β-(1–4)-2-amino-D-glucose units with the latter being the main component (Elsabee and Abdou, 2013). Chitosan is described in terms of degree of deacetylation and average molecular weight, which influence its antimicrobial property in conjunction with physical characteristics including viscosity, permeability and film-formation (Aider, 2010). As a renewable resource generally obtained from the by-products of the processing of crustaceans (e.g., shrimp, lobster and crab), it has many benefits including antibacterial activity, biocompatibility and film-forming properties. Chitosan can be a natural food preservative that can be used for edible coatings or films (Chien, Sheu, and Yang, 2007; Devlieghere, Vermeulen, and Debevere, 2004; Fernandez-Saiz et al., 2013). Nowadays, it has become the most widely studied coating/film material when working with fishery products. Table 1 shows some of the recent studies on the effects of chitosan-based coatings for the shelf life extension of refrigerated fishery products to different extents depending on the composition of chitosan-based coating solutions, fish species and product form. Chitosan-based coatings reduced microbial number and the accumulation of harmful metabolites, and resulted in better physical and sensorial qualities because of their bio-activities as well as the selective permeability to gasses (Elsabee and Abdou, 2013; Souza et al., 2010).

In addition, the protective effects of chitosan coatings are also correlated with solution concentration. Antimicrobial activities of chitosan solutions are dose-dependent verified on the basis of *in vitro* trials and complex fillets matrix. Cao, Xue, and Liu (2009) indicated that the growth inhibition zone for specific spoilage organisms (SSO) of fish could be increased with increasing chitosan concentration. In addition, Mohan et al. (2012) and Yu et al. (2017a) showed that total viable counts (TVC) of fillets (Indian oil sardine and grass carp) coated with 2% chitosan solution decreased 1 to 1.5 log_{10} CFU/g compared to 1% chitosan solution treatment during refrigerated storage. Given solubility limitations of chitosan, chitosan coating solutions with fishery products have been between 1 and 2% (Fan et al., 2009; Ojagh et al., 2010; Souza et al., 2010). Higher concentrations are too viscous and do not significantly ($p \geq 0.05$) improve product shelf life (Yu et al., 2016). Besides, chitosan particle size is another important factor that needs to be considered. Several methods including ionotropic gelation are used to prepare nano-chitosan, which has excellent physicochemical features and generally a greater positive effect on product quality. Higher antibacterial activity of chitosan nanoparticles *in vitro* has been observed (Du et al., 2009). Ramezani, Zarei, and Raminnejad (2015) also found a significant difference ($p < 0.05$) between chitosan and nano-chitosan coatings on the quality of refrigerated silver carp (*Hypophthalmichthys molitrix*) fillets, with the latter showing more inhibition of TVB-N and microbial growth. Furthermore, Chouljenko et al. (2016) showed using fluorescence that chitosan with smaller size enhanced particle penetration into muscle tissue, thus increasing contact between chitosan and microorganism, and reducing microbial numbers.

Alginate

Alginate extracted from brown seaweed has become another appealing coating material of natural origin. Based on unique colloidal characteristics, alginate has an ability to form strong gels or insoluble polymers through cross-linking reactions with polyvalent metal ions (Rhim, 2004), and Ca^{2+} is frequently used as the most effective gelling agent (Gennadios, Hanna, and Kurth, 1997; Lu et al., 2010; Lu et al., 2009). Generally, application of aqueous sodium alginate solutions (1.5 to 4%) on fishery products is done by dipping or spraying followed by immersing in a calcium salt solution (2%) to induce gelation (Hamzeh and Rezaei, 2012; Lu et al., 2009; Song et al., 2011). The alginate gel films help maintain quality of fishery products by inhibiting aerobic bacteria, decreasing water loss, slowing lipid oxidation, and reducing cross contamination (Song et al., 2011). Alginate coating also serves as a carrier of antimicrobial and antioxidant compounds to improve shelf life of fishery products as alginate itself has limited bio-activity. Cai et al. (2015b) formulated alginate coatings incorporating 6-gingerol, and found that they extended the edible shelf life of refrigerated sea bream (*Pagrosomus major*) fillets compared with the control or the alginate coating. Jalali, Ariiai, and Fattahi (2016) found that silver carp treated with an alginate coating enriched with clove essential oil had the best chemical and microbial characteristics after 16 days of storage when compared to the other treatments. Cai et al. (2015a) synthesized an alginate-ε-polylysine coating that maintained the sensory quality of Japanese sea bass by retarding nucleotide breakdown, lipid oxidation and protein degradation. Ehsani, Paktarmani, and Yousefi (2017) also used similar methods to show that a sodium alginate coating with lycopene helped preserve rainbow trout. These alginate composite coatings also reduced the growth of spoilage and pathogenic bacteria in aquatic products, such as *Listeria monocytogenes*, *Salmonella anatum* and *Escherichia coli*, (Datta et al., 2008; Jalali, Ariiai, and Fattahi, 2016).

Gelatin

Gelatin is obtained by partial denaturation or hydrolysis of collagen, which is the most ubiquitous protein in higher animals. Gelatin is a promising coating material because of its film-forming or gelling abilities, as well as its resistance to drying, light and oxygen (Feng et al., 2017; Mohtar, Perera, and Hemar, 2014). Like other coatings, gelatin has the potential to be used as a carrier for antioxidants or antibacterial agents. Gelatin-based coatings are usually applied by dipping, spraying or brushing, with the solution concentration between 1 and 8% (Alparslan et al., 2014; Andevari and Rezaei, 2011; Feng et al., 2017). Feng et al. (2017) incorporated 0.4% tea polyphenols into 1.2% gelatin solutions, and found that the coating delayed the degradation of myosin light chains and troponin, and reduced volatile spoilage markers in refrigerated fillets of golden pomfret (*Trachinotus blochii*). The TVC and total psychrotrophic count (TPC) were lower in fillets treated with the gelatin-tea polyphenols. Andevari and Rezaei (2011) evaluated the effect of a gelatin coating enriched with cinnamon oil on the quality of rainbow trout, and found that gelatin coatings with 1.5% cinnamon oil significantly ($p < 0.05$) inhibited the growth of bacteria and reduced TVB-N and lipid oxidation. Similar results were also reported when gelatin coatings included oregano or laurel essential oils (Alparslan et al., 2014; Hosseini et al., 2016). In addition, the positive effects of gelatin-chitosan coatings on quality retention of fishery products were also verified from the evaluations of protein nanostructure and peptide composition (Farajzadeh et al., 2016; Feng, Bansal, and Yang, 2016).

Whey protein

Whey protein, a by-product of cheese manufacturing, has been used because of its biodegradability and oxygen, aroma and oil barrier characteristics (Henriques, Gomes, and Pereira, 2016). Besides, whey protein has the advantage of the presence of lactoperoxidase (LPO), which has a broad spectrum antibacterial activity. If needed, additional LPO can be added. Shokri, Ehsani, and Jasour (2015) showed that a whey protein-LPO coating effectively inhibited TVC and specific spoilage bacteria (*Pseudomonas spp.*, *P. fluorescens* and *S. putrefaciens*), as well as retarded the quality deterioration induced by bacterial activity in refrigerated rainbow trout fillets. they also found that the antibacterial activity of the whey protein-LPO coatings were correlated with the LPO concentration. Rostami, Abbaszadeh, and Shokri (2017) showed that the combination of MAP and whey protein-LPO coating had a synergistic effect on quality retention of pike-perch (*Sander lucioperca*) fillets. However, lipid oxidation was not decreased significantly using whey protein coatings mixed with or without LPO (Shokri, Ehsani, and Jasour, 2015; Yildiz and Yangilar, 2016). Shokri and Ehsani (2017) then found that adding α-tocopherol to the coating lowered TBARS about 64%. Similarly, other plant extracts, e.g., thyme and cinnamon essential oils have been used to prepare whey protein-based coatings with better anti-oxidative properties (Bahram et al., 2016; Tokur et al., 2016).

Other natural materials

Other proteins or polysaccharide-related substances with some biological activity have been studied. Wang et al. (2017) investigated the effects of a tartary buckwheat (*Fagopyrum tataricum Gaertn.*) polysaccharide (TBP)-based coating on the shelf life of tilapia (*Oreochromis niloticus*) fillets. TBP had limited antibacterial and antioxidant activity, yet the shelf life of 1.5% TBP+1% nisin coated fillets was double that of the control. Volpe et al. (2015) developed active coatings using carrageenan and found 1% carrageenan coating increased the quality of rainbow trout fillets at 4 ± 1°C for 15 days based on inhibition of lipid oxidation and bacterial growth. Binsi et al. (2016) showed the efficacy of edible gum arabic coatings in delaying spoilage and improving the quality of chilled Indian mackerel (*Rastrelliger kanagurta*). Cai et al. (2014) evaluated the effects of gum arabic coatings with ergothioneine on the sensory and physicochemical characteristics of red sea bream, and indicated that the coating slowed nucleotide breakdown, lipid oxidation, protein degradation and microbial growth. Raeisi et al. (2015) used carboxy methyl cellulose (CMC)-based coatings enriched with *Zataria multiflora Boiss.* essential oil and grape seed extract to increase the shelf life of rainbow trout fillets. Jouki et al. (2014) showed the benefit of quince seed mucilage in coatings/films for rainbow trout fillets. In addition, other protein-based substances, such as collagen and casein were also used to produce coatings for aquatic products (Wang et al., 2017c; Zargar et al., 2016).

Composite additives

Coating carriers, such as chitosan and whey protein maintain the quality of chilled fishery products to some degree, but their limited antimicrobial and antioxidation activities cannot completely suppress spoilage and satisfy the consumer's needs for longer shelf life and better edible quality of fishery products. In the case of chitosan coatings, the TBARS and/or peroxide values of coated fillets from different fish species still sharply increased ($p < 0.05$) during storage, just a little lower than that of the control, and TVC was only reduced 0.5-1.5 $\log_{10}$ CFU/g after coating treatments (Cai et al., 2013; Ramezani, Zarei, and Raminnejad, 2015; Yu et al., 2017a). To address the problem, more active biological compounds can be added to the coating. As long as they do not negatively impact the film properties, this is often the most efficient and convenient means to improve the properties of the composite coatings. The more active compounds can be divided by their initial source into additives of plant-, animal-, or microorganism-origin.

Additives of plant extracts

With fishery products, plant-derived water-soluble and alcohol-soluble extracts have been extensively studied as coating enhancers to improve antibacterial and antioxidant activity. Recent publications with regard to plant extracts blended in coating solution for fishery product preservation are summarized in Table 2. It has been reported that when added to coatings, these extracts significantly inhibited lipid oxidation during refrigerated storage (Li et al., 2012; Qiu et al., 2014; Yildiz, 2017). Alginate coatings containing 0.3% TP maintained low TBARS values with refrigerated bream (*Megalobrama amblycephala*) during 21days of storage (Song et al., 2011). Sea bass fillets treated with chitosan coatings including citric acid or licorice extract showed an increased delay of TBARS and peroxide values when compared to the control (Qiu et al., 2014). Chitosan coatings combined with cinnamon oil stabilized the fatty acid composition of frozen rainbow trout (Ojagh, Rezaei, and Razavi, 2014). A gelatin-cinnamon oil coating significantly reduced TBARS values and free fatty acids in rainbow trout fillets throughout storage (Andevari and Rezaei, 2011). Besides, Atarés and Chiralt (2016) and Bonilla et al. (2012) also reviewed the effect of incorporating essential oils on the antioxidant properties of edible coatings. They indicated that the antioxidant capacity improvement of edible composite coatings mainly depended on the following two actions. First, plant extracts *in vitro* acted as free radical scavengers; second, some plant extracts have specific bioactivities that can be expressed when they are absorbed into the product's tissues. For examples, Shi et al. (2014a) indicated grape seed and clove bud extracts showed strong DPPH and Fe^{2+}-chelating scavenging activity. Yu et al. (2017b) and Li et al. (2015) indicated that essential oils and pepper leaf extracts helped maintain the antioxidant enzyme activities of superoxide dismutase, catalase and glutathione peroxidase in fish muscle.

Moreover, plant extracts generally help to inhibit the bacterial growth synergistically with coating carriers. Essential oils and water-soluble extracts (such as tea polyphenols) are rich in bioactive compounds (terpenoids, phenolic compounds, etc.), which have been considered to be antimicrobial agents (Ruiz-Navajas et al., 2013). The antibacterial mechanisms for these plant extracts' activity have been mainly attributed to the damaging of the phospholipid bilayer of the cell membrane, the disrupting of enzyme systems and the compromising of genetic material of bacteria (Atarés and Chiralt, 2016). The positive effect of plant extracts on the antibacterial properties of edible coating has been confirmed *in vitro* using various methods as reviewed by Atarés and Chiralt (2016), but also confirmed *in situ* with fishery products. Yuan et al. (2016b) indicated that the total aerobic plate count of Pacific white shrimp coated with chitosan+1.5% pomegranate peel extract further reduced the $\log_{10}$ CFU/g about 1 unit when compared to chitosan or 1.5% pomegranate peel extract treatments after 10 days of iced storage. Jafari, Jafarpour, and Safari (2017) also reported that the combination of 1% chitosan and 0.5% rosemary extract showed significant ($p < 0.05$) inhibition of the growth of *L. monocytogenes* in beluga sturgeon (*Huso huso)* fillets during storage compared to chitosan or rosemary extract used solely. Wu et al. (2016) developed an edible coating of chitosan and gallic acid for Pacific mackerel (*Pneumatophorus japonicus*) fillets, and indicated that the chitosan-gallic acid treatment was more effective than either treatment alone in inhibiting microbial growth as well as for other traits. Yildiz (2017) and Li et al. (2017b) found that chitosan coatings enriched with thyme oil or clove oil were each more effective in inhibiting the growth of spoilage bacteria in fillets during cold storage. It was also reported that sodium alginate + rosemary extract coatings synergetically enhanced the inhibition of TVC, *Pseudomonas sp.*, H_2S-producing bacteria, *Enterobacteriaceae* and lactic acid bacteria (LAB) in chilled abalone (*Haliotis discus hannai Ino*) (Hao et al., 2017).

Additives of animal and microorganism-origins

Animal and microorganism-origin additives are also frequently used for edible coatings. The commonly used animal and microorganism-origin additives in food system mainly contain functional enzymes (lysozyme and lactoperoxidase) and bacteriocins (nisin, natamycin and ε-polylysine). Compared with plant extracts, they have less diversity, but with relative high stability under varying pH and temperature conditions (Branen and Davidson, 2004), and excellent antibacterial ability, particularly against Gram-positive bacteria by affecting composition and function of their cell membranes (Tiwari et al., 2009). At present, these components have been used in coatings for fishery products as antibacterial agents. Datta et al. (2008) indicated the *L. monocytogenes* and *S. anatum* on the surface of smoked salmon coated with an alginate-based coating enriched with lysozyme further reduced the bacteria by 1.2-1.5 $\log_{10}$ CFU/g compared to calcium alginate coating treatments after 35 days of refrigerated storage. Composite edible coatings of 4% collagen enriched with lysozyme (0.1-0.7%) also significantly ($p < 0.05$) inhibited bacterial growth in fresh-salmon fillets (Wang et al., 2017c). It was reported that a whey protein-LPO complex coating effectively retarded microbial spoilage in refrigerated rainbow trout fillets (Shokri, Ehsani, and Jasour, 2015) or pikeperch fillets (Rostami, Abbaszadeh, and Shokri, 2017; Shokri and Ehsani, 2017). Japanese sea bass fillets treated with an ε-polylysine/sodium alginate coating showed the lowest microbial counts, including TVC, TPC, enterobacteria, lactic acid bacteria (LAB) and yeasts among all treatments tested (Cai et al., 2015a). Hui et al. (2016) investigated the combination of chitosan and nisin on large yellow croaker, and found that chitosan-nisin treatments showed better quality rentention of fillets than chitosan alone using TVC growth and other evaluation indicators. Similar results were also reported with edible coatings with nisin and alginate or polysaccharide (Lu et al., 2010; Wang et al., 2017).

Coating methods

The study and utilization of edible coatings on fresh and processed food is rapidly growing because of the positive effects on shelf life extension, and even as a vehicle for incorporating functional ingredients. Coatings for preservation can be applied directly or indirectly. Direct coating refers to forming edible layer on the food surface, and it can be done by dipping, brushing or spraying (Andrade, Skurtys, and Osorio, 2012). At present, dipping is the most widely studied technology for applying coatings to fishery products. For instance, Mohan et al. (2012) used chitosan dipping to extend the shelf life of refrigerated oil sardine by 3--5 days. The chitosan-gelatin solutions used as dipping coatings slowed the spoilage of refrigerated shrimp and golden pomfret (Farajzadeh et al., 2016; Feng, Bansal, and Yang, 2016). Dipping coatings using chitosan and oregano or thyme essential oils controlled the growth of spoilage and pathogen microorganisms, and improved the sensorial quality of ready-to-eat peeled shrimps (Carrion-Granda et al., 2016). However, in industrial practice, dipping leads to dilution and contamination problems. On the other hand, spraying or brushing does not have these drawbacks, and also provides the possibility of more uniform coating, thickness control and multilayer applications, but requires more complex equipment which is relatively inefficient when products require a lot of coating (Andrade, Skurtys, and Osorio, 2012).

Indirect coating involves applying a coating solution to a food-grade film (e.g., polylactic acid film) with a brush or as a spray to make a double-layer film with specific functions. *In vitro* tests confirmed that the edible coating layer on food packaging film improved the gas barrier properties, and provided excellent antibacterial and antioxidant capacities as reviewed by Tawakkal et al. (2014). Torlak and Sert (2013) showed the broad spectrum antibacterial activity of antibacterial polypropylene films. In this study, six foodborne pathogens (*Bacillus cereus*, *Cronobacter sakazakii*, *E. coli O157:H7*, *L. monocytogenes*, *Salmonella typhimurium* and *S. aureus*) CFU were reduced 3.9-5.6 log *in vitro* after treating with a chitosan-propolis coated film compared to the control film. Lei et al. (2014) also indicated that polyethylene terephthalate /polypropylene films assembled with chitosan and ε-polylysine had high antimicrobial activity against *E. coli* and *B. subtilis* with almost 100% inhibition ratios. At present, functional films using indirect coating have been widely studied for practical applications as effective and promising packaging material to extend the shelf life of food. Guo, Jin, and Yang (2014) indicated that chitosan-based antimicrobial coatings on polylactic acid films significantly controlled *Listeria* and *Salmonella* in fluid culture medium and a ready-to-eat meat. Similar results were also reported for other food, such as fresh beef and cheese (Han et al., 2014; Torlak and Nizamlioğlu, 2011). Apparently, indirect coatings also have the potential to be applied to fishery products. It needs to be emphasized that both coating methods have their own advantages. Direct coating will often be more appropriate for foods with irregular surfaces. However, the drying process after coating slows down production efficiency. By contrast, functional films can be customized commercially and used as a regular packaging material.

Protective effects of edible coatings for fishery products

As a highly perishable food item, the postmortem changes of fishery products caused by biochemical reactions and microbial metabolism result in rapid deterioration of their edible quality. Many studies have shown the potential application value of edible coatings to prolong the shelf life of fresh fishery products based on bacterial enumeration, physicochemical analysis and sensory evaluation. These studies will be summarized below.

Effect of edible coating on microbial quality of fishery products

Generally, TVC is an important index in many standards that are used to judge the freshness of fishery products. In many cases, TVC of 7.0 $\log_{10}$ CFU/g is regarded as the maximal permissible limit for fishery products (ICMSF, 1986). In addition, some auxiliary indicators of spoilage and pathogenic bacteria are used, including *Pseudomonas sp.*, H_2S-producing bacteria (including *Shewanella sp.*), *Aeromonas sp.*, *Enterobacteriaceae*, *L. monocytogenes*, and LAB. Recently, additional evidences have reiterated the close links between quality deterioration of fishery products and spoilage bacteria. For instance, Wang et al. (2014) indicated that *Shewanella* and *Aeromonas* were the main organism that produced putrescine and cadaverine in refrigerated carp fillets. Li et al. (2017a) reported that the degradation process from inosine monophosphate (IMP) to hypoxanthine ribonucleoside (HxR) and hypoxanthine (Hx) was correlated with microorganism proliferation. Wang et al. (2017b) and Liu et al. (2018) confirmed spoilage flora isolated from spoiled fillets had the ability to produce volatile compounds with unpleasant odors.

Some of publications showing a significant inhibition of microbial spoilage with bio-based coatings of fishery products during refrigerated storage are shown in Table 3. Coating carriers as well as natural preservatives were considered as antibacterial agents and may be synergistic in maintaining the microbiological quality of fishery products. Chitosan edible coatings (2%) reduced TVC 1.9 $\log_{10}$ CFU/g with Indian oil sardines after 9 days of refrigerated storage (Mohan et al., 2012). Similarly, chitosan coatings enriched with ergothioneine delayed microbial spoilage of Japanese sea bass during storage with reductions of 1.5-2.5 $\log_{10}$ CFU/g for mesophilic and psychrophilic bacteria, *Pseudomonas*, and LAB (Cai et al., 2013). White shrimps treated with alginate-calcium coatings combined with a *Citrus wilsonii Tanaka* extract or chitosan coating decreased the final TVC 1.2 and 0.9 $\log_{10}$ CFU/g, respectively (Liu et al., 2016). The combined coating of chitosan and gelatin significantly ($p < 0.05$) inhibited microbial growth in refrigerated shrimp, and the largest reductions of nearly 3.5 and 4.5 $\log_{10}$ CFU/g of TVC and TPC, respectively, were obtained compared to the control at day 8 of storage (Farajzadeh et al., 2016). Shrimps treated with chitosan coatings incorporated with active shrimp waste (shrimp protein-lipid concentrate) extended the lag phase of microbial growth for 3--7 days (Arancibia et al., 2015). Nowzari, Shabanpour, and Ojagh (2013) compared the effects of chitosan-gelatin composite coatings and films on the quality of rainbow trout, and the results indicated both treatments were effective in controlling bacterial spoilage with no significant difference ($p \geq 0.05$) between the two treatment systems. Carrion-Granda et al. (2016) studied the potential synergies of chitosan coatings with 0.5% of oregano and thyme essential oils on the microbiological quality of ready-to-eat peeled shrimps, and found that chitosan-thyme essential oil treatment was more effective in inhibiting microorganisms although both coatings were effective.

Effect of edible coatings on the physicochemical quality of fishery products

During postmortem storage, physicochemical changes will affect both sensory and nutritional characteristics of fishery products (Liu et al., 2013). Lipid oxidation, nucleotide degradation, nitrogenous compounds accumulations, as well as the changes of physical properties (texture, water and color) are commonly used and important indicators to assess the physicochemical quality of fishery products.

Lipid oxidation

Lipid oxidation leads to the development of discoloration, rancid flavors and potentially toxic compounds (Farvin, Grejsen, and Jacobsen, 2012). Moreover, lipid oxidation intermediates will also react with proteins, resulting in the decrease of protein functionality and nutritional loss of some amino acids. At present, the increasing studies have reported so far on oxidation inhibition using edible coatings for fishery products. Feng et al. (2017) indicated that fish gelatin-tea polyphenols coatings for golden pomfret fillets significantly reduced the accumulation of oxidative spoilage markers, including alcohols, aldehydes and ketones, which are responsible for fishy and rancid odors. Qiu et al. (2016) reported the significant inhibition of lipid oxidation in frozen ovate pompano fillets using chitosan-licorice extract coatings, with reductions of 64 and 50% of TBARS and peroxide values, respectively compared to the control at the end of storage. Qiu et al. (2014) developed chitosan coatings with citric acid or licorice extract for Japanese sea bass. The results indicated that licorice extract had greater antioxidant activity, and the TBARS values of chitosan-licorice extract coated fillets decreased by 64% compared to the control after 8 days of storage. Similar results were also reported for rainbow trout, lingcod (*Ophiodon elongates*), snakehead (*Channa argus*) and shrimp using edible coatings (Duan, Cherian, and Zhao, 2010; Lu et al., 2009; Ojagh et al., 2010; Yuan et al., 2016). These results suggested that edible coatings effectively retarded lipid oxidation of fishery products during storage, mainly as an oxygen barrier and with the antioxidant properties provided by coating components. In addition, plant extracts contributed to maintain the activities of antioxidant enzymes in food matrix, such as superoxide dismutase and glutathione peroxidase (Li et al., 2015; Yu et al., 2017b; Yuan, Chen, and Li, 2016a).

Nucleotide degradation

The nucleotide degradation of adenosine triphosphate (ATP) to Hx is an important biochemical change in fishery products during postmortem storage. It involves both autolytic breakdown and bacterial action (Li et al., 2017a). The changes of ATP-related compounds that affect the freshness and flavor quality of fishery products was reviewed by Hong, Regenstein, and Luo (2017). Among these compounds, inosine monophosphate (IMP) is a kind of umami enhancer, while HxR and Hx are responsible for off-odor and bitterness. The ratio of ATP-related compounds (defined most commonly as the K value) is widely used to evaluate the freshness of fishery products, with K value less than 20% as very fresh, 20--60% as moderately fresh and more than 60% as subject to rejection (Ehira, 1976). Research shows that edible coatings have a positive effect on decreasing nucleotide degradation. Yu et al. (2018) reported that chitosan and clove essential oil coatings for grass carp fillets delayed the degradation of IMP and accumulation of HxR and Hx. Hui et al. (2016) found the final K value of large yellow croaker treated with 1% chitosan, 1% chitosan+0.2% nisin and 1% chitosan+0.6% nisin were ~ 82, 71 and 61% lower, respectively, compared to the control. Similarly, edible coatings with or without plant extracts also significantly ($p < 0.05$) reduced K values in other refrigerated fishery products (Li et al., 2013; Li et al., 2017b; Soares, Mendes, and Vicente, 2013; Souza et al., 2010). The positive effect of edible coatings on nucleotide degradation inhibition may be due to the inactivation of enzymes and bacteria involved in the ATP degradation process (Wu et al., 2016b).

Nitrogenous compounds

The accumulation of nitrogenous compounds (such as TVB-N, trimethylamine (TMA), and biogenic amines) in fishery products is caused by the metabolisms of spoilage bacteria and enzymes, and ultimately affects the flavor, sensory quality, nutrition and safety of products (Li et al., 2011). For example, TMA is one of the major substances responsible for fishy odor, and some biogenic amines (such as histamine, cadaverine and putrescine) are potentially toxic for humans (Howgate, 2010; Yassoralipour et al., 2012). Significant decreases ($p < 0.05$) of TVB-N and TMA contents were obtained using edible coatings with various fish species, such as sauced silver carp (Rezaei and Shahbazi, 2018), refrigerated or frozen rainbow trout (Alp Erbay et al., 2017; Coban, 2013; Jouki et al., 2014; Yildiz, 2017), frozen salmon (Soares et al., 2017), refrigerated silver pomfret (Wu et al., 2016b), refrigerated white shrimp (Liu et al., 2016), defrosted hake (*Merluccius capensis*) fillets (López de Lacey, López-Caballero, and Montero, 2014) and refrigerated grass carp (Yu et al., 2017a). Total and spoilage biogenic amines were also reduced in many cases. Hao et al. (2017) indicated reductions of 66 and 77% of cadaverine and putrescine, respectively, were observed with alginate-rosemary extract coated abalone compared to the control. At the same time, the total content of all biogenic amines was only one-third of the control. Similar results were also reported by Wu et al. (2016) that histamine, cadaverine and putrescine in Pacific mackerel significantly decreased using a chitosan-gallic acid coating during 12 days of refrigerated storage. This is due to the inhibition of spoilage bacteria such as *Shewanella*, *Aeromonas* and *Enterobacteriaceae* that produce these toxic compounds.

Physical properties

The deterioration of physical properties (including texture, water retention and color changes) may negatively influence flavor, appearance and texture, and are of great economic importance as fishery products are sold by weight (Huff-Lonergan and Lonergan, 2005). Fishery products, especially fish fillets, are sensitive to texture deterioration within the first few days of storage, decreasing by 30--60% for texture indicators such as hardness or shear force compared to initial values (Duun and Rustad, 2008; Ge, Xu, and Xia, 2015; Rodrigues et al., 2017). Endogenous enzymes such as calpains, lysosomal cathepsins, collagenase and matrix metalloproteinases have been shown to be involved in the postmortem softening of refrigerated fishery products (Jiang et al., 2015; Wang et al., 2011). In the latest studies, the texture deterioration of refrigerated fishery products measured instrumentally could be significantly retarded using edible coatings

(Carrion-Granda et al., 2016; Farajzadeh et al., 2016; Wang et al., 2017c). The reasonable explanation is that the edible coating treatments inhibited enzyme activities, and *in-vitro* assays probably confirmed this hypothesis as some compounds from natural sources such as green tea, garlic and *Allium* species were shown to be enzyme inhibitors (Ge et al., 2016a; Olivan et al., 2011; Xu et al., 2015). In addition, edible coatings also contribute to improve water retention. Mohan et al. (2012) reported that the drip loss decreased 72% and the water holding capacity increased 76% with 2% chitosan coated oil sardine compared to the control after 9 days of refrigerated storage. Farajzadeh et al. (2016) also found chitosan-gelatin coatings significantly ($p < 0.05$) reduced weight loss of refrigerated shrimp. Khan et al. (2015) observed a similar reduction in drip loss for rohu (*Labeo rohita*) fillets coated with whey protein after 40 days of frozen storage. The fewer water changes in coated samples may be due to the inhibition of protein denaturation, leading to better retention of hydration capacity. Also, edible coatings may function as moisture sacrificing agents and barriers to cut down exudates from products (Sathivel et al., 2007). In addition, color of fishery products is often monitored by determining L^*, a^* and b^*. Lipid oxidation is the primary reason for the color changes (Sun et al., 2017). Results suggested edible coatings reduced discoloration, resulting in smaller b^* values and higher L^* *value* compared to the control during refrigerated storage (Arancibia et al., 2015; Cai et al., 2015a; Li et al., 2017c). However, the change of a^* varies, depending on species. In general, edible coatings prevent increased yellowness and decreased lightness by effectively inhibiting oxidation.

Effect of edible coatings on the sensorial quality of fishery products

Sensory evaluation has been widely used to assess the freshness of fishery products in term of sensorial preference scores. At present, the commonly used sensory methods using experienced and trained panelists for fishery products are the European Union (EU) and Quality Index Method (QIM), which can standardize sensory assessments for different species as reviewed by Cheng et al. (2015). The organoleptic deterioration of fishery products is often seen as texture softening, discoloration and unpleasant odors, which are caused by microbial spoilage, enzyme hydrolysis and lipid oxidation (Zhang et al., 2017). Edible coatings have been confirmed to be reliable methods to maintain the sensorial quality of fish and fishery products. Yu et al. (2018) indicated the organoleptic deterioration of refrigerated grass carp fillets was significantly ($p < 0.05$) decreased with a reduction of unpleasant compounds (such as TMA and volatile oxidation products) with chitosan-based coatings. Lu et al. (2009) reported similar conclusions with alginate-calcium-based coatings improving the overall sensory scores of snakehead fillets during refrigerated storage. Ojagh, Rezaei, and Razavi (2014) found chitosan coatings with cinnamon oil protected fish sensory characteristics. These improvements comprehensively reflected the antioxidant, antimicrobial and barrier capacities of edible coatings.

Challenge and future perspective

From the literature reviewed above, bio-edible coatings have become promising alternative to maintain the quality and extend the shelf life of fresh fishery products during storage. However, most studies have only focused on the observing physicochemical changes, bacterial enumeration and sensory evaluation as shown in Figure 1, without trying to understand the underlying mechanisms of the protective effect of edible coating. Therefore, the future research of edible coating is to explore the protective mechanisms in terms of film-forming characteristics, synergistic effects for microorganism and oxidation control, flavor and sensory influences, and enzyme inhibition to optimize its application in the preservation of fishery products. The specific suggestions include:

- At present, dipping-draining is the preferred option for fishery product. For coating such as those with chitosan and gelatin, this method requires a long drain time, and may lead to non-homogenous coating.

More work is needed to understand factors that affect the thickness and uniformity of films forming, and develop drying ways to control the film formation and shorten drain time.

- Although many researchers investigated the effects of edible coating on microbial succession by enumeration, only a few microorganisms have been cultivated. Actually, only one or several microorganisms are predominant communities during spoilage of fishery products. Therefore, monitoring the changes of the comprehensive bacterial diversity of coated samples by more methods will be able to better explain the preservation mechanism(s) at the microbial level.
- Studying the effects of edible coatings on the changes of taste and flavor precursors of fishery products during storage, which contributes to a better understanding of flavor and sensory quality retentions for coated products.
- Developing a better understanding of any synergistic effects among natural preservatives to optimize the formulas for the composite coatings with better synergistic antioxidant and antibacterial activity, as well as negligible negative effect on sensory qualities of products, especially avoiding the color darkening and irritating odors from natural preservatives.
- Although edible coatings inhibit texture softening induced endogenous enzymes during storage, further work is needed to further slow this deterioration. Novel natural enzyme inhibitors may provide one solution.

Conclusion

Bio-based edible coatings are increasingly attracting research attention. This review has introduced many aspects of fishery products coating preservation including coating carriers including those formulated with composites of natural additives, coating methods and their benefits, and short-comings as well as the protective effects as determined using microbial, physicochemical and sensorial evaluations. To better promote the industrial application of edible coatings for fishery products, effort should be directed toward further optimization of coating solution formulas and exploring the potential preservation mechanisms.

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Table 1. Application of chitosan-based coatings for refrigerated fishery products.

Fishery products	Coatings	Findings
Grass carp	Chitosan + glycerol monolaurate	Shelf life was extended by 5~8 days
Olive flounder	Chitosan + clove essential oil	Shelf life was extended by nearly 6 days
	Chitosan + hawthorn flavonoid	Shelf life was extended by 4~6 days

Pacific white shrimp (*Litopenaeus vannamei*)	Chitosan + pomegranate peel extract	Shelf life was extended to more than 10 days
Common carp (*Cyprinus carpio*)	Chitosan + black pepper essential oil	Shelf life was extended by nearly 8 days
Pacific mackerel	Chitosan + gallic acid	Shelf life was extended by 6 days
Shrimp (*Litopenaeus vannamei*)	Chitosan +gelatin	Shelf life was extended by 6 days
	Nanochitosan	Shelf life was extended significantly without specific values
	Chitosan + active shrimp waste	Shelf life was extended by nearly 5 days
Ready-to-eat peel shrimp (*Penaeus vannamei*)	Chitosan + oregano or thyme essential oil	Shelf life was extended significantly without specific values
Silver carp	Chitosan +orange or pomegranate peel extract	Shelf life was extended significantly without specific values
	Chitosan or nanochitosan	Shelf life was extended significantly without specific values
Rainbow trout	Chitosan + lactoperoxidase	Shelf life was extended by at least 4 days
Japanese sea bass	Chitosan + citric or licorice	Shelf life was extended significantly without specific values

	Chitosan + ergothioneine	Shelf life was extended significantly without specific values
Indian oil sardine (*Sardinella longiceps*)	Chitosan	Shelf life was extended by 3~5 days

Table 2. Application of plant extracts in fishery product coatings for preservation.

roduct	Plant extract	Coating carriers	References
p	Clove essential oil	Chitosan-based	Yu et al. (2018)
nder	Clove essential oil	Chitosan-based	Li et al. (2017b)
p	Rose polyphenol	Chitosan-based	Zhang et al. (2017)
	Bamboo leaf extract and rosemary extracts	Sodium alginate-based	Hao et al. (2017)
omfret	Tea polyphenol	Gelatin-based	Feng et al. (2017)
smoked ell (*Anguilla anguilla*)	Rosemary extracts	CMC-based	Choulitoudi et al. (2
hite shrimp	Pomegranate peel extract	Chitosan-based	Yuan et al. (2016b)
trout	*Zataria moltiflora* essential oil	Sodium caseinate-based	Zargar et al. (2016)
npano (*Trachinotus ovatus L.*)	Citric acid or licorice extract	Chitosan-based	Qiu et al. (2016)

imps (*Litopenaeus vannamei*)	*Citrus wilsonii tanaka* extract	Calcium alginate-based	Liu et al. (2016)
ream	6-Gingerol	Alginate-based	Cai et al. (2015b)
trout	*Zataria multiflora Boiss.* essential oil and grape seed extract	CMC-based	Raeisi et al. (2015)
trout	Thyme essential oil	Whey protein-based	Karakaya Tokur et a
p	*Pimpinella affinis* essential oil	Methylcellulose-based	Ariaii et al. (2014)
(*Sciaenops ocellatus*)	Grape seed extract and tea polyphenols	Chitosan-based	Li et al. (2013)

CMC, carboxyl methyl cellulose.

Table 3. Significant inhibition of microbial growth in fishery products with edible coatings.

	Coating	Microbial indicators	References
rp	Chitosan-glycerol monolaurate	TVC, TPC, Pseudomonads, H_2S-producing bacteria	Yu et al. (2017c
trout	Chitosan-cinnamon oil	TVC, TPC	Ojagh et al. (201
	Chitosan-thyme oil	TVC, TPC, LAB, *Pseudomonads*, *Enterobacteriaceae*	Yildiz (2017)
ream	Alginate-gingerol	TVC, TPC, LAB, *Pseudomonads*, *Shewanella putrefaciens*, Enterobacteria	Cai et al. (2015b
sea bass	Alginate-ε-polylysine	TVC, TPC, LAB, Enterobacteria, Yeast	Cai et al. (2015a
	Chitosan-ergothioneine	TVC, TPC, LAB, *Pseudomonads*,	Cai et al. (2013)

ell	CMC-rosemary extracts	TVC, LAB, *Pseudomonads*	Choulitoudi et al
	Chitosan-shrimp waste extract	TVC, TPC, LAB, H_2S-producing bacteria, Luminescent bacteria, *Pseudomonads*,	Arancibia et al. (
-eat peeled	Chitosan-oregano or thyme essential oil	TVC, TPC, LAB, *Enterobacteriaceae*	Carrion-Granda (2016)

LAB, lactic acid bacteria; TPC, total psychrophilic count; TVC, total viable count

Figure 1. The general scheme and results of traditional coating preservation for fishery products.