Biopreservation of pre-processed fresh fish by bio-based coatings

Don Hettiarachchige Udana Eranda, Manat Chaijan, Ilke Uysal-Unalan, Worawan Panpipat, Azza Silotry Naik, Amira Leila Dib, Supatra Karnjanapratum, Mohammed Gagaoua

Biopreservation of pre-processed fresh fish by bio-based coatings: A single strategy with multiple benefits towards waste prevention

Don Hettiarachchige Udana Eranda [a], Manat Chaijan [a], Ilke Uysal-Unalan [b,c], Worawan Panpipat [a], Azza Silotry Naik [d], Amira Leila Dib [e], Supatra Karnjanapratum [f] and Mohammed Gagaoua [g,h] *

[a] Food Technology and Innovation Research Center of Excellence, Division of Food Science and Innovation, Department of Food Industry, School of Agricultural Technology and Food Industry, Walailak University, Nakhon Si Thammarat, 80161, Thailand

[b] Department of Food Science, Aarhus University, Agro Food Park 48, 8200, Aarhus N, Denmark

[c] CiFOOD – Center for Innovative Food Research, Aarhus University, Agro Food Park, 48, 8200, Aarhus N, Denmark

[d] School of Food Sciences and Environmental Health, Technological University Dublin, Grangegorman, D07 ADY7, Dublin, Ireland

[e] Gestion de La Santé et Productions Animales Research Laboratory, Institut des Sciences Vétérinaires El-Khroub, Université Constantine 1 Frères Mentouri, Constantine, 25000, Algeria

[f] Division of Marine Product Technology, Faculty of Agro-Industry, Chiang Mai University, Chiang Mai, Thailand

[g] Food Quality and Sensory Science Department, Teagasc Ashtown Food Research Centre, Ashtown, Dublin 15, Ireland

[h] PEGASE, INRAE, Institut Agro, 35590, Saint-Gilles, France

* Corresponding author: mohammed.gagaoua@inrae.fr

Abstract

The demand for pre-processed fresh fishery products is growing due to their convenience for subsequent processing and cooking. However, when improperly stored, the combined impacts of microbial deterioration and chemical reactions render them inedible, leading to significant food waste. To tackle this issue, several approaches have been proposed, among which bio-based edible coating provides a promising solution with a green approach. Edible coatings are formed of bio-based polymers, particularly using macromolecules such as proteins and polysaccharides that are biodegradable, edible, and can serve as carriers for naturally sourced active agents. Coatings made from a variety of proteins and polysaccharides with the main focus on gelatin and chitosan to preserve pre-processed fish products are discussed in this review along with their properties from the microbial, physicochemical, and sensory perspectives. Coating carriers and composite natural preservatives as well as formula optimization and investigation of coating mechanisms, challenges, and potential research prospects have been further reviewed. Overall, edible coatings with active substances can be used to efficiently preserve freshly pre-processed fish. The underlying mechanisms are multiple, and the applications were mainly for preventing or reducing moisture loss and purge accumulation, postponing microbial spoilage, and restricting the growth of pathogenic microorganisms, slowing and/or inhibiting lipid, protein, and pigment oxidation, and extending the shelf-life along with improving sensory properties. Edible coatings are viewed as ecologically friendly and sustainable packaging alternatives for the preservation of pre-processed fish products.

Keywords: Sustainable products; Bio-based polymers; Edible coatings; Fish products; Shelf-life; Sensory properties, Food wastage, Packaging.

1. Introduction

Sustainable development is a global goal that requires an interdisciplinary approach to addressing current and future environmental, climate change, economic, and resource efficiency concerns. Food sustainability must be a global priority if we are to maintain our planet for future generations; nevertheless, this lofty target is difficult to achieve due to two fundamental difficulties in food handling, production, and storage, these being food loss and waste. Among food products of animal origin, fish is a perishable raw material that, more than other matrices, faces the issues of food waste and loss (up to 40 % in some middle-low income countries) (Racioppo et al., 2021). Food loss is defined as a decrease in the quantity and quality of food because of the decisions made by food suppliers, excluding retail, providers, and consumers (FAO, 2019). The best example of food loss in the fishing industry is so-called low-value fish, which is frequently discarded since it is not of acceptable intrinsic quality for consumers. Fish loss transpires at every step of the value chain, from catch to final consumption. Loss is influenced by a number of factors, including the species of fish, the associated physical characteristics (i.e. composition, weight, and structure), the perceived value of the fish, the volumes handled, the level of seasonality, and the geographic location. Moreover, due to technical, financial, infrastructural, and managerial constraints, fish companies in developing countries are likely to incur greater fish losses than those in developed ones during loading and unloading, processing, storage, transportation, and marketing (De Silva, 2011). However, not all the seafood that is made accessible is consumed. Volumes of wastes are produced by discards, bycatch on board, and wastage ashore. The processing discards, such as skins, skulls, heads, viscera, fillet cut offs, spoilage discards, and others, account for up to 40 % of the processed raw material (Venugopal & Sasidharan, 2021). In the past few decades, there has been a significant upsurge in close consideration surrounding the issue of food waste. This is mostly due to the numerous adverse effects of food waste and loss (FWL), as well as the growing recognition of the problem's global scale. Specifically, there is a heightened awareness of the associations between food waste and loss, food security, and climate change (Mokrane et al., 2023). Millions of people, including those in regions where malnutrition and micronutrient deficiencies are pervasive (FAO, 2011) are affected by the loss or nutritional degradation of highly nutritious materials. In fact, due to high ambient temperatures, lack of access to services, infrastructure, and basic technology, reliance on more traditional smoking and drying techniques for preservation, and absence of cooling (cold chain) facilities, spoilage and quality degradation of the product are more likely to occur in low-income economies (HLPE, 2014). Because of its significance in coastal and marine pollution, improper disposal of fishery waste in marine and coastal areas has received growing attention. Improved use of seafood waste can help meet the global demand for seafood, while avoiding the negative impacts of seafood harvesting and production.

The primary cause of fish quality degradation in fresh or minimally preserved fish is microbial decomposition, which in extreme circumstances can lead to 25 %–30 % loss of marketable fish (Mei et al., 2019; Nie et al., 2022; Tavares et al., 2021). Fresh fish has a distinct microflora, a relatively short shelf life, and its spoilage is caused by gram-negative aerobic bacteria such as *Pseudomonas* sp. and *Shewanella* sp. (Donna et al., 2007). Notably, some mesophilic and psychrotolerant bacteria, such as *Morganella psychrotolerans* and *Photobacterium* spp., can produce histamine in fish during storage by decarboxylating free histidine in the fish muscle, which can result in histamine fish poisoning (De Silva, 2011; Tsironi et al., 2008). In addition to microbiological problems, oxidative deterioration has a major detrimental effect on the quality of fish (Amit et al., 2017). Lipid oxidation

can further degrade the flavor, color, and texture as well as a concurrent reduction in the nutritional attributes of the stored fish (Amit et al., 2017). As lipids spontaneously react with atmospheric oxygen, auto-oxidation of lipids is the most frequent form of oxidative deterioration in fish (Hassoun and Emir Çoban, 2017). As a result, fish tissues with high levels of unsaturated lipids are extremely vulnerable to oxidation and faster deterioration (Sahari et al., 2014). Another issue with dark-fleshed fish such as that of tuna and mackerel, is the discoloration caused by the redox instability of myoglobin when kept at a cold temperature, which can lead to sensory unacceptability (Nakazawa et al., 2020; Thiansilakul et al., 2011; Wongwichian et al., 2015). The brighter reddish hue of dark-fleshed fish meat is typically attributed to the presence of red pigment, primarily oxymyoglobin, which undergoes various biochemical changes during handling and storage to become brown metmyoglobin (Chaijan & Panpipat, 2017; Singh et al., 2021). Myoglobin has a close relationship with lipid oxidation which could further influence the deterioration in food (O'grady et al., 2001). Thus, both microbial and chemical actions can cause the deterioration in the quality of fish flesh during storage (Nawaz et al., 2020; Qiu et al., 2014; Singh et al., 2021).

The most popular method of delaying the microbiological and biochemical decomposition of fish is to lower the temperature with ice or mechanical refrigeration (Trigo et al., 2022). However, some disadvantages of cold storage include dehydration, textural hardness, nutritional loss, and decreased protein extractability. The shelf life of fresh fish fillets at 4 °C is 1–2 days. While being stored in the refrigerator, fish fillets will soon lose quality and become unfit for consumption in a very short time (Lahreche et al., 2020). Therefore, finding new approaches to lower quality loss and extend the shelf life of refrigerated fish fillets is of importance given the rising demand for refrigerated fresh fish fillets. Several processing technologies may be used to increase the raw fish's shelf life (Kulawik & Dordević, 2020), likely ultra-low temperature storage (Nakazawa et al., 2020), stepwise chilling (Park et al., 2021), modified atmospheric packaging (Abel et al., 2018), antimicrobial absorbent pads (Otoni et al., 2016), cold pasteurization/irradiation (Gautam & Venugopal, 2021) and the use of natural preservatives (Singh et al., 2021) or the combination of these techniques. In addition, recent EU regulations highlight the importance of limiting of the weight and volume of packaging to a minimum adequate amount without compromising the quality and safety of food products (Dörnyei et al., 2023; European Commission, 2020). Therefore, (active) bio-based coating as a part of food preservation and food packaging can be seen as a key strategy to cutting down the use of plastic by co-acting as a shelf-life extender together with primary plastic packaging. Moreover, edible coatings have been regarded as the optimal replacement for conventional packaging systems owing to its intrinsic properties, including water solubility, fats and oil resistance, flexibility, biodegradability, and superior barrier characteristics (Firouz et al., 2021; Syafiq et al., 2020). Edible coatings are thin layers made up of polysaccharides, proteins, lipids, bioactive substances, and composite materials. They are applied directly to the surface of food by either using the techniques of submerging or spraying (Baghi et al., 2022; Cheng et al., 2021). Edible coatings endure the capacity to serve as a vehicle for various bioactive substances, including natural antioxidants, phenolic compounds, and antimicrobials, and thus improve their efficacy in preserving food and impede microbial activity on the surface of the food (Pedreiro et al., 2021; Xu et al., 2022). There is a persistent need to develop economically feasible innovative methods for preserving the quality of fish and fish products, thus justifying the need for further research on coatings.

2. Spoilage mechanisms of fresh fish

Fish are highly perishable due to their high moisture content (70 %–80 %), large amounts of small molecules, and neutral pH, which all provide ideal conditions for microbial and biochemical spoilage (Ojagh et al., 2010; Ramezani et al., 2015). Endogenous enzymatic reactions, oxidation, and microbial activities occur shortly after death in fish, causing changes in sensory and nutritional properties and limiting shelf-life (Karoui & Hassoun, 2017; Kostaki et al., 2009; Olatunde & Benjakul, 2018). In the dark-fleshed fish, the discoloration, formation of unpleasant odors and flavors, as well as the development of harmful molecules, are notable effects of lipid oxidation, with negative health and economic implications (Kuuliala et al., 2018; Mahmoud et al., 2016). Thus, any change in the initial condition of fish that results in an unpleasant odor, taste, appearance, or texture is referred to as spoilage. Fish spoilage can be classified into three distinct mechanisms, including microbial, autolytic, and oxidative spoilages.

2.1. Microbial spoilage

The biochemical composition of fish and seafood promotes bacterial growth, including Gram-positive and Gram-negative types that can survive in a wide temperature range. As a result, microbial spoilage is regarded as one of the primary causes of fish quality degradation, accounting for up to 25 %–30 % of such product loss (Mei et al., 2019). Microbial growth and metabolism generate biogenic amines like putrescine, histamine, and cadaverine, as well as organic acids, sulphides, alcohols, aldehydes, and ketones with irritating and undesirable off-flavors (Bulushi et al., 2009). Every fish species has a unique microflora that is determined by its microbial environment, raw materials, manufacturing parameters, and subsequent storage conditions, as well as the microorganisms' ability to withstand preservation conditions (Chaillou et al., 2015). For example, psychrotolerant Gram-negative bacteria, such as those belonging to the genera *Pseudomonas* and *Shewanella*, have been shown to be the most common spoilage bacteria in aerobically stored chilled fish. CO_2-tolerant microbes, such as *Photobacterium phosphoreum* and lactic acid bacteria, on the other hand, may dominate the microflora and lead to the spoilage of packed fish products (Chaillou et al., 2015). While fresh fish is normally contaminated with many microorganisms, only a small percentage of these microorganisms, known as specific spoilage organisms (SSO), cause spoilage. The SSO differ depending on the type of fish and the preservation conditions (Table 1). *Pseudomonas* was found to be the SSO for bighead carp (*Aristichthys nobilis*) fillets sprinkled with 2 % salt, whereas *Aeromonas* was found to be the SSO for unsalted bighead during 4 °C storage (Hassoun & EmirÇoban, 2017; Liu et al., 2017). By assimilation of nonprotein-nitrogen in fish tissue, SSO have the potential to dominate and generate metabolites, resulting in unpleasant and undesirable off-flavors that directly impact the organoleptic properties of fish, leading to consumer rejection (Boziaris et al., 2013).

Table 1. Microorganisms and specific spoilage organisms (SSO) in fish and seafood products during storage.

Specific spoilage organisms (SSO)	**Fish product/seafood species**	**Packaging technology used, gas and water vapor barrier properties and storage conditions**	**Analysis method**	**References**
Acinetobacter johnsoni *Acinetobacter lwoffii* *Shewanella baltica* *Pseudomonas Fragi* *Pseudomonas*	Hybrid sturgeons (*Acipenser schrenckiid* female × *Huso dauricus* males, females, 60 ± 5 kg)	Packaging technology used: wrapped in plastic bag, and packaged in a cardboard box with gel ice packed around the inner side	Plate colony-counting method Plate count agar (PCA) PCA plate method MALDI Biotyper	Li et al. (2021)

Specific spoilage organisms (SSO)	Fish product/seafood species	Packaging technology used, gas and water vapor barrier properties and storage conditions	Analysis method	References
koreensis *Pseudomonas antarctica*		Storage condition: kept in the cold storage (−40 °C) for 0.5–1 h	(MBT, Brucker Daltonoics)	
Photobacter phosphoreum *Psychrobacter* spp. *Moritella* spp. *Carnobacterium* spp. *Shewanella* spp. *Vibrio* spp.	Fresh hake fillets with skin (*Merluccius*)	Packaging technology used: Modified atmosphere packaging Gaseous composition: 50 % CO_2/50 % N_2 under gas/product ratio of approximately 2:1 Storage temperature: stored at four varied temperatures of 1,4,7 and 10 °C	Maxwell 16 Lev Blood DNA Extraction Kit (Promega, Madison, USA), qPCR analysis, high-throughput 16S rRNA gene sequencing	Antunes-Rohling et al. (2019)
Lactobacillus algidus *Pseudomonas fluorescens*	fresh yellowfin tuna fillets (*Thunnus albacares*)	Packaging technology used: Vacuum packaged Film thickness: high barrier film (90 µm in thickness) Oxygen transmission rate at 23 °C and 75 % Relative humidity: 1 cm^3 m^{-2} 24 $h^{-1}atm^{-1}$	Agar spread plate, PCR amplification 16S rRNA sequencing	Jääskeläinen et al. (2019)
Lactic acid bacteria (LAB) *Pseudomonas* spp. *B. thermosphacta*	Atlantic cod (*Gadus morhua*)	Packed under different atmospheres gas-product ratio 2:1, tray sealer MECA 900 Multilayer packaging trays (PP/EVOH/PP) oxygen transmission rate at 23 °C and 50 % RH: 0.03 cm^3/tray *24h Top film (PA/EVOH/PA/PP) Oxygen transmission rate at 23 °C, 50 % RH and 1 atm: 6.57 cm^3/m^2*24h*atm	Total psychotropic count (TPC) using Marine agar lactic acid bacteria (LAB) count using Man Rogosa Sharpe agar or modified MRS Pour plate method	Kuuliala et al. (2018)
Staphylococcus aureus *Pseudomonas fluorescence* *Escherichia coli* *Vibrio cholerae* *Salmonella typhi* *Aspergillus niger*	Indian mackerel fish (*Rastrelliger kanagurta*)	Storage temperature: Stored in a refrigerator at 4 °C	Pour plate method (Serial dilution technique) Sterile Nutrient agar and Sabouraud's dextrose agar Quebec colony counter, Colony morphology Mobility tests, routine mycological methods	Srinivasan and Saranraj (2017)
Pseudomonas spp. *Shewanella* spp. *Janthinobacterium* spp. *Photobacterium* spp. *Acinetobacter* spp.	farmed Atlantic salmon fillets	Packaging technology used: Separate boxes (expanded polystyrene; EPS boxes) Storage condition: Stored on ice <1 °C (verified by the temperature logging)	Iron agar medium partial 16S rRNA gene sequencing Phylogenic analysis by Sequence Scanner software 2 (Applied biosystems)	Møretrø et al. (2016)
Rhodanobacter terrae *Brochothrix thermosphacta* *Pseudomonas* spp. Enterobacteriaceae spp. Lactic acid bacteria (LAB)	tropical yellowfin tuna (*Thunnus albacares*)	**First batch packaging and storage condition:** Vacuum-packed individually in 80 µm thickness plastic bags made from polyamide and polypropylene Gas permeability: 2.78 cm^3 m^2/day for water vapor O_2 permeability: 19.95 cm^3/m^2/day	Plate count agar (PCA) ELK and STAA PCR amplification and Bacterial 16S rRNA gene amplification barcode sequencing	Silbande et al. (2016)

Specific spoilage organisms (SSO)	Fish product/seafood species	Packaging technology used, gas and water vapor barrier properties and storage conditions	Analysis method	References
		CO_2 permeability: 164.87 cm3/m2/day **Second batch packaging condition:** Vacuum-packed in 80 μm thickness plastic bags used Storage condition: Iced in a cool box by altering a fish layer with a layer of ice and stored in a cold room at 4 °C **Third batch storage condition:** Placed in a film plastic tray. Packaging technology used: MAP (70 % CO_2 and 30 % O_2		
Pseudomonas fluorescens *Psychrobacter* spp. *Macrococcus caseolyticus* *Pseudomonas fragi* *Pseudomonas veroni* *Carnobacterium maltaromaticum* *Carnobacterium divergens* *Vagococcus fluvialis*	Sea bream fillet (*Sparus aurata*)	Packaging material used: Polystyrene boxes with melted ice. Storage conditions: under air or MAP MAP gas concentration: 60 % CO_2/10 % O_2/30 % N_2 (MAP) MAP film material: BDF 8050 F packaged in insulated boxes with melted ice, stored in incubators operating at 0 °C and 5 °C	Cycloheximide (actidione) agar (STAA) tryptone soy agar (TSA Cephaloridine fucidin cetrimide (CFC) agar Polymerase chain reaction method (PCR) with 6S rRNA gene fragments amplification	Parlapani et al. (2014)
Photobacterium phosphoreum	Fillets of coalfish	Storage temperature: Stored at 10 °C or 5 °C Gaseous composition: CO_2/N_2 (60 %/40 %) (MAP)	Agar plates & tissues/Real time Polymerase Chain Reaction (PCR)/T-RFLP, amplification & sequencing	Rudi et al. (2004)
Brochothrix thermosphacta *Carnobacterium divergens* *Carnobacterium piscicola*	Fillets of salmon	Storage temperature: Stored at 10 °C or 5 °C Gaseous composition: CO_2/N_2 (60 %/40 %) (MAP)	Agar plates & tissues/Real time PCR/T-RFLP, amplification & sequencing	
S. putrefaciens *Pseudoalteromonas* spp. *Pseudomonas* spp.	Squid (*Todaropsis eblanae*)	Storage medium: Ice Storage method: Squid to ice ratio was approximately 2:1 (crushed freshwater ice), new ice was added periodically to maintain the ratio	Spread-plated chilled Iron Agar Lyngby (ADSA Micro), Iron agar with salt used	Paarup et al. (2002)

Abbreviations: TPC-total psychrotrophic count; LAB- lactic acidbacteria; PCA -plate count agar; MAP-modified-atmosphere packaging; PCR-polymerase Chain Reaction; T-RFLP- A terminal restriction fragment length polymorphism.

2.2. Autolytic spoilage

Autolysis, or protein degeneration caused by endogenous proteases, starts shortly after rigor mortis onset. This mechanism aids in the creation of an environment favorable to microbial growth (Olatunde & Benjakul, 2018). Even under refrigeration or freezing conditions, autolysis in fish continues at a very slow rate (Robertson, 2016). Protease and lipase enzymes, commonly found in

fish muscle and viscera, contribute to the postmortem deterioration of fish muscle and other tissues during storage and processing. In addition, proteases and lipases are responsible for changes in fish sensory characteristics (Engvang & Nielsen, 2001).

Protein degradation occurs rapidly in inappropriate storage. In fact, proteolytic products (free amino acids and peptides) may act as nutrients for microbial growth in conjunction with the production of biogenic amines, culminating in spoilage (Fraser & Sumar, 1998). The enzymes in the fish gut cause rapid protein decomposition, resulting in belly burst, a common occurrence in fish. Temperature and pH are the most important factors influencing the activity of proteases. When the pH is between alkaline and neutral, most proteases perform better (Ashie et al., 1996). Endogenous or microbial enzyme's function and metabolism raise the pH of stored seafood by converting trimethylamine oxide (TMAO) to TMA and other major volatile compounds (Olatunde & Benjakul, 2018). Lipase and phospholipase are two enzymes that can hydrolyze lipids in fish (Aryee et al., 2007). In the presence of water, triacylglycerol acyl hydrolases hydrolyze glycerides (mono, di, and tri) to glycerol and fatty acids (Fernandes, 2016; Olatunde & Benjakul, 2018). Fish and other seafood release free fatty acids (FFAs), which contribute to the development of fishy odors (*i.e.* off-odors). The fishy odor is caused by aldehydes, primarily polyunsaturated aldehydes (Maqsood et al., 2014). Furthermore, lipoxygenase, which is primarily found in the gills or skin, can cause oxidation in preserved fish, particularly when the fish is kept for an extended period (Fernandes, 2016). Table 2 lists various fish proteolytic and lipolytic enzymes and products, along with information on how they are controlled.

Table 2. Different enzymes and products of proteolysis and lipolysis in fish and their prevention strategies.

Enzyme (s)	**Substrate**	**Effect/final products**	**Prevention**	**References**
Acid phosphatase	Lyzozome	Lysosome disruption	Storage at higher pressure of 75 MPa/25 °C	Fidalgo et al. (2020)
Cathepsin D Chymotrypsin, Trypsin, Carboxy-peptidases	Proteins Proteins, peptides	Disruption of lyzozomes Belly-bursting	Store at 37 °C (residual activity 7 % & 21 %) Problem increased with freezing/thawing or long-term chill storage	
Cathepsins Cathepsin B	Proteins, peptides Proteins	Softening of tissue Hydrolysis of tissue proteins	Avoid rough handling during storage Stored at 25 °C or 37 °C (at AP; 42 and 3 %, respectively)	FAO (2005) Fidalgo et al. (2020)
Calpain Collagenases	Myofibrillar proteins Connective tissue	Softening Softening and gaping of tissue Degradation of Type 5 collagen	Removal of calcium Time and temperature of chilled Storage	FAO (2005)
Trimethylamine Oxide (TMAO) demethylase	TMAO	Formaldehyde formation	Storage temperature less than −30 °C physical abuse, freeze/thawing	FAO (2005)
Glycolytic enzymes	Glycogen	Lactic acid production, resulting in pH drop	Avoid pre-rigor stress	FAO (2005)
Nucleotide breakdown Enzymes	ATP, ADP, AMP, IMP	Gradual production of hypoxanthine	Avoid pre-rigor stress and improved handling	FAO (2005)
Lipoxygenase (LOX)	Polyunsaturated fatty acids (PUFA) Linoleic acid Linolenic acids Decosahexaenoic	13- and 9-hydroperoxides	Application of inhibitors Nordihydroguaiaretic acid (NDGA), esculetin (catechols), Butylated hydroxyanisole (BHA), Butylated	Banerjee et al. (2001)

Enzyme (s)	Substrate	Effect/final products	Prevention	References
	acid Arachidonic acid		hydroxytoluene (BHT), Epicatechin gallate (ECG), Epicatechin (EC), Potassium cyanide (KCN)	
Nucleodepolymerases Ribonuclease Acid deoxyribonuclease	RNA, DNA	Mononucleotides enhance the flavor of fish products	Blanching of fish in steam at 100 °C Reducing the water activity by drying	Mukundan et al. (1986)
Lipase Phosphorilipase	Lipids	Free fatty acids and glycerol, lipolysis off flavor, hydrolytic rancidity and oxidative rancidity	Blanching of fish in steam at 100 °C Reducing the water activity by drying	Mukundan et al. (1986)

Abbreviations: AP: atmospheric pressure; TMAO- trimethylamine oxide; ATP- adenosine triphosphate; ADP- Adenosine diphosphate; AMP- adenosine monophosphate; IMP- inosine monophosphate; NDGA- nordihydroguaiaretic acid; BHA- butylated hydroxyanisole; BHT- butylated hydroxytoluene; ECG- epicatechin gallate; EC- epicatechin; KCN- potassium cyanide; PUFA- Polyunsaturated fatty acids; LOX- lipoxygenase.

2.3. Oxidative spoilage

Spoilage caused by lipid oxidation causes a variety of issues, including the development of off-flavors, changes in color and texture, and nutrient value alteration (Losada et al., 2007). Lipids can be oxidized in a variety of ways, including photo-oxidation, thermal oxidation, enzymatic oxidation, and auto-oxidation. The latter is defined as the spontaneous reaction of atmospheric oxygen with lipids (Hassoun & Emir Çoban, 2017). Typically, oxidation involves the reaction of oxygen with fatty acid double bonds. As a result, seafood with higher levels of polyunsaturated fatty acids (PUFAs) are more prone to oxidation. Other factors influencing the rate of oxidation include the availability of oxygen, light, the presence of metals, moisture, temperature, and the degree of unsaturation of the lipid (Domínguez et al., 2019; Maqsood, Benjakul, Abushelaibi, & Alam, 2014). Lipid oxidation occurs in three stages: initiation, propagation, and termination of free radicals. The initiation phase can begin with the abstraction of a hydrogen atom adjacent to a double bond in a fatty acid, which may be aided by light, heat, or metal ions to form a free radical. The free radicals react with oxygen to form peroxyl radicals, which then react with other lipid molecules to form hydroperoxides and a new free radical during the propagation phase. The process is terminated when free radicals associate to create non-radical products (Domínguez et al., 2019).

3. Edible coating as a biopreservation method for preprocessed fresh fish

3.1. General perspectives on edible coating

Edible coating has been extensively researched and proven to be an effective and green process for ensuring food quality and safety, including muscle foods, during refrigerated storage (Gagaoua et al., 2021). The implementation of edible films and coatings on the surface of foods aids in the control of moisture movement, lipid oxidation, microbial contamination, and enzyme activity, all of which are regarded as major contributors to food spoilage (Unalan et al., 2011, 2013). According to the largely increasing number of works in edible film and coating systems (Farris et al., 2014; Sapper & Chiralt, 2018; Suhag et al., 2020), bringing along their renewable resources and less independency to oil-

based conventional primary packaging, such systems can be recognized as "food and packaging waste reduction-focused sustainable system approach". In particular, edible coating, is a thin layer of edible material obtained through the consecutive three stages; i) "wet process" in which biopolymer as a main matrix is dispersed or dissolved in a coating-forming solution, ii) the "deposition" in which coating solution is directly applied onto the surface of food via immersion or spraying techniques (Campos et al., 2011; Kang et al., 2013), and iii) "solvent evaporation" that takes place for drying of coating on the food surface.

Overall, the coating serves as a barrier against gases and water vapor, which reduces oxygen levels and helps to regulate microbial, enzyme, and oxidative reactions of the coated product during storage (Sapper & Chiralt, 2018). The composition of edible coatings affects their effectiveness and stability. Active compounds, mainly, proteins, bacteriocins, essential oils, and plant extracts are incorporated into coatings with the target of controlling or delaying active compound release towards food (Gagaoua et al., 2022). Consumer awareness for food safety and clean labels motivate the transition from synthetic to natural antimicrobial and antioxidant active compounds (Wong et al., 2020) in the fish preservation such as chilled fish fillets (Pan et al., 2021; Qiu et al., 2014). Antioxidants can also prevent oxidation by decreasing or delaying the production of free radicals, whereas antimicrobial compounds can inhibit or stop the proliferation of bacteria, hence boosting food safety (Wong et al., 2020).

Over the last decade, it has been demonstrated that a variety of edible coating materials, such as proteins (like gelatin and whey protein) and polysaccharides (like chitosan, alginate, and starch), can extend the shelf life of fishery products (Hosseini, Javidi, & Rezaei, 2016; Mohan et al., 2012; Neetoo et al., 2010; Yildiz & Yangilar, 2016), particularly in sea bass (*Lateolabrax japonicas*), rainbow trout (*Oncorhynchus mykiss*) (Andevari & Rezaei, 2011; Shokri et al., 2015), white leg shrimp (*Litopenaeus vannamei*) (Wang et al., 2015), silver pomfret (*Pampus argentus*) (Wu, Fu, et al., 2016), grass carp (*Ctenopharyngodon idellus*) (Yu, Li, et al., 2017), olive flounder (*Paralichthys olivaceus*) (Li et al., 2016), Asian sea bass (*Lates calcarifer*) (Chaijan et al., 2022), large yellow croaker (*Larimichthys crocea*) (Pei et al., 2022) and these studies are reported in Table 3 and Table 4 with relevant details.

Table 3. Different types of edible coating materials used for pre-processed fishery products under the dipping coating method.

Fish/fishery product	**Coating formulation**	**Results**	**References**
Mackerel (*Auxis thazard*)	Rice starch (RS) Mon-pu (*Glochidion wallichianum*) leaf extract (0.1 %,0.5 %,1.0 %) RS RS/MPE (0.02 %) RS/MPE (0.1 %) RS/MPE (0.5 %) RS/MPE (1.0 %)	pH, TBARS, TVB-N, TMA, TVC, TPC↓ Heme protein degradation, Metmyoglobin↓ WHC, Liking score↑ Shelf-life (9 days) ↑	Chumsri et al. (2022)
Mackerel Tuna (*Euthynnus affinis*)	Xanthan gum (1.5 %)/Glycerol (0.5)/Ethanolic extract of Propolis (1 %) Xanthan gum (1.5 %)/Glycerol (0.5)/Ethanolic extract of Propolis (2 %) Xanthan gum/Ethanolic extract of Propolis (1:1) Xanthan gum/Ethanolic extract of Propolis (1:2)	pH, Peroxide value, TBARS, TVB-N, K-value ↓ TVC, PTC, Enterobacteriaceae, *E. coli* ↓ *Pseudomonas fluorescens*, Lactic acid bacteria ↓	Sheikha et al. (2022)

Fish/fishery product	Coating formulation	Results	References
		Yeasts/molds ↓ Color, taste, odor↑ Shelf-life (7 days) ↑	
Zander Fish Fillets *Sander lucioperca* (L.)	Xanthan gum (1 %)/Black tea extract (1 %) Xanthan gum (1 %)/Black tea extract (2 %) Xanthum gum (10) Xanthum gum/Black tea extract (10:1) Xanthum gum/Black tea extract (10:2)	pH, Cooking loss, TBA, FFA↓ Total bacterial count, Total yeast mold count, Total antioxidant activity↓ Physical quality, Shelf life (12 days) ↑	Anwar et al. (2022)
Silver pomfret (*Pampus argenteus*)	Corn starch (2 % w/v) fumaric acid (0.5 % w/v) Corn starch/fumaric acid (2:0.5)	pH, TVB-N, PV, TBA↓ Total mesophilic bacteria count↓ Total psychotropic bacteria count↓ *Pseudomonas* spp., *Shewanella putrefaciens*↓ Sensory Score ↑ Shelf -life (15 days) ↑	Remya et al. (2022)
Yellowfin Tuna (*Thunnus albacares*)	Chitosan (1 %), Lemon peel extract (LPE) (1 %), Chitosan (1 %)/LPE (1 %), Chitosan (2 %)/LPE (2 %)	pH, TVB-N, TMA-N, PV, TBARS, TPC↓ Sensory Score, Shelf -life (10–12 days) ↑	Sabu et al. (2020)
Blue tilapia (*Oreochromis aureus*)	Fish gelatin (Gf-1.5 %), Kappa-carrageenan (Cr-0.75), pomegranate peels (PPE-0.5 %,1.0 %,1.5 %, 2.0 %) Gf/Cr/PPE (1.5:0.75:0.5) Gf/Cr/PPE (1.5:0.75:1.0) Gf/Cr/PPE (1.5:0.75:1.5) Gf/Cr/PPE (1.5:0.75:2) Gf/Cr (1:2)	TVB-N, PV, TBARS↓ Microbial total count, Aerobic count↓ Psychotropic count ↓ Sensory Score. Shelf-life (10–15 days) ↑	Khojah (2020)
Shrimp (*Litopenaeus vannamei*)	Chitosan (1 %)/Fish gelatin (3 %)	pH, TVB-N, TBARS, K-Value, TVC↓ Color, Texture, Sensory value↑ Shelf-life (13 days) ↑	Farajzadeh et al. (2016)
Refrigerated Beluga sturegeon (*Huso*)	Whey protein concentrate (8 %)/Glycerol (1 %)/Tween 80 (0.2 %)/Cinnamon essential Oil (1.5 %)	pH, TVB-N, PV, TBA, TVC↓ Sensory score↑ Shelf-life (16 days) ↑	Bahram et al. (2016)
Rohu (*Labeo rohita*)	whey proteins concentrate (8 % protein; w/w), Sorbitol, Glycerol whey protein/Glycerol (1:2) whey protein/sorbitol (1:2) whey protein/glycerol/sorbitol (1:1:1)	pH, TBARS, POV, TVB-N, Drip loss↓ Color, Thaw yield, Sensory score, texture ↑ Shelf life ↑	Khan et al. (2015)
Shrimp (*Parapenaeus longirostris*)	Chitosan (1 %)/Garlic Oil (0 %, 0.5 %, 1.0 %, or 1.5 %)	pH, APC, TVB-N, PV, TBA, Weight Loss↓ Color, Shelf-life (11 days) ↑	Asik and Candogan (2014)
Atlantic salmon (*Salmo salar)*	Whey protein concentrate (WPC) (8 % Protein w/w), WPC (1 %)/Glycerol (1 %), WPC (2 %)/Glycerol (1 %), WPC (1 %)/Sorbitol (1 %), WPC (2 %)/Sorbitol (1 %)	PV, TBARS, weight loss, drip loss, P^H↓ Yield, sensory score, Shelf life↑	Rodriguez-Turienzo et al. (2011)
Refrigerated Bream (*Megalobrama amblycephala*)	Sodium alginate (1.5 %)/Glycerin (10 %) Sodium alginate (1.5 %)/Glycerin (10 %)/Vc antioxidant (5 %)	pH, TVB-N, TBA, TVC, Water loss, ↓ K-value, Sensory	Song et al. (2011)

Fish/fishery product	Coating formulation	Results	References
	Sodium alginate (1.5 %)/Glycerin (10 %)/TP antioxidant (0.3 %)	characteristics↑ Shelf -life (12 days) ↑	

Abbreviations: RS- Rice starch; MPE- Mon-pu (Glochidion wallichianum) leaf extract; TBARS- thiobarbituric acid reactive substances; TVB-N- total volatile basic nitrogen; TMA-trimethylamine; TVC- total viable counts; TPC- total psychrophilic bacterial count; WHC- water holding capacity; PTC- psychotropic count; TBA-thiobarbituric acid; FFA-free fatty acids; PV-peroxide value; TMA-N- tri-methyl amino nitrogen; TPC-total aerobic plate count; POV- peroxide value; APC- aerobic Plate Count; Vc-purchased from (Biodee Biotechnology co., Ltd., Beijing, China) and added as an antioxidant; TP- purchased from (Keyi Chemical Co., Ltd., Zhengzhou City, China) and added as anti-oxidant.; LPE- Lemon peel extract; PPE-pomegranate peels; WPC- Whey protein concentrate.

Table 4. Effect of fish gelatin dip coating method on quality and shelf life of pre-processed fishery products.

Pre-processed fish product	Gelatin concentration (w/w %) or (w/v %) and active compound/concentration	Additional preservation	Results	References
Common carp (*Cypirnius carpio*)	Furcellaran (3.5 %) (w/v): gelatin (3:7)	Thyme (5 %) Rosemary (5 %) Stored at 4 °C	TVC, pH, Biogenic amines ↓ Sensory score, Shelf-life (12 days) ↑	Tkaczewska et al. (2023)
Smooth-hound shark (*Mustelus*)	Gelatin 3 % (w/v) Moringa oleifera extract 20 µg/m (w/v)	Stored at 4 °C without packaging	pH, TVB-N, weight loss, MDA↓ Mesophilic, psychrophilic, lactic acid bacteria↓ H_2S bacterial count↓ Sensory score, color, odor↓ Overall acceptability↑ Shelf-life (6 days)↑	Mezhoudi et al. (2022)
(*Ctenopharyngodon idellus)*	Gelatin (8 % w/v)	Ginger essential oil (0.5 % v/v) Stored at 4 °C	Weight loss, texture, TVC ↓ Volatile flavor ↓ Color, taste, shelf-life (8 days) ↑	Li et al. (2022)
Red Snappers	Gelatin (8g)	kaffir lime leaf essential oil (1 %, 1.5 %.2 % w/v) Stored at room temperature	pH, Moisture, elasticity ↓ TPC, fat content ↓ Color, ash content, protein content ↑ Shelf-life ↑	Febriana et al. (2021)
Asian seabass (*Lates calcarifer*)	Gelatin 4 % (w/v) Grape seed extract 0.5 % (w/v)	Vacuum pressure (10 s), Stored at 4 °C	Drip loss, TVC, putrescine, cadaverine ↓ Color, Shelf-life (12 days)	Zhao et al. (2021)
Blue tilapia (*Oreochromis aureus*)	Fish gelatin 1.5 % (w/v)	K-Carrageenan 0.75 % (w/v) Extract of pomegranate peel (0.5 %, 1.0 %, 1.5 % and 2.0 % w/v) Stored at 4 ± 1 °C	Total aerobic count, psychotropic bacteria ↓ TVB-N, PV, TBARS ↓ Sensory score, Shelf-life (30 days) ↑	Khojah (2020)
Golden pompano (*Trachinotus blochii*)	Gelatin 2.5 % and 5 %, (w/v)	Vacuum packaging stored at 4 °C	TVB-N, TBARS, TVC, pH, drip loss ↓ Freshness index, color, gel strength ↑ Shelf-life ↑	Wei et al. (2019)

Pre-processed fish product	Gelatin concentration (w/w %) or (w/v %) and active compound/concentration	Additional preservation	Results	References
Golden Pomfret	Gelatin (1.2 %, 2.4 %, 3.6 % w/w)	Tea Polyphenol (0.4 % w/v) Stored at +4 °C in high quality polyethylene zip lock bags	Weight loss, pH, AMC ↓ Myofibril degradation ↓ PUFA oxidation ↓ TMA, TVB-N, TMAO ↓ Shelf life (17 days) ↑	Feng et al. (2016)
Rainbow trout (*Oncorhynchus mykiss*)	Cold water fish skin gelatin (4 % w/v)	Oregano essential oil (1.2 % w/v) Stored at 4 °C	pH, TVB-N, PV, TBA, TVC ↓ Shelf-life (16 days) ↑	Hosseini et al. (2016)
Fresh white shrimp (Penaeus vannamei)	Catfish skin gelatin 5 % (w/w)	Potassium sorbate (2 %) + Sodium tripolyphosphate (2 %) Glycerol (20 %) Stored in ice (0 °C)	ABC, PBC ↓ No significant change in pH and springiness Color, Shelf-life (10 days) ↑	Jiang et al. (2011)
Salmon (*Onchorhynchus keta*)	Gelatin (4g)	Glycerol (60 % w/v), Sorbitol (1 % w/v) Stored at 5 ± 1 °C	Moisture, Volatile Basic Nitrogen ↓ Peroxide Value ↓ fatty acid composition ↓ Color, Shelf-life (12 days) ↑	Heu et al. (2010)

Abbreviations: TVC-total viable count; TVB-N-total volatile basic nitrogen; MDA-malondialdehyde; H_2S-dihydrogen monosulfide; TPC-total plate count; PV-peroxide value; TBARS- thiobarbituric acid reactive substances; AMC- aerobic mesophilic count; PUFA-polyunsaturated fatty acid; TMA-trimethylamine; TMAO- trimethylamine oxide; TBA-thiobarbituric acid; ABC-aerobic bacterial count; PBC-psychrophilic bacterial count.

3.2. Edible coating materials for fish products

Because of raw fish's initial high microbial load and the increasing global demand for safe, convenient, and environmentally sustainable seafood, research for green and efficient preservation methods or technologies necessitates the application and development of novel packaging solutions (Augusto et al., 2016). Increasing awareness and thereby demand of consumers towards natural, healthful and safe products is closely associated with implementation of edible coatings as a promising approach to preserve or improve fish quality without compromising safety. Food quality changes caused by moisture transfer, oxidation processes, volatile flavor loss, or microbial growth can be reduced or even prevented by selecting appropriate matrices (Tavassoli-Kafrani et al., 2016). In this part, biopolymers, particularly proteins and polysaccharides, that have been intensively used to create coating matrices for shelf life studies of preprocessed fishes have been discussed.

3.2.1. Gelatin and its potential applications in pre-processed fish

Protein-based materials are one of the most commonly used raw materials. The global gelatin market size is expected to reach USD 13.14 billion by 2030, as per the new report by Grand View Research, Inc. with an expansion of Compound Annual Growth Rate (CAGR) of 9.5 % from 2022 to 2030 (Jiang et al., 2023). Because it is a plentiful product, mammalian gelatin has received research attention as a biopolymer. However, because of mammalian gelatin allergies, its use can cause both ethical and health issues. Furthermore, the food industry's byproducts are being used to create more sustainable solutions. Fish gelatin has gained popularity as an alternative to mammalian gelatin due

to its excellent biocompatibility, biodegradability, non-toxicity, and film forming abilities (Etxabide et al., 2017). Thermal denaturation or partial hydrolysis of collagen can be used to extract gelatin from fish industry byproducts such as heads, skin, bones, fins, muscle pieces, scales, viscera, and others (Huang et al., 2017). The use of pretreatments, with either acid or alkali, to allow the swelling of collagen to increase gelatin extraction is associated with collagen thermal denaturation. Depending on the end goal or application, gelatin properties can be adjusted by varying the pH, temperature ranges, and time applied during both pre-treatments and the extraction process (Ahmad et al., 2017). Fish gelatin extraction procedure depicted in Fig. 1 (Montero & Acosta, 2020).

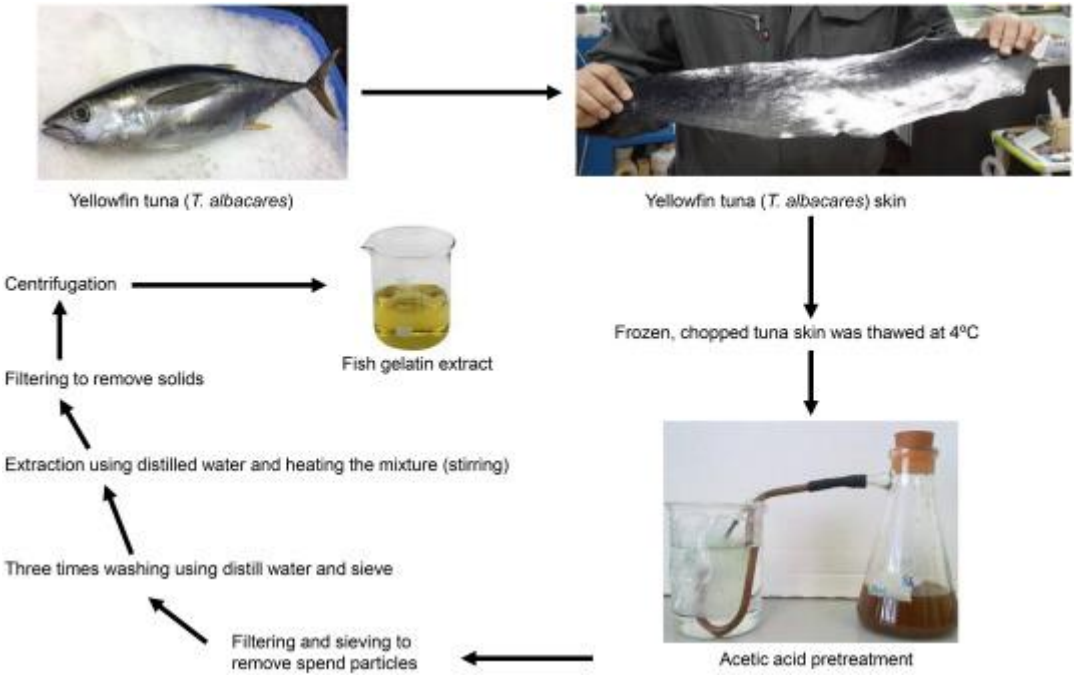

Fig. 1. Simplified procedure highlighting the steps for extracting fish gelatin from Tuna skin (Montero & Acosta, 2020).

Another important consideration is the incorporation of natural bioactive compounds, which add functionality to coatings. Because of fish gelatin's excellent biocompatibility, fish gelatin-based coating can gain active functional properties including antioxidant, antimicrobial, and antifungal by the addition of bioactive compounds (Etxabide et al., 2017). The basic physicochemical properties of gelatin, such as solubility, composition parameters, color, transparency, absence of odor and taste, are the main attributes that best define its overall commercial quality. Likewise, gel strength (expressed as a normalized “bloom value") and viscosity should be regarded as the most important physical properties because they influence gelatin quality and potential applications. These distinct properties can be listed in two groups: (i) properties related to surface behavior, such as protective colloidal function, emulsion and foam formation and stabilization, adhesion and cohesion, and film forming capacity, and (ii) properties related to gelling behavior, such as gel formation, thickening, texturizing, and water binding capacity (Schrieber & Gareis, 2007). Thus, gelatin seems to continue growing and create unique opportunities in a broad range of applications including but not limited to food, packaging and pharmaceutical (Galus & Kadzińska, 2015). In packaging industry, due to widely-explored and accepted film forming properties of gelatin, its packaging film implementation to protect food from dryness, light exposure, and/or oxygen exposure during its shelf life were largely investigated (Lu et al., 2022). Gelatin, due to its highly hygroscopic nature, tends to swell or dissolve

when in contact with the surface of foodstuffs with high moisture content. Several research studies have been conducted to assess the overall effect of adding various substances, such as crosslinkers, strengthening agents, plasticizers, or additives with antimicrobial or antioxidant properties, to gelatin-based products in order to improve the functional properties of gelatin and the shelf-life of food products (Mellinas et al., 2016; Ortiz-Zarama et al., 2016). These properties improve when the intermolecular forces of protein chains are reduced by the action of molecular structures that modify their hydrophilic character or promote the formation of strong covalent bonds in the film's protein network (Alfaro et al., 2014). Zhao et al. (2016) demonstrated the feasibility of using a natural extract as a new natural crosslinker for the modification of gelatin (type B, from bovine bone) through the formation of hydrogen bonds between water and free hydroxyl groups of amino or polyphenol groups. The results showed that adding this extract to gelatin significantly increased gel strength when compared to untreated gelatin (Zhao et al., 2016). Combining gelatin with different biopolymers, such as whey proteins (Fakhouri et al., 2015; Zhao et al., 2016), starch (Fakhouri et al., 2015; Zhao et al., 2016), chitosan (Benbettaïeb et al., 2016a, b) or pectin (Gupta et al., 2014) could be a good strategy for the development of films with desirable mechanical and water resistance properties.

Gelatin has been developed to preserve the quality and increase the shelf-life of fish products (Feng et al., 2016). Gelatin coatings, for example, have been developed to act as a barrier for water and oxygen, preventing contamination of the food surface (Chen et al., 2019), resulting in reduced water loss, lipid oxidation, and bacterial growth. Furthermore, gelatin enzymatic hydrolysate has been shown to have antioxidant properties (Hosseini, Rezaei, et al., 2016) and can be applied to formulate antioxidant coatings. However, there is a lack of studies on coating applications of gelatin for processed fish (Table 4, Table 5) and some promising findings have been briefly summarized below.

Table 5. Characteristics of gelatin-biopolymer mixtures in an edible coating in fishery products.

Formulation	**Physical/chemical/mechanical Characteristics**	**Biological characteristics**	**Application**	**References**
Gelatin, chitosan, gallic acid Clove oil	Prevent the reduction of lightness in the fillets TBARS, pH ↓ Free thiol value (39–40 nmol thiol/mg) Retard the lipid and protein oxidation	combination of gallic acid and clove oil further enhanced the antimicrobial effect Antioxidant activity ↑ Shelf-life (5 days) ↑	Edible coating for fresh salmon fillet	Xiong, et al. (2021)
Sturgeon gelatin Portulaca oleracea extract	Moisture (62 %), Protein (13 %) ↑ pH (5.6), TBARS (0.48) ↓	TVC (4.8 CFU g-1) ↓ Total mold (1.3 CFU/g) ↓ Shelf-life (30 days) ↑	Edible coating for tuna fillet Crucian carp sausages	Tanha et al. (2021)
Gelatin, Furcellaran green tea or pu-erh extract	TBARS (0.47), pH (5.63) ↓ TVB-N (10.15) ↓	not cause any significant inhibition of any of the studied groups of microorganisms (6 log CFU/g) Did not extend the shelf life	Edible coating for salmon sushi	Kulawik et al. (2019)
Gelatin Red Pitaya Peel Methanol Extract, ε-polylysin	Gelatin Red Pitaya Peel Methanol Extract, ε-polylysin	free amino acid content (31.78 mg/100g) ↓ Antioxidant activity (DPPH-38.54 %, ABTS – 0.39 mM) Muscle fiber is more regular, Muscle Fiber was not significantly	Edible coating for cray fish (*Procambarus clarkia*)	Liu et al. (2019)

Formulation	Physical/chemical/mechanical Characteristics	Biological characteristics	Application	References
		broken (SEM) Shelf-life (7 days) ↑		
Fish gelatin Grape seed extract Vacuum impregnation	hardness (1500/g), springiness (40 %) ↑ more organized (α & β) protein structures higher stabilization of myofibrillar protein ATPase activity(0.24 μmol/mb/min) ↑	Myofibril degradation ↓ Myofibril length (4.22 μm) ↑ Sulfhydryl groups (2.29–4.45 mol/105g protein) ↓ Disulphide bonds (113.60 %) ↓ Protein oxidation ↓ Aerobic Psychrophilic count (1.19 log CFU/g) ↓ Shelf-life (12 days) ↑	Edible coating for chilled thilapia fillets	Zhao et al. (2019)
Fish skin gelatin Hydrolysate Fish gelatin	pH (8.31 ± 0.16) ↓ FFA (1.68 ± 0.00) ↓ TVB-N (24.49 ± 0.67) ↓ Lipid oxidation (0.54 ± 0.07) ↓	Total microbial count (6.74 ± 0.74) ↓ Psychrotrophic count (4.74 ± 0.384) ↓ Lactic acid bacterial count (4.31 ± 0.584) ↓ Effectively extend the shelf life by 9 days ↑	Active coating for whole shrimp (*Penaeus metguiensis*)	Kouhdasht and Nasab (2019)
Fish gelatin, cucurmin and βCD based emulsion	Weight loss (10 %), TVB-N (6.56 mg/100 g) ↓ PV (0.9 mmol cumene hydroperoxide kg^{-1}) ↓ TBA (0.75 mg MDA kg^{-1}) ↓	Inhibit the degradation of high salt soluble protein (HSP), Free amino acids (FAA) (0.504 %) ↓ TVC (6.2 1og10 CFU/g) ↓ *Pseudomonas* spp. (6 1og10 CFU/g) ↓ H_2S-producing bacteria (5.5 1og10 CFU g-1) ↓ Shelf-life (9 days) ↑	Edible coating for grass calf (*Ctenopharyngodon idellus*)	Sun et al. (2018)
Thunnus obesus skin gelatin *Codium* spp. or *Fucus vesiculosus* extract	pH (6.55 + 0.01), TBA (4.2 + 1.12) ↓ TVB-N (26) ↓ WI (33.11 ± 3.09), AE (8.36) ↓	TVC (6.8 log10 CFU g−1) ↓ Antioxidant activity DPPH (2.56 ± 0.70) ↑ Total phenolic content (0.079 ± 0.015) ↑ Shelf-life (12 days) ↑	Edible coating for tuna fillet (*Thunnus obesus*)	Vala et al. (2017)
Gelatin Orange leaf essential oil (*Citrus sinensis* (*L*) *Osbeck*)	Surface with holes and porous morphology pH (8.51), TVB-N (41.08), TBA (1.03) ↓ PV (3.9) ↓	Total Viable count (5.9 log CFU/g) ↓ Psychrotrophic bacteria count (6.4 log CFU/g) ↓ DPPH radical scavenging activity (52 %) ↑ Effectively extend the shelf life by 14 days ↑	Edible coating for pink shrimp (*Parapenaeus longirostris* L. 1846)	Alparslan et al. (2016)
Gelatin Benzoic acid	VBN (15 mg/100g) ↓ Color (5.94 + 1.82) ↑ Flavour (6.18 + 1.47) ↑	Aerobic plate count (6.5 x l06 CFU/g) ↓ Anerobic plate count (l06 CFU/g) ↓ Antimicrobial gelatin coating effectively controls both aerobic and anerobic microbial growth and Effectively extending the shelf life.	Edible coating for refrigerated tilapia fillet	Ou et al. (2002)

Abbreviations: CFU/g- Colony-forming unit per gram; TBA-thiobarbituric acid; MDAkg-1- malondialdehyde per unit mass; WI- whiteness index; DPPH- 2,2diphenyl-1-picrylhydrazyl; ABTS- 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulphonic acid; SEM-scanning electron microscopy; HSP- high salt soluble protein;

FAA- Free amino acids; TVC- Total viable counts; H_2S-Dihydrogen monosulfide; VBN-Volatile basic nitrogen; TVB-N- total volatile basic nitrogen; PV- peroxide value.

Catfish gelatin has been used to extend the shelf-life of fresh white shrimp (*Penaeus vannamei*) by acting as an antimicrobial coating (Jiang et al., 2010). Moreover, rheological, structural and preservation effect of *Hemiramphus far* skin gelatin has been studied on the smooth hound fillet (Abdelhedi et al., 2018). Preservation effect of fish gelatin coating enriched with Curcumin/β-cyclodextrin emulsion was investigated on grass carp (*Ctenopharyngodon idellus*) fillets (Sun et al., 2018). Another earlier study has been conducted to characterize a sprayable edible coating using salmon bone gelatin on Atlantic salmon fillets (Char et al., 2019) and shelf life extension of whole shrimp was studied with an application of active edible coating made up of fish skin gelatin hydrolysate (Kouhdasht and Nasab, 2019). In the implementation of active packaging approach into coatings, many recent researches highlighted the multi-functionality of (bio) active coatings on pre-processed fish (Mezhoudi et al., 2022; Zhao et al., 2021) including targeted and controlled delivery of bioactive compounds in addition to the functionality of traditional coatings. Recently, an active edible gelatin coating extracted from the skin of gray triggerfish (*Balistes capriscus*) was enriched with a leaf extract and applied to the fillet of the smooth-hound shark (*Mustelus*) (Mezhoudi et al., 2022).

3.2.2. Whey proteins and their potential applications in pre-processed fish

Whey proteins (WP) are the most economically and technologically interesting fraction of whey, accounting for nearly 15 %–20 % of total milk proteins (De Castro et al., 2017; Schmid & Müller, 2019). The WP composition varies according to cheese type, manufacturing process, coagulation method (acid or enzyme), milk origin (bovine, ovine, or caprine), feeding regime, and lactation stage. These differences have a significant impact on emulsification and other functional properties (Ramos et al., 2012; Yadav et al., 2015). The WP are heat labile, dephosphorylated, and less sensitive to calcium. They are compact secondary, tertiary, or quaternary globular molecules with various combinations of cross-sulfur bonds (Henriques et al., 2016).

Because of advancements in membrane and ion exchange techniques, the global production of WP has increased dramatically, making it easier to recover WP with preferred and appropriate functional properties (acid stability, gelation, film-forming efficiency, and aeration) and emulsification characteristics (Perez-Gago & Krochta, 2002). The WP recovery processes such as ultrafiltration, diafiltration, electrodialysis, gel filtration, ion-exchange chromatography, and reverse osmosis are commonly used (Milani & Tirgarian, 2020). whey protein concentrates (WPC) are created by selectively removing high molecular-weight fractions from whey permeate during the ultrafiltration process (Bhattacharjee et al., 2015). The WPC is low in fat and cholesterol but high in bioactive compounds when compared to other commercial whey formulations. Whey protein isolates (WPI) are made by removing minerals and lactose from WPC through an additional ion-exchange chromatographic step (Khwaldia et al., 2004). The WPI are high in protein but low in bioactive compounds. Both of these fractions have these essential characteristics that make them suitable for application in food: high amino acid and protein content; low calorie, fat, and sodium content; lack of pathogens and toxic metabolites; biocompatibility and generally recognized safe status; ready availability; and low price (Yadav et al., 2015). Using the spray-drying process, both WPC and WPI fractions can be dehydrated and used in coating applications.

The WP film is primarily composed of a dry, highly interacting polymer network with a three-dimensional gel-like structure. Regardless of the film-formation techniques used, the final films can result in a spatially reorganized gel arrangement containing the additional film forming agents (Henriques et al., 2016). The WP films are made using the solvent casting method, in which the film solution is poured onto flat surfaces to form a dried gel, which is then used to wrap food products. In the case of WP coatings, the food products are typically immersed in the film-forming solution for a specific time period (30 s or 1 min) to ensure complete exposure of the food surface with good adherence and perfect integrity, and then air-dried (Fernandes et al., 2020; Ramos et al., 2012). The WP differs from other film-forming polymers in several ways, including its amphiphilic nature, conformation, denaturation, and electrostatic charges. Charge density and the hydrophilic-hydrophobic balance, for example, can modify the WP conformation, as these factors will eventually define the physical and mechanical properties of films/coatings (Perez-Gago & Krochta, 2002; Karaca et al., 2019). Because of its compact globular structure and small molecular size, native WP cannot be considered as a good adhesive polymer candidate. Under certain conditions, the globular structure can be reformed into relatively linear structures and then into irreversible aggregates via a thiol-disulfide exchange. Native WP can also form coherent films based on low-energy bonding such as electrostatic interactions, hydrogen bonding, or van der Waals force (Schmid & Müller, 2019).

The process of creating WP-based films and coatings can be broken down into several steps, which include dissolving WPC or WPI (5 %–12 %) in distilled water, adjusting the pH of the solution (either 7 or 8), and then heating (80–90 °C/10–30 min) for protein denaturation (Perez-Gago & Krochta, 2002). Other ingredients can be added before or after heating, depending on their compatibility. Heat-tolerant ingredients (prebiotics, starches, and blends) are added early in the process, while heat-sensitive ingredients (antioxidants, antimicrobial compounds, and probiotics) are added after heating (Fernandes et al., 2020).

Even though several heat treatment methods are available for gel formation, denaturation is the most commonly used technique for forming coherent films. The majority of the hydrophobic and sulfhydryl (SH) groups in native WP are buried in the center of the protein molecule. Denaturation exposes WP's functional and hydrophobic groups, resulting in the formation of a three-dimensional chemical network that promotes intermolecular disulphide (S–S) bonding and hydrophobic interactions during drying. Due to food intermolecular interactions, WP films produced without heat treatment easily break into tiny parts during drying (Ramos et al., 2012). At pH 6.0, the thermal denaturation process occurs in two steps. The first step occurs when β-lactoglobulin dimers dissociate into monomers at temperatures above 40 °C. Denaturation at temperatures above 65 °C unfolds the β-lactoglobulin molecule and exposes hydrophobic and thiol groups, which contribute to the formation of smaller aggregates with β-lactoglobulin or other thiol-containing proteins. These smaller aggregates then interact in a second step to form high-molecular-weight irreversible aggregates (Khwaldia et al., 2004; Schmid & Müller, 2019).

After forming a heat or cold-set gel, WP films are formed by dehydrating the gel. Drying under ambient conditions, usually between 21 and 23 °C and 50 % relative humidity (RH), is a common dehydration method. Nonetheless, when applying edible coatings to foods, the drying process must be handled carefully because quick drying changes the characteristics of the film, making it thinner, stiffer, and less flexible (Ramos et al., 2012). The drying method, and final film or coating properties are significantly affected by changes in drying rate, temperature, and humidity.

Casting, dipping, extrusion, enrobing, fluidization, foaming, spraying, and UV polymerization are currently used to produce edible WP films/coatings (Ramos et al., 2012). Monitoring the processing conditions is critical because changes in handling environments can alter the kinetics and reaction mechanisms involved in film formation (Perez-Gago & Krochta, 2002; Ramos et al., 2012). To be considered edible, the WP film-formation methods must continue to be suitable for holding foods despite changes in pH, salt levels, heat, enzymatic variation, drying, solvent usage, and other chemicals. Furthermore, plasticizers and other additives must work well with the biopolymer (Henriques et al., 2016).

The WP can be used to coat fish fillets to overcome any inherent changes in quality during storage (Wang et al., 2019). Recent work demonstrated that WP coating fortified with crude ginger extract could extend the shelf-life of Asian sea bass fish by 15 days when compared to the control (8 days) (Chaijan et al., 2020). Furthermore, the same authors have lately addressed the new preservative approach of pre-treated fish with plasma activated water (PAW) before coating with WPI-crude ginger extract (Chaijan et al., 2022). The PAW-treatment demonstrated the potential to reduce the microbial load in fish steak, while the WPI coating acted as an oxygen barrier, limiting oxygen participation in the oxidation reactions caused by the early PAW treatment. The presence of phenolic compounds in the ginger extract has been proposed to further delay lipid oxidation through free radical scavengers and delaying the proliferation of spoilage microorganisms during fish storage. With this treatment, the shelf-life of Asian sea bass steak was extended to 30 days. In the case of salmon, which is high in fat, reduction in shelf life is due to unsaturated fatty acids that are easily oxidized. The WP coating on frozen king salmon reduced moisture loss by 42 %–65 % within the first three weeks of storage and slowed lipid oxidation as seen through a decreased peak peroxide value (Stuchell & Krochta, 1995). Coatings applied after freezing improved thaw yield, reduced drip loss, and altered color constraints in frozen and thawed fillets in a study comparing application of WP coating before and after freezing Atlantic salmon (Rodriguez-Turienzo et al., 2011). Another study demonstrated that ultrasound–treated WP coatings with or without microbial transglutaminase (TGase) addition delayed lipid oxidation in frozen Atlantic salmon as effectively as heat treated coatings containing TGase (Rodriguez-Turienzo, et al., 2013). Coatings made with 13 % WP were found to reduce lipid oxidation during frozen storage of gutted Kilka (Hasanzati Rostami et al., 2010).

3.2.3. Chitosan and its coating applications for pre-proceed fish

Chitosan, derived from the second most abundant biopolymer chitin which is found in the exoskeleton of crustaceans such as crabs and shrimps, in fungal cell walls, and in other biological materials, has been studied *in vitro* and in complex food matrices as an edible film and coating (Nanda et al., 2021). In addition to its well-known and proven film-forming properties, the increased awareness of upcycling of waste or by-products to value-added bio-based products, and research in food packaging has intensified the focus on broadening the implementation of chitosan (Nanda et al., 2021). For example, the upcycling of seafood wastes (Chakravarthy & Edwards, 2022) into chitosan could contribute to a circular economy in multiple ways including reducing global seafood waste, reducing loss of resources, and increasing waste-streamed bio-based and biodegradable coating materials, and adding longer shelf-life to food products.

Implementing chitosan produced from seafood waste as a preservative or as a quality enhanced coating onto fish product is recognized as a sustainable approach. Soares et al. (2015) evidenced that

Atlantic salmon products coated with 1.5 % (w/v) chitosan performed better in terms of color stability and control of microbial contamination in frozen and thawed samples. Surimi gels made from African catfish (*Clarias gariepinus*) with 1.5 % chitosan, on the other hand, showed the greatest improvement in gel strength, whiteness, and water holding capacity. The lowest Total volatile basic nitrogen (TVB-N) value was obtained by incorporating 2.0 % (w/w) chitosan into gels. During the storage period, peroxide value (PV) and thiobarbituric acid (TBARS) increased at a slower rate in the chitosan-treated gels than in the control gels (Amiza & Kang, 2013). Bonilla et al. (2018) reported an 8-day increase in shelf-life in catfish fillets treated with a chitosan solution. Similarly, the chitosan and propolis extract, contains the major source of polyphenols (Ebadi et al., 2019), reduced the extent of lipid oxidation, as measured by TBA and free fatty acid (FFA), improving the TVB-N and pH values of *Nemipterus japonicus* compared to untreated samples, and thus extending the shelf-life of *N. japonicus* fillet by approximately 10 days (Ebadi et al., 2019). Fernandez-Saiz et al. (2013) investigated the biotic effectiveness of chitosan as an internal layer of fresh hake (*Merluccius*) and sole (*Solea*) fillet packaging. Under vacuum packaging conditions, the microbial species, primarily total aerobic mesophilic bacteria, hydrogen sulfide-producing bacteria, and *Pseudomonas*, were significantly inhibited by increasing the lag phase. Coatings not only promoted preservation but also had an effect on cooking characteristics as seen in fish fingers coated with chitosan and chitosan nanoparticles, resulting in the reduced oil uptake from 16.42 % to 4.56 % and increased moisture content from 34.61 % to 52.7 %. Essentially, the shelf-life increased by up to one month when compared to non-coated fish finger (Osheba et al., 2013). Jeon et al. (2002) found that chitosan coating reduced or prevented moisture loss, lipid oxidation, and microbial growth in herring and cod, resulting in a moderate to strong viscosity-dependent preservative effect in both fish. Interestingly, chitosan coating extracted from crab processing waste in cooked comminuted samples of herring flesh demonstrated lower peroxide values, TBA, and total volatile aldehydes than low viscosity chitosan (Kamil et al., 2002). The chitosan treatment preserved favorable sensory properties in sardine for a longer period, extended the lag phase, and reduced the formation of volatile bases and oxidation products. When compared to untreated samples, it also helped to maintain good water holding capacity, reduce drip loss, and improved the textural changes. The shelf-life of 1 % and 2 % chitosan treated samples was 8 and 10 days, respectively, compared to only 5 days for untreated sardine (Mohan et al., 2012). In another work, chitosan coating not only preserved the sensory quality of refrigerated grass carp (*Ctenopharyngodon idellus*) fillets but also significantly reduced microbial population, characteristic spoilage biogenic amines, TVB-N, increased physiochemical and sensory qualities, and extended shelf-life (Yu, Jiang, et al., 2017).

In addition to mono polymer chitosan systems, blending of chitosan with other type of biopolymer has been proposed. Aleman et al. (2016) found that incorporating a chitosan-gelatin matrix into Pacific white shrimp (*Litopenaeus vannamei*) cooking juice increased the lag phase of total viable microorganisms and enterobacteria to 15 and 10 days, respectively, and significantly inhibited growth of these microbial groups. The TVB-N and pH values decreased as well, and no *S. aureus* or lactic acid bacteria were detected in any batches during storage. Feng et al. (2016) found that 0.4 % chitosan coating blended with 7.2 % gelatin significantly reduced the deterioration of golden pomfret (*Trachinotus blochii*) fillets during 17 days of cold storage. According to Jasour et al. (2015), combining enzyme chitosan coating with endogenous enzyme lactoperoxidase (LPO) increased the shelf-life of rainbow trout while significantly reducing the number of *Shewanella putrefaciens*, *Pseudomonas fluorescens*, and psychrotrophic and mesophilic bacteria. When compared to control samples, the coating treatments with chitosan and LPO increased the shelf-life of trout fillets by at

least 4 days. Similar to LPO, lysozyme obtained from hen egg white is one of mostly used enzyme for active packaging due to its generally recognized as safe (GRAS) status, and its stability and activity in food and packaging system at cold temperatures (Unalan et al., 2011, 2013). The use of chitosan-lysozyme coating has a high efficiency in inhibiting microorganism growth, lipid oxidation, and preserving sensorial quality, making it a promising method for preserving the quality and extending the shelf-life of refrigerated large yellow croaker (*Larimichthys crocea*) (Wu et al., 2018).

As discussed earlier, phenolic-rich natural plant extracts and phenolic compounds are of high interest in active film and coating systems. For instance, chitosan film wrapping with young apple polyphenols delayed the increase in microbial load, PV, thiobarbituric acid reactive substances (TBARS), TVB-N, and pH values caused by microbial growth and oxidation of lipids and proteins in grass carp fillets (GCF) and silver carp fillets during cold storage, along an increase of water holding capacity, functional properties of soluble myofibrillar protein, external acceptability, textural properties, and amino acids (Ramezani, Zarei, & Raminnejad, 2015; Sun et al., 2018; Yu, Jiang, Xu, & Xia, 2017). The acceptability was evaluated based on sensory evaluation system comprised of five indices, including odor, color, tissue elasticity and surface character. It was reported that the polyphenol-incorporated chitosan film could retard the spikes in colony forming units (CFU), PV, TBARS, TVB-N, pH, and *b** values caused by microbial reproduction and lipid and protein oxidation in GCF during cold storage (Sun et al., 2018). Yuan et al. (2016) discovered that during the later stage of iced storage, the melanosis and sensory scores, TVB-N, and total aerobic plate counts of white shrimp coated with chitosan in the combination of pomegranate peel extract (PPE) were lower than those treated with chitosan coating or PPE alone. Wang et al. (2015) demonstrated that 1 % chitosan coatings improved TVB-N amounts, K values, total viable count (TVC), hardness, and springiness of postharvest white leg shrimp stored at 4 °C for 10 days. Similarly, coating *P. japonicas* with gallic acid and chitosan inhibited microbial growth, protein decomposition, biogenic amine formation, lipid oxidation, nucleotide breakdown, and the preservation of better sensory characteristics during storage, resulting in a 6-day shelf-life extension (Wu, Li, et al., 2016). Since amines are synthesized at the end of a product's shelf life, their levels can be recognized as spoilage indices as compared to quality indices (Ozogul & Ozogul, 2006). A combination of chitosan (1.5 % w/v), tea polyphenol (0.2 % w/v), and rosemary extract (0.2 % w/v) effectively maintains good quality and extends the shelf-life of refrigerated *L. crocea* by 8–10 days compared to the untreated group (Li et al., 2012). Similarly, chitosan matrix incorporated propolis extract, contains the major source of polyphenols, reduced the extent of lipid oxidation, as measured by TBA and free fatty acid (FFA), improving the TVB-N and pH values of *Nemipterus japonicus* compared to untreated samples, and thus extending the shelf-life of *N. japonicus* fillet by approximately 10 days (Ebadi et al., 2019). Citric acid or licorice extract can significantly improve chitosan's preserving function by slowing lipid oxidation and inhibiting microbial growth, as reflected in TBA and TVC, respectively, and thus extend the shelf-life of Japanese sea bass fish fillets during refrigerated storage (Qiu et al., 2014). Cao et al. (2020) treated snakehead fish fillets with a chitosan solution containing chlorogenic acid (CGA). In their study, the lipid and protein oxidation were found to be inhibited by 2 % chitosan, 0.5 % CGA in 2 % chitosan, and 1.0 % CGA in 2 % chitosan coated fish fillet. All CGA/CS coatings caused a brown color and delayed the increase in pH. The combination of vanillin (2 mg/mL) and 1 % chitosan coating improves the sensory and chemical quality of turbot (*Scophthalmus maximus*) fillets and extends shelf life by 6–7 days (Li et al., 2020). Similarly, chitosan coating combined with sodium phytate, the sodium salt of phytic acid, effectively inhibited bacterial growth, increased pH and TVB-

N values, and decreased sensory properties of fresh Antarctic krill (*Euphausia superba*) during partially frozen storage (Liu et al., 2020).

As exemplified above, great efforts are being devoted to the development of chitosan films and coatings, however, high vapor permeability and water sorption of chitosan at the moist environments lowers its protection performance, therefore the combination of chitosan with essential oils which are concentrated hydrophobic liquids containing volatile aroma compounds, has deserved special attention in food packaging by developing an active coating layer with enhanced water vapor barrier performance. Essential oil is primarily composed of low-molecular weight aliphatic and aromatic secondary metabolite wherein terpenes (i.e., *p*-cymene, limonene, or pinene), terpenoids (i.e., thymol, carvacrol, or menthol), and phenylpropenes (i.e., eugenol, cinnamaldehyde, or vallinin) are key compounds (Kumar et al., 2020).

In Table 6, studies on chitosan coatings incorporated essential oils as preservation approach for pre-processed fish products have been summarized. Cinnamon oil containing chitosan active coating successfully inhibited lipid and microbial oxidation in refrigerated rainbow trout fillets and extended their shelf-life until the end of the storage period (Day 16) without significant loss of texture, odor, color, or overall acceptability, and without significant microbial growth, whereas control samples had a shelf-life of only 12 days (Ojagh et al., 2010). Rezaeifar et al. (2020) combined lemon verbena essential oil and extract with chitosan coating in rainbow trout meat, resulting in an enhancement of sensory characteristics. Chitosan coating (1.5 %) combined with lemon and thyme essential oils maintained the firmness, retarded lipid and protein oxidation, improved color and texture properties, reduced microorganism counts, and extended shelf-life of grass carp and European eel (*Anguilla*) fillets to 16 days (Cai et al., 2018; El-Obeid et al., 2018). Furthermore, the chitosan-citrus essential oil composite coating exhibits strong superoxide anion radical scavenging activity as well as hydroxyl radical scavenging activity with excellent antibacterial properties. It inhibits microbial growth more effectively, reduces lipid oxidation and peroxide production, and extends the shelf-life of Pacific mackerel by about 3 days (Li et al., 2019).

Table 6. The preservation effect of utilizing chitosan and essential oil-based edible coatings on pre-processed fishery products under the dip coating method.

Fish/fishery product	**Preservative Coating formulation**	**Results**	**References**
Hairtail (*Trichiurus haumela*)	Chitosan 1 % (w/v) Eugenol 11.61 % (w/w)	pH, TBA, TVB-N, TVC ↓ WHC, Sensory score ↑ Shelf-life (18 days) ↑	Liu et al. (2021)
Scomberoides commersonnianus	Chitosan 1 % (w/v) Whey protein 1 % (w/v) Tarragon *Artemisia dracunculus* essential oil (TEO)	pH, TVB-N, TBARS, FFA ↓ No difference in TMC and PTC Sensory acceptance score ↑ Shelf -life (12 days) ↑	Farsanipour et al. (2020)
white shrimp (*Litopenaeus vannamei*)	Chitosan 1.5 % (w/v) Fully deacetylated chitosan (FDCH) 1.0 %, 1.5 % (w/v) Clove essential oil (CEO) 0.5 %, 0.25 % (w/v) kojic acid (0.5 %, 0.25 % (w/v)	pH, TVB-N, weight loss, TPC ↓ Hardness, Sensory score ↑ Shelf-life (15 days) ↑	Liu et al. (2020)
Rainbow trout (*Oncorhynchus mykiss*)	Chitosan 20 g/L (w/v) Alginate 2 % (w/v) *Mentha Piperita* essential oil	TBARS, TVBN ↓ TVC, TPC, LAB ↓ Shelf-life (12 days) ↑	Raeisi et al. (2020)

Fish/fishery product	Preservative Coating formulation	Results	References
	(MPEO) 0.2 % (w/v) *Artemisia dracunculus* essential oil (ADEO) 0.2 % (w/v) *Zataria multiflora* essential oil (ZMEO) 0.2 % (w/v)		
Rainbow trout (*Oncorhynchus mykiss)*	Chitosan 1 % (w/v) Lemon verbena Essential oil 0.5 %,1 %,2 % (v/v) Lemon verbena extract 0.5 %, 1 %, 2 % (v/v)	TBARS, PV, TVN, pH, TVC ↓ Psychrotrophic bacteria, H_2S producing bacteria, Enterobacteriaceae spp ↓ Shelf-life (16 days) ↑	Rezaeifar et al. (2020)
frozen tambaqui fillet (*Colossoma macropomum*)	Chitosan 2 % (w/v) Clove essential oil 0.08 % and 0.16 % (w/v)	pH, Moisture, TBARS, CPB count ↓ Sensory score ↑ Shelf-life (120 days) ↑	Vieira et al. (2019)
Pacific mackerel (*Pneumatophorus japonicus*)	Chitosan 1.5 % (w/v) Citrus essential oil 1.5 % (w/v)	Drip loss, pH, TBARS, TVB-N, BA ↓ TVC, TPC ↓ Superoxide anion radical scavenging activity ↑ Hydroxyl radical scavenging activity ↑	Li et al. (2019)
Tilapia (*Oreochromis niloticus*)	Chitosan 2 % (w/v) Carvacrol 0.125 %, 0.25 % (w/v)	TVBS, pH, WRC ↓ Total aerobic count, Total coliform count ↓ *V. parahaemolyticus, V. cholerae* ↓	Chaparro-Hernandez et al. (2015)
Japanese sea bass (*Lateolabrax japonicas*)	Chitosan 1.5 % (w/v) citric acid 0.6 % (v/v) Citric acid 0.5 % (w/v) Locorice extract 1 % (w/v)	pH, TVB-N, TBARS, TPC ↓ Sensory score ↑ shelf life (12 days) ↑	Qiu et al. (2014)
Large yellow croaker (*Pseudosciaena crocea*) fillet	Chitosan 1.5 % (w/v) Rosemary extract 0.2 % (w/v) Tea polyphenol 0.2 % (w/v)	pH, PV, TBARS, TVC, TVB-N, K value ↓ Sensory score, shelf-life (8–10 days) ↑	Li et al. (2012)

Abbreviations: TBA-thiobarbituric acid; TVB-N- total volatile base and nitrogen; TVC- total viable count; WHC- water holding capacity; TBARS- thiobarbituric acid reactive substances; FFA-free fatty acids; TMC-total mesophilic count; PTC- psychrotrophic bacteria values; TPC- total aerobic plate counts; PV- peroxide value; TVN- total volatile nitrogen; CPB- culturable psychotropic bacteria; BA-biogenic amine; TPC- total psychrotrophic count; WRC- water retention capacity.

3.2.4. Mode of action of chitosan

Several review papers have described the antibacterial mechanisms of chitosan, however, in the light of increased research efforts for chitosan, description needs an update with the most recent and relevant studies. Chitosan has antibacterial activity against both gram-positive and gram-negative bacteria. Chitosan's mechanism of action involves the modification of the cell envelope or the disruption of the integrity of the cytoplasmic membrane (Devlieghere et al., 2004; Hu & Ganzle, 2019). Chitosan exhibits antimicrobial activity only when its pH ranges between 6.2 and 7, and it can be dissolved in 1 %–2 % acetic acid concentration or as chitosan-based packaging film (Hu & Ganzle, 2019). However, chitosan's antimicrobial activity is influenced by several other factors, including molecular weight, degree of deacetylation, and degree of polymerization, as well as pH, as it is only soluble in acidic conditions (Ma et al., 2017; Qi et al., 2004). Chitosan with a higher degree of

deacetylation has a higher positively charged density, resulting in a stronger electrostatic interaction with the cell surface and increased antimicrobial activity (Chung et al., 2004; Younes et al., 2014).

Above all, when used in food preservation, chitosan can act in a variety of ways. According to Goy et al. (2009), chitosan can bind to bacterial DNA, inhibiting mRNA transcription and possibly interacting with microorganism surface molecules. However, the mechanism of DNA binding remains unknown due to chitosan's inability to reach targets within the cytoplasm; it could be hypothesized that it binds the bacterial membrane and disrupts it (Bowman & Leong, 2006; Ma et al., 2017). However, because of its larger size, chitosan is unable to cross the cell wall and interact directly with the membrane, more research is needed to understand this (Raafat et al., 2008).

Another mechanism that could alter the cell membrane is the polycationic nature of chitosan (Hu & Ganzle, 2019; Ma et al., 2017). Chitosan contains glucosamine amine groups (NH_3^+), and many microorganisms have negatively charged surface components; interaction of those compounds causes extensive alteration of the cell surface, resulting in leakage of intracellular substances and cell death. The lipopolysaccharide and teichoic acid found in gram-positive and gram-negative bacteria play a major role in binding chitosan to the cell membrane, altering, destabilizing, and ultimately disrupting cell wall dynamics (Ganan et al., 2009; Raafat et al., 2008). For example, 0.01–5 g/L chitosan increases *E. coli* and *Salmonella* sp. outer membrane permeabilization (Helander et al., 2001; Hu & Ganzle, 2019).

Chitosan may have antifungal properties similar to its antibacterial properties (Ma et al., 2017). Fungal and yeast strains such *Fusarium oxysporum*, *Botrytis cinerea*, *Rhizoctonia solani*, *Candida lambica*, and *Phomopsis asparagi* are inhibited by chitosan's antifungal potential. Chitosan and its derivative possess broad-spectrum antifungal activity and can inhibit the germination of sporangia, germination tubes, and mycelium development of pathogenic fungi (Qin et al., 2020). Further, through the action of plant host hydrolytic enzymes, fungal pathogens' cells are lysed following which chitosan can enter the nuclei of fungi and interfere with RNA and protein synthesis (Muzzarelli et al., 1986). Tayel et al. (2010) investigated the mode of action of chitosan with *Candida albicans* and discovered an interaction between chitosan and the microbe's cell, resulting in severe swelling and cell wall lysis. Furthermore, chitosan inhibited the growth of *Aspergillus flavus*, *Alternaria alternate*, *Fusarium solani*, and aflatoxin production in culture (Dutta et al., 2009; Reddy et al., 1997). Fungi are thought to be more responsive to chitosan than bacteria (Goy et al., 2009).

Chitosan's strong hydrogen-donating ability makes it a promising antioxidant for food preservation with enhanced scavenging activity. The antioxidant activities of chitosan are enhanced by oxidation products such as reactive oxygen species (ROS), superoxide anion radicals, hydroxyl radicals, and hydrogen peroxide. Aside from that, chitosan's low molecular weight and higher degree of quaternization have an influence in its antioxidant capacity (Vinsova & Vavrikova, 2011). Chitosan was investigated as a potential antioxidant in several studies, where the lipid peroxidation of phosphatidylcholine and linoleate liposomes was inhibited by chitosan scavenging of hydroxyl radicals (Feng et al., 2008).

It is also worth mentioning that Yen et al. (2008) reported that chitosan from crab shells with varying degrees of deacetylation had higher scavenging activities as well as high chelating abilities. Chitosan's high chelating capacity makes it useful as a food supplement (Vinsova & Vavrikova, 2011).

Consumer demand for synthetic antioxidant-free sea foods may encourage greater use of chitosan (Chiang et al., 2000), because chitosan significantly reduced lipid oxidation even after cooking. For example, viscous nature of chitosan has been found to protect cooked cod from oxidation (L'opez-Caballero et al., 2005; Shahidi et al., 2002). Similarly, chitosan combined with modified atmosphere packaging improved lipid stability in cold-storage lingcod (*Ophiodon elongates*) for 21 days (Duan et al., 2010). Another study showed chitosan enriched with cinnamon oil may delay peroxidation in rainbow trout (*Oncorhynchus mykiss*) after a 16-day storage period (Ojagh et al., 2010). A proposed antibacterial mechanism of chitosan is depicted in Fig. 2.

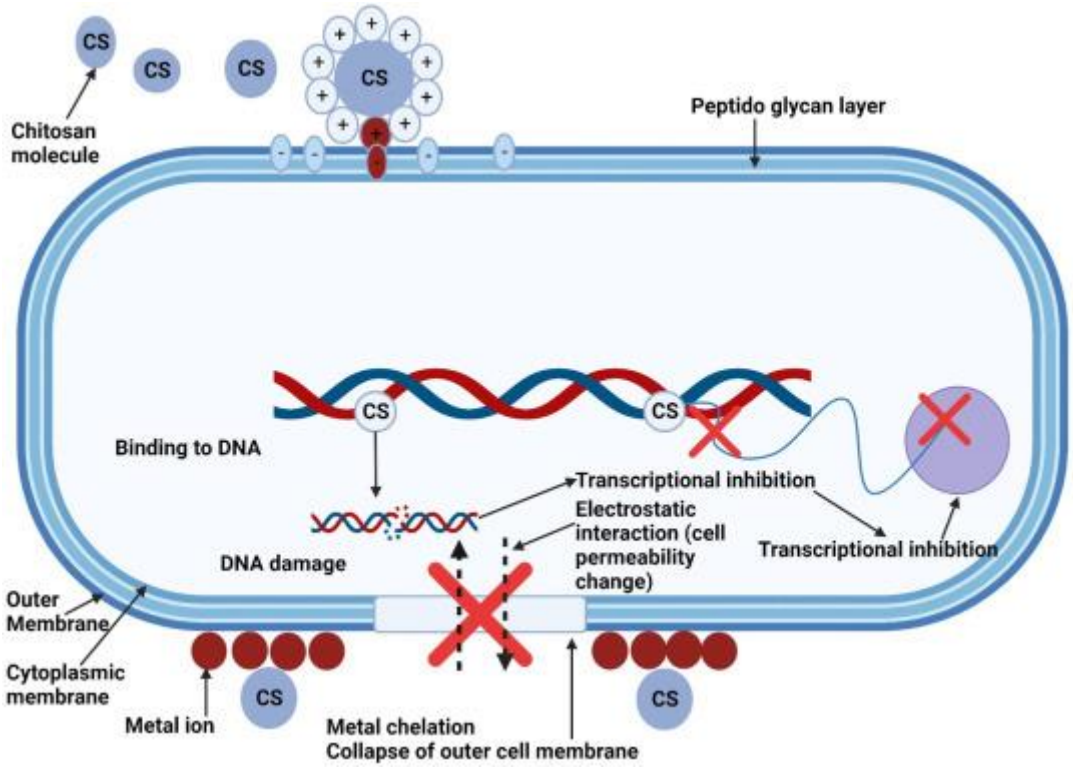

Fig. 2. Summary of the postulated mechanism of antibacterial activity of chitosan.

4. Essential oils as preservative agents in edible coating for fresh pre-processed fish

Essential oils are complex mixtures of volatile organic compounds extracted from various plant parts such as leaves, barks, stems, roots, flowers, and fruits (Calo et al., 2015). Essential oils frequently have antimicrobial and antioxidant properties, and a growing demand for natural preservatives has led to the consideration and use of essential oils as possible chemical preservative substitutes (Jayasena & Jo, 2013). Oregano, rosemary, thyme, laurel, sage, cinnamon, clove, and basil are the most used essential oils in fish and fish products as antimicrobial and antioxidant compounds. Other essential oils, such as cumin and spearmint (Cai et al., 2015), *Zataria multiflora* Boiss (Emir Çoban & Tuna Keleştemur, 2017), horsemint (Heydari et al., 2015), orange, grapefruit, mandarin, and lemon (Durmus, 2020), turmeric, and lemongrass (Masniyom et al., 2012) are also explored by researchers for their taste enhancing as well as antimicrobial properties.

Essential oils can be used in a variety of ways in the fish processing industry, the most common being the direct application of essential oils or their compounds to fish and other seafoods. However, higher concentrations of essential oils may cause undesirable sensory characteristics on treated fish, reducing

the acceptability of fish and seafood products (Atares & Chiralt, 2016). To tackle the organoleptic challenges of direct application of essential oils onto fish and other seafoods, the incorporation of essential oils into active films and coatings for food protection has been proposed. In fact, several studies have been so far conducted to evaluate the effectiveness of essential oil added films and coatings in the packaging of fish and fisheries products. For example, on refrigerated bream fillets, a pectin coating enriched with clove essential oil at two concentrations (1 % and 1.5 %) was tested (Nisar et al., 2019). The results showed that this treatment reduced the rate of lipid oxidation and TVB-N, as well as the microbial growth, as measured by TVC, psychrophilic bacteria count, hydrogen sulfide-producing bacteria, lactic acid bacteria, *Pseudomonas*, and Enterobacteriaceae count, hence extending the shelf-life by at least 6 days. In another case, shrimp treated with gelatin coating enriched with orange leaf essential oil (2 %) improved sensory and microbial attributes while also extending shelf-life (14 days) compared to the control (6 days) (Alparslan et al., 2016).

Nanocomposite films based on soy protein isolate, montmorillonite, and clove essential oils were used to preserve bluefin tuna fillets during refrigerated storage, with films promoting a reduction in the microbial count and delaying lipid oxidation until 12 days (Echeverría et al., 2018). Ehsani et al. (2020) investigated the effect of chitosan, alginate, and gelatin-based films containing sage essential oil on fish burgers stored at 4 °C. The results showed that film wrapping significantly reduced the proliferation of microorganisms such as *Pseudomonas* sp. and *Shewanella* sp. Furthermore, Arfat et al. (2015) discovered that sea bass slices wrapped in fish protein/fish gelatin composite films infused with basil leaf essential oil had a shelf-life of 10–12 days compared to 6 days for the control.

An alternative strategy for incorporating essential oils into fish and other food products through micro- and nano-emulsions has recently been proposed as a promising alternative to direct essential oil addition. This technique is gaining popularity as a novel technique and as a model carrier for the transport of lipophilic substances such as essential oils due to its ease of preparation, small particle size, higher bioavailability, and kinetic stability (Ozogul et al., 2017). Recently, the effectiveness of nano-emulsions containing 4 % orange, grapefruit, mandarin, and lemon essential oils was assessed on the quality of rainbow trout fillets stored at 4 °C. When compared to the control group, the results showed that nano-emulsions based on essential oils eliminated fishy odor, improved organoleptic quality and delayed the growth of bacteria. Furthermore, the shelf-life of grapefruit and mandarin essential oils, lemon and orange essential oils treated and control samples were 16, 14, and 10 days, respectively (Durmus, 2020). Similarly, micro-emulsion-based lemon essential oil at two concentrations (0.3 % and 1 %) influenced the microbiological quality of salted sardines, with essential oil treated fish having significantly lower levels of Enterobacteriaceae, *Staphylococci*, and rod lactic acid bacteria than the control group (Alfonzo et al., 2017). Many volatile organic compounds belonging to monoterpene hydrocarbons, oxygenated monoterpenes, and sesquiterpene hydrocarbons may be responsible for the preservative functions of lemon essential oil. In fact, the antimicrobial activity of essential oils has been attributed to their main constituents, particularly phenolic constituents, as well as minor constituents found in oils (Bakkali et al., 2008).

The primary mode of action of essential oil components is targeting a broad spectrum of bacteria by disrupting their cell membrane and cytoplasm. They can also enter the bacterial cell's interior and inhibit its functional properties while also inducing cell morphology changes (Calo et al., 2015). Gram-positive bacteria are more sensitive to essential oils than Gram-negative bacteria (Trombetta et al., 2005); for example, essential oil from geraniol was found to be more active against

Staphylococcus aureus (Gram-positive) than *E. coli* (Gram-negative) (Zanetti et al., 2015). This is due to lipoteichoic acids in gram-positive bacteria cell membranes, which may facilitate the penetration of hydrophobic essential oil compounds, making them susceptible to essential oils. An extrinsic membrane surrounding the Gram-negative bacterial cell wall, on the other hand, slows the diffusion rate of those compounds through the lipopolysaccharide layer, conferring some resistance (Rodriguez-Garcia et al., 2016; Tongnuanchan & Benjakul, 2014).

The hydrophobicity of essential oils leads to interaction with the lipids of the bacterial cell membrane and mitochondria, making the cell more permeable. This interaction between cell membranes and essential oils inhibits both gram-positive and gram-negative bacterial growth (Calsamiglia et al., 2007; Friedly et al., 2009).

5. Challenges and future directions

Based on the literature reviewed above, bio-based edible coatings have emerged as a promising approach for preserving the quality and extending the shelf life of fresh fishery products during storage. However, most studies have solely focused on observing physicochemical changes, bacterial enumeration, and sensory evaluation, rather than attempting to understand the underlying mechanisms of edible coating's protective effect. To optimize its application in the preservation of fishery products, future studies on bio-based edible coating need to investigate the protective mechanisms in terms of film-forming characteristics, synergistic effects for microorganisms and oxidation control, flavor and sensory properties, and enzyme inhibition. Among the specific recommendations we propose.

- Dip-draining is currently the preferred method for fishery product. This method requires a long drain time for coatings containing chitosan and gelatin and may result in non-homogeneous coating. More research is needed to understand the factors affecting the thickness and uniformity of forming films, as well as to develop drying methods to control film formation and shorten drain time.
- Although many researchers studied the effects of bio-based edible coating on microbial succession through enumeration, only a few microorganisms were cultivated. During the spoilage of fishery products, only one or a few microorganisms were found dominant communities. As a result, monitoring the changes in the overall bacterial diversity of coated samples using high-throughput methods in the frame of foodomics would allow us to better explain the preservation mechanism(s) at the microbial level.
- Investigating the effects of bio-based edible coatings on the changes in taste and flavor precursors of fishery products during storage, with the goal of improved understanding of flavor and sensory quality retentions in coated products is required.
- Developing a better understanding of the synergistic effect among natural preservatives is needed to optimize the formulation of composite coatings according to the targeted effect as well as negligible negative impact on product sensory qualities, particularly avoiding color darkening and irritating odors from natural preservatives.

- Although edible coatings have shown the proof in reducing texture softening induced by endogenous enzymes during storage, further discoveries are needed in the enzyme inhibition mechanisms to slow this deterioration even further.

A dearth of study has also been conducted on the development of novel synergistic gelling systems. In turn, it is possible to conduct such a comparative investigation. The majority of research on edible coating applications has been conducted in the laboratory, resulting in a paucity of actual applications. Future applied research ought to focus on edible coatings given that they can extend food's shelf life. To eliminate these concerns, coating application methods can be modified to include a recycling process that does not waste an excessive amount of coating solution, reduce the number of microorganisms in the solution during recycling, develop spraying techniques for uneven surfaces, design industrial-sized vacuum tanks, and so on.

This permits novel applications of food contact films and coatings on a large scale. The development of edible films and coatings spanning two or more nanomaterials is anticipated to be a future trend in edible packaging. These products are anticipated to have improved gas barrier properties, superior product stability, unique color and flavor, and a greater nutritional value. New approaches for modulating mechanical properties and gas transport must be investigated in order to maintain food quality. By altering their properties in response to environmental factors such as relative humidity and temperature, edible films and coatings must assist food products in adapting to their environments. To effectively regulate the passage of oxygen, carbon dioxide, and water vapor in a system, nanomaterials must be meticulously evaluated.

The use of gelatin-based edible films and coatings is an exciting new route for developing new food packaging materials. Because of gelatin's hygroscopic properties, some research studies have been conducted to evaluate the overall effect of adding different substances such as crosslinkers, strengthening agents, plasticizers, or additives with antimicrobial or antioxidant properties to gelatin-based products in order to improve the functional properties of gelatin-based edible films and the shelf-life of food products. A growing number of publications have reported the development of gelatin-based films for meat applications as coatings to reduce lipid oxidation-induced color deterioration from red to brown. In the case of fish products, various studies have focused on the use of gelatin in conjunction with other biopolymers or active additives to protect fresh fish from cooking processes and microbial/oxidation deterioration. Extensive research on new methods for gelatin-based film formation is still required to improve final properties and expand the applications.

The WP and active ingredients are being incorporated into edible films/coatings, which can be used in a variety of food products. Depending on the purpose, product, nature of the film, type of active ingredient, and various inclusions, numerous combinations could be used on an industrial scale. We described several characteristics of edible WP films/coatings as novel packaging materials in this review. There are numerous promising approaches for improving food quality, extending shelf life, and ensuring safety, maintaining functionality, and reducing environmental impacts. Furthermore, these films and coatings can be used as separate pouches of homogeneous substances and active ingredient carriers. In food packaging, the formulation of a biopolymer coating using WP-based plastic films can replace existing synthetic oxygen-barrier layers, such as ethylene vinyl alcohol (EVOH). Whey is not a direct food competitor because it is a byproduct of cheese production and in terms of intrinsic edibility and biodegradability, WP-based films/coatings outperform synthetic

plastics. The WP films/coatings described in this review demonstrated exceptional optical and barrier properties that outperformed existing biopolymers. In this regard, WP coatings have been demonstrated to be effective gas barriers capable of acting as vehicles for a variety of compounds such as antioxidants, antimicrobials, or various nutrients, though their mechanical properties need to be improved. Thus, chemical, physical, or enzymatic protein cross-linking (Di Pierro et al., 2018), as well as other ways such as blending and nanotechnology, are potential methods for improving the tensile strength and elongation at break characteristics of WP films. The greatest commercial potential for WP films/coatings, in our opinion, includes its use for a delivery vehicle of functional and bioactive compounds in fresh fish and seafood products, thereby extending shelf life and improving safety, nutrition, and sensory qualities. The WP-based multilayer laminates have been successfully validated for the storage of a variety of food products. This novel WP coating can be detached, allowing multilayer films to be reused. Due to the use of natural by-products from the food industry as raw materials, WP-based packaging ideas may play beneficial roles in sustainability due to the possibility of recycling materials rather than incineration, as done in synthetic laminates. However, in the face of industrial setbacks, cost-effectiveness will always be a driving force in current and future WP processing developments. The industrial application of this new technology is still dependent on additional scientific research to identify the mechanism of film formation to improve the performance of both the product and the process. Furthermore, consumer studies and long-term toxicity assessments must be investigated before gaining a significant market share. On the other side the exorbitant cost of equipment for novel technologies used in food preservation such as plasma or irradiation is not associated with coating technology.

Due to its nontoxic, antibacterial, and antifungal qualities, chitosan has garnered considerable interest. Because of this, chitosan is regarded as an ideal material for the development of food grade films/coatings. Due to the protonation of the amino groups, chitosan has a positive charge and is soluble at pH levels below 6.5. Chitosan can be shaped into numerous forms, including films, gels, and nanoparticles (Koc et al., 2020). Wang, Liao, et al. (2019) stated that it is among the most researched polysaccharides for the production of packaging film due to its exceptional film-forming capacity. Gelatin is commonly used as a composite component with chitosan to sidestep problems associated with using coating made from individual biopolymers (Wang et al., 2021). United States Food and Drug Administration (FDA) has classified chitosan as GRAS (GRAS notification number GRN 170) (FDA, 2005), in 2007 under the European union regulation (No. 749/2012) and China national standards (GB 29941–2013) (Nair et al., 2020). When incorporating food-grade functional materials within the limits specified by the regulations, chitosan-gelatin composite films could have improved physical and chemical properties without compromising the safety and edibility, indicating an excellent packaging potential (Wang et al., 2021). The acute and subacute toxicity of two chitosan derivatives, produced by a depolymerization procedure, was assessed by orally administering them to a mouse model (Punarvasu & Prashanth, 2023). The findings indicate that administering a dosage of chitosan derivatives up to 5000 mg/kg bw did not result in fatalities or any other proof of toxicity. Hence, the LD50 value of both the chitosan derivatives exceeds 5000 mg/kg bw. Furthermore, in the subacute toxicity assessment, the chitosan derivatives exhibited no discernible destruction following daily oral doses of 1000 and 2000 mg/kg bw. In an overview, the chitosan derivatives (LMWC and SAMC) that underwent investigation showed no signs of toxicity in mice. There were no instances of fatalities or alterations in general behavior observed during both single and repeated dose administration studies. Therefore, these derivatives appear to be safe for use in biomedical and food applications (Punarvasu & Prashanth, 2023).

Multiple investigations have demonstrated that the incorporation of various active chemicals into chitosan films results in intriguing modifications to their mechanical, barrier, and functional properties. J.P. Verwijs, a frozen fish vendor based in the Netherlands, recently switched to organic biodegradable packaging for its diverse range of seafood items (Kearns, 2019). J.P. Verwijs asserted that the design of the fresh packaging was influenced by the principles of the circular economy, a business strategy that values sustainability, transparency, simplicity, and excellence. By adopting its novel biodegradable packaging solution, developed from agricultural waste, the supplier can effectively diminish its plastic waste production and substantially reduce its carbon dioxide emissions. The packaging is fully compliant with the European Food Safety Authority (EFSA) and FDA regulations, as well as Europe's biodegradable and compostable standards EN 13432/14995. It is also an innovative biodegradable approach. The presence of phenolic compounds has been demonstrated to improve both mechanical and barrier characteristics. Chitosan-based edible films containing antioxidant properties were fabricated by adding *Zataria multiflora* Boiss essential oil (ZEO) at concentrations of 5 and 10 g/L, as well as grape seed extract (GSE) at a concentration of 10 g/L, both on its own and in combination. Except for the 10 g/L GSE +10 g/L ZEO film, all other films showed reduced strength and elongation values. The inclusion of only 10 g/L ZEO in the GSE film enhanced the water vapor transmission rate of chitosan films (Moradi et al., 2012). Talón and co-workers investigated the antioxidant properties and physical characteristics of various polymeric matrices composed of chitosan and starch (Talón et al., 2017). These matrices were modified by including a thyme extract (TE) that is abundant in polyphenols, along with the inclusion of tannic acid (TA) as a cross-linking agent. The integration of TE resulted in modifications to the microstructural and physical properties of the films, contingent upon the specific matrix employed. Thyme extract was found to be most effective in improving the properties of chitosan-based films. This is attributed to the cross-linking activity between the polyphenols and chitosan, resulting in enhanced tensile response characterized by increased resistance at break and improved stiffness (Talón et al., 2017). As for the functional qualities of the films, the addition of essential oils, phenolic compounds, and fruit extracts considerably enhanced their antibacterial and antioxidant capacities. To build chitosan-based packaging that can meet practical criteria and compete with petroleum-based packaging, however, considerably more research is required. It is being proposed to conduct further investigations (1) on chitosan and its combination with other materials to suit practical needs, (2) Conduct research on chitosan films and determine the potential risks associated with their use, (3) Determine interaction of types of foods with chitosan packaging (Florez et al., 2022).

Sustainable development is an overarching goal that mandates an interdisciplinary approach to resolve the societal challenge of climate change, environment, resource efficiency, and raw materials. In this context, the first step in closing the waste-to-consumption loop in accordance with the seventh main objective of the circular economy that is the valorization of abundant and readily available bio-waste with a high potential for manufacturing products with added value. Biomass leftovers can serve as a viable substitute for fossil fuel sources in the production of plastic packaging for food. Substituting biomass residues for fossil fuel sources in plastic manufacture has two primary benefits: severing the connection between food packaging and fossil fuels, and utilizing agricultural by-products to minimize demand for plastic derived from fossil fuel-based sources. Although bioplastic food packaging holds promise, it confronts numerous hurdles such as exorbitant production expenses, inadequate policy and standard support, and a scarcity of composting facilities (Symons, 2022). Plastic derived from secondary biomass resources, such as by-products, effectively confronts numerous issues associated with society and the environment. This includes the reduction of

greenhouse gas emissions, without compromising food security by substituting food crops. In along with substituting fossil fuel sources, the potential benefits of recycling or composting at the end of a product's life cycle enhance the environmental and social benefits. Efforts have been undertaken to measure both the cost and the benefits of shifting to biomass plastics, such as the economic gains resulting from declined greenhouse gas emissions and reduced plastic waste in marine ecosystems. However, these studies are broad in scope and prone to uncertainty. Several studies have utilized the life cycle analysis methodology to calculate these figures. However, these studies fail to comprehensively account for all the costs and benefits, as they do not incorporate various end-of-life alternatives. The financial expenditures linked to the adoption of biomass plastics are substantial and encompass elevated costs of using biomass sources, expenses for research and development, and shortfalls in economies of scale. These hurdles are substantial and necessitate additional investigation, beginning with the establishment of a baseline for the costs of packaging made from fossil fuels. This will help identify the cost benchmarks that biomass plastics must meet. Moreover, a further investigation is necessary to determine the complete environmental and economic implications of various end-of-life circumstances, as well as the potential advantages and disadvantages of waste systems that incorporate composting infrastructure (Symons, 2022).

The future development of bioplastic production will be strongly influenced by the fluctuation of conventional plastic costs. In addition, the development is impacted by other factors such as technological advancements, economies of scale, and raw material costs (Döhler et al., 2022). By increasing the scale of bioplastics manufacturing, organizations can leverage cost efficiencies by distributing current fixed expenses over a larger amount, resulting in higher output at reduced average costs per unit. At present, the production volume of bioplastics remains fairly modest. Simultaneously, the expenses associated with constructing structures and acquiring equipment constitute a substantial portion of the overall manufacturing costs (Manandhar & Shah, 2020). Simultaneously, the expenses associated with constructing buildings and acquiring equipment, known as fixed capital expenditures, constitute a substantial portion of the overall production costs (Manandhar & Shah, 2020). This implies a notable potential for untapped economies of scale. The cost progression in increasingly sophisticated biotechnologies demonstrates the actualization of these capabilities as time passes (de Jong et al., 2017; Skovsgaard & Jacobsen, 2017).

The enormous quantities of waste generated during the refining of seafood can be effectively managed to produce renewable and biodegradable raw materials (Caba et al., 2019). This management incorporates the use of environmentally benign and cost-effective extraction techniques to ensure that innovative biorefinery practices designed to add value to byproducts contribute to the sustainable development of materials. Currently, chitosan and fish gelatin production has been scaled up, and these materials are commercially available. Utilizing side streams, co-products, or even seafood processing waste (specially the crustacean shell fish processing waste) can support the concept of a circular bio-economy, provide more sustainable solutions, and maximize the use of our natural resources. Considering the annual amounts produced and the rising demand for biodegradable films/coatings in the food and agriculture industries, the processing or fabrication of animal-based products generates a substantial amount of potential feedstock.

6. Conclusion

Bio-based edible coatings are gaining momentum in the sustainable and circular ecosystem. This review has covered many aspects of coating preservation approach for fishery products, such as coating formulations and carriers, including those formulated with natural additive compounds, coating application methods and their benefits and challenges, and protection capacity and mechanism as determined by microbial, physicochemical, and sensorial evaluations. More discoveries and deep understanding are very critical and essential to engineering and designing fish product-specific bio-based coating formulations with recycling in mind, without the need for complex processing aids.

CRediT authorship contribution statement

Don Hettiarachchige Udana Eranda: Writing – original draft, Investigation, Data curation, Conceptualization. **Manat Chaijan:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Ilke Uysal-Unalan:** Writing – review & editing, Investigation, Data curation. **Worawan Panpipat:** Writing – review & editing. **Azza Silotry Naik:** Writing – review & editing. **Amira Leila Dib:** Writing – review & editing. **Supatra Karnjanapratum:** Writing – review & editing, Supervision. **Mohammed Gagaoua:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Data curation, Conceptualization.

Declaration of competing interest

All authors declare that they have no conflicts of interest.

Acknowledgements

This work has been supported by Walailak University Ph.D. Scholarships for High Potential Candidates to Enroll in Doctoral Programs (Contract No. HP018/2021). Also, this research was financially supported by Walailak University Graduate Research Fund (Contract No. CGS-RF-2023/07).

Data availability

No data was used for the research described in the article.

References

Abdelhedi, O., Jridi, M., Nasri, R., Mora, L., Toldra´, F., & Nasri, M. (2018). Rheological and structural properties of skin gelatin: Potential Hemiramphus for use as an active fish coating agent. Food Hydrocolloids, 87, 331–341. https://doi.org/10.1016/j. foodhyd.2018.08.005

Abel, N., Rotabakk, B. T., Rustad, T., & Lerfall, J. (2018). The influence of lipid composition, storage temperature, and modified atmospheric gas combinations on the solubility of CO2 in a seafood model product. Journal of Food Engineering, 216, 151–158. https://doi.org/10.1016/j.jfoodeng.2017.08.020

Ahmad, T., Ismail, A., Ahmad, S. A., Khalil, K. A., Kumar, Y., Adeyemi, K. D., & Sazili, A. Q. (2017). Recent advances on the role of process variables affecting gelatin yield and characteristics with special reference to enzymatic extraction: A review. Food Hydrocolloids, 63, 85–96.

Aleman, A., Gonzalez, F., Arancibia, M. Y., Lopez-Caballero, M. E., Montero, P., & Gomez-Guillen, M. C. (2016). Comparative study between film and coating packaging based on shrimp concentrate obtained from marine industrial waste for fish sausage preservation. Food Control, 70, 325–332. https://doi.org/10.1016/j. foodcont.2016.06.007

Alfaro, A. T., Balbinot, E., Weber, C. I., Tonial, I. B., & Machado-Lunkes, A. (2014). Fish gelatin: Characteristics, functional properties, applications and future potentials. Food Engineering Reviews, 7, 33–44.

Alfonzo, A., Martorana, A., Guarrasi, V., Barbera, M., Gaglio, R., Santulli, A., et al. (2017). Effect of the lemon essential oils on the safety and sensory quality of salted sardines (Sardina pilchardus Walbaum 1792). Food Control, 73, 1265–1274. https:// doi.org/10.1016/j.foodcont.2016.10.046

Alparslan, Y., Yapıcı, H. H., Metin, C., Baygar, T., Günlü, A., & Baygar, T. (2016). Quality assessment of shrimps preserved with orange leaf essential oil incorporated gelatin. LWT - Food Science and Technology, 72, 457–466. https://doi.org/10.1016/j. lwt.2016.04.066

Amit, S. K., Uddin, M. M., Rahman, R., Islam, S. M. R., & Khan, M. S. (2017). A review on mechanisms and commercial aspects of food preservation and processing. Agriculture & Food Security, 6, 51.

Amiza, M. A., & Kang, W. C. (2013). Effect of chitosan on gelling properties, lipid oxidation, and microbial load of surimi gel made from African catfish (Clarias gariepinus). International Food Research Journal, 20(4), 1585–1594.

Andevari, G. T., & Rezaei, M. (2011). Effect of gelatin coating incorporated with cinnamon oil on the quality of fresh rainbow trout in cold storage. International Journal of Food Science and Technology, 46(11), 2305–2311.

Antunes-Rohling, A., Calero, S., Halaihel, N., Marquina, P., Raso, J., Calanche, J., Beltr´an, J. A., A´lvarez, I., & Cebria´n, G. (2019). Characterization of the spoilage microbiota of hake fillets packaged under a modified atmosphere (MAP) rich in CO2 (50 % CO2/50 % N2) and stored at different temperatures. Foods, 8(10), 489. https:// doi.org/10.3390/foods8100489

Anwar, D. A., Eid, H. R., & Rashad, S. (2022). Impact of Xanthan Gum incorporated with Black tea extract as edible coating for shelf life extension and quality maintenance of Zander fish fillets (Sander lucioperca). Egyptian Journal of Aquatic Biology & Fisheries, 26(6), 279–298.

Arfat, Y. A., Benjakul, S., Vongkamjan, K., Sumpavapol, P., & Yarnpakdee, S. (2015). Shelf-life extension of refrigerated sea bass slices wrapped with fish protein isolate/ fish skin gelatin-ZnO nanocomposite film incorporated with basil leaf essential oil. Journal of Food Science & Technology, 52(10), 6182–6193. https://doi.org/10.1007/ s13197-014-1706-y

Aryee, A. N. A., Simpson, B. K., & Villalonga, R. (2007). Lipase fraction from the viscera of grey mullet (Mugil cephalus). Enzyme and Microbial Technology, 40(3), 394–402. https://doi.org/10.1016/j.enzmictec.2006.07.009

Ashie, I. N. A., Smith, J. P., Simpson, B. K., & Haard, N. F. (1996). Spoilage and shelf-life extension of fresh fish and shellfish. Critical Reviews in Food Science and Nutrition, 36 (1–2), 87–121. https://doi.org/10.1080/10408399609527720

Asik, E., & Candogan, K. (2014). Effects of chitosan coatings incorporated with Garlic oil on quality characteristics of shrimp. Journal of Food Quality, 37(4), 237–246. https:// doi.org/10.1111/jfq.12088

Atares, L., & Chiralt, A. (2016). Essential oils as additives in biodegradable films and coatings for active food packaging. Trends in Food Science & Technology, 48, 51–62. https://doi.org/10.1016/j.tifs.2015.12.001

Augusto, A., Simoes, T., Pedrosa, R., & Silva, S. F. J. (2016). Evaluation of seaweed extracts functionality as post-harvest treatment for minimally processed fuji apples. Innovative Food Science & Emerging Technologies, 33, 589–595.

Baghi, F., Gharsallaoui, A., Dumas, E., & Ghnimi, S. (2022). Advancements in biodegradable active films for food packaging: Effects of nano/microcapsule incorporation. Foods, 11(5), 760.

Bahram, S., Rezaie, M., Soltani, M., Kamali, A., Abdollahi, M., Ahmadabd, M. K., & Nemati, M. (2016). Effect of whey protein concentrate coating Cinamon oil on quality and shelf life of refrigerated Beluga Sturegeon (Huso huso). Journal of Food Quality, 39(6), 743–749. https://doi.org/10.1111/jfq.12227

Bakkali, F., Averbeck, S., Averbeck, D., & Idaomar, M. (2008). Biological effects of essential oils a review. Food and Chemical Toxicology, 46(2), 446–475. https://doi. org/10.1016/j.fct.2007.09.106

Banerjee, S., Khokhar, S., & Apenten, R. K. O. (2001). Characterization of lipoxygenase from mackerel (Scomber scombrus) muscle. Journal of Food Biochemistry, 26, 1–19. https://doi.org/10.1111/j.1745-4514.2002.tb00046.x

Benbettaïeb, N., Chambin, O., Assifaoui, A., Al-Assaf, S., Karbowiak, T., & Debeaufort, F. (2016a). Release of coumarin incorporated into chitosan-gelatin irradiated films. Food Hydrocolloids, 56, 266–276.

Benbettaïeb, N., Chambin, O., Karbowiak, T., & Debeaufort, F. (2016b). Release behavior of quercetin from chitosan-fish gelatin edible films influenced by electron beam irradiation. Food Control, 66, 315–319.

Bhattacharjee, C., Nath, A., Cassano, A., Tahergorabi, R., & Chakraborty, S. (2015). Conventional macro- and micromolecules separation. In Food waste recovery (pp. 105–126). Amsterdam, The Netherlands: Elsevier.

Bonilla, F., Chouljenko, A., Reyes, V., Bechtel, P. J., King, J. M., & Sathivel, S. (2018). Impact of chitosan application technique on refrigerated catfish fillet quality. Lebensmittel-Wissenschaft & Technologie, 90, 277–282. https://doi.org/10.1016/ jlwt.2017.12.010

Bowman, K., & Leong, K. W. (2006). Chitosan nanoparticles for oral drug and gene delivery. International Journal of Nanomedicine, 1(2), 117–128. https://doi.org/ 10.2147/nano.2006.1.2.117

Boziaris, I. S., Stamatiou, A. P., & Nychas, G.-J. E. (2013). Microbiological aspects and shelf life of processed seafood products. Journal of the Science of Food and Agriculture, 93(5), 1184–1190. https://doi.org/10.1002/jsfa.5873

Bulushi, I. Al, Poole, S., Deeth, H. C., & Dykes, G. A. (2009). Biogenic amines in fish: Roles in intoxication, spoilage, and nitrosamine formation—a review. Critical Reviews in Food Science and Nutrition, 49(4), 369–377.

Caba, K.d. L., Guerrero, P., Trung, T. S., Cruz, M., Kerry, J. P., Fluhr, J., Maure, M., Kruijssen, F., Albalat, A., Bunting, S., Burt, S., Little, D., & Newton, R. (2019). From seafood waste to active seafood packaging: An emerging opportunity of the circular economy. Journal of Cleaner Production, 208, 86–98. https://doi.org/10.1016/j. jclepro.2018.09.164

Cai, L., Cao, A., Bai, F., & Li, J. (2015). Effect of ε-polylysine in combination with alginate coating treatment on physicochemical and microbial characteristics of Japanese sea bass (Lateolabrax japonicas) during refrigerated storage. LWT - Food Science and Technology, 62(2), 1053–1059. https://doi.org/10.1016/j.lwt.2015.02.002

Cai, L., Leng, L., Cao, A., Cheng, X., & Li, J. (2018). The effect of chitosan-essential oils complex coating on physicochemical, microbiological, and quality change of grass carp (Ctenopharyhgodon idella) fillets. Journal of Food Safety, 38(1), 1–9. https:// doi.org/10.1111/jfs.12399

Calo, J. R., Crandall, P. G., O'Bryan, C. A., & Ricke, S. C. (2015). Essential oils as antimicrobials in food systems – a review. Food Control, 54, 111–119. https://doi. org/10.1016/j.foodcont.2014.12.040

Calsamiglia, S., Busquet, M., Cardozo, P. W., Castillejos, L., & Ferret, A. (2007). Invited review: Essential oils as modifiers of rumen microbial fermentation. Journal of Dairy Science, 90(6), 2580–2595. https://doi.org/10.3168/jds.2006-644

Campos, C. A., Gerschenson, L. N., & Flores, S. K. (2011). Development of edible films and coatings with antimicrobial activity. Food and Bioprocess Technology, 4, 849–875.

Cao, X., Islam, M. N., Chitrakar, B., Duan, Z., Xu, W., & Zhong, S. (2020). Effect of combined chlorogenic acid and chitosan coating on antioxidant, antimicrobial, and sensory properties of snakehead fish in cold storage. Food Sciences and Nutrition, 8(2), 973–981. https://doi.org/10.1002/fsn3.1378

Chaijan, M., Chaijan, S., Panaya, A., Nisoa, M., Cheong, L., & Panpipat, W. (2022). Combined effects of prior plasma-activated water soaking and whey protein isolate- ginger extract coating on the cold storage stability of Asian sea bass (Lates calcarifer) steak. Food Control, 135, Article 108787. https://doi.org/10.1016/j.foodcont.2021.108787

Chaijan, M., & Panpipat, W. (2017). Mechanism of oxidation in foods of animal origin. In Natural antioxidants (pp. 21–58). Apple Academic Press.

Chaijan, S., Panpipat, W., Panya, A., Cheong, L. Z., & Chaijan, M. (2020). Preservation of chilled Asian sea bass (Lates calcarifer) steak by whey protein isolate coating containing polyphenol extract from ginger, lemongrass, or green tea. Food Control, 118, Article 107400. https://doi.org/10.1016/j.foodcont.2020.107400

Chaillou, S., Chaulot-Talmon, A., Caekebeke, H., Cardinal, M., Christieans, S., Denis, C., et al. (2015). Origin and ecological selection of core and food-specific bacterial communities associated with meat and seafood spoilage. The ISME Journal, 9(5), 1105–1118.

Chakravarthy, J., & Edwards, T. A. (2022). Innovation from waste with biomass-derived chitin and chitosan as green and sustainable polymer: A review. Energy Nexus, 8, Article 100149. https://doi.org/10.1016/j.nexus.2022.100149

Chaparro-Hernandez, S., Ruiz-Cruz, S., Marquez-Rios, E., Ocano-Higuera, V. M., Valenzuela-Lopez, C. C., Ornelas-Paz, J. D. J., & Del-Toro-Sanchez, C. L. (2015). Effect of chitosan-carvacrol edible coatings on the quality and shelf life of tilapia (Oreochromis niloticus) fillets stored in ice. Food Science and Technology, 35, 734–741.

Char, C., Padilla, C., Campos, V., Pepczynska, M., Caldero´n, P. D., & Enrione, J. (2019). Characterization and testing of a novel sprayable crosslinked edible coating based on salmon gelatin. Coatings, 9(10), 595. https://doi.org/10.3390/coatings9100595

Chen, H., Wang, J., Cheng, Y., Wang, C., Liu, A., Bian, H., Pan, Y., Sun, J., & Han, W. (2019). Application of protein-based films and coatings for food packaging: A review. Polymers, 11(12), 2039. https://doi.org/10.3390/polym11122039

Cheng, H., Chen, L., McClements, D. J., Yang, T., Zhang, Z., Ren, F., … Jin, Z. (2021). Starch-based biodegradable packaging materials: A review of their preparation, characterization and diverse applications in the food industry. Trends in Food Science & Technology, 114, 70–82.

Chiang, M.-T., Yao, H.-T., & Chen, H.-C. (2000). Effect of dietary chitosans with different viscosity on plasma lipids and lipid peroxidation in rats fed on a diet enriched with cholesterol. Bioscience Biotechnology & Biochemistry, 64(5), 965–971. https://doi. org/10.1271/bbb.64.965

Chumsri, P., Panpipat, W., Cheong, L., Panya, A., Phonsatta, N., & Chaijan, M. (2022). Biopreservation of refrigerated mackerel (Auxis thazard) slices by Rice starch-based coating containing polyphenol extract from Glochidion wallichianum leaf. Foods, 11, 3441. https://doi.org/10.3390/foods11213441

Chung, Y.-C., Su, Y.-P., Chen, C.-C., Jia, G., Wang, H., Wu, J. C. G., et al. (2004). Relationship between antibacterial activity of chitosan and surface characteristics of cell wall. Acta Pharmacologica Sinica, 25(7), 932–936.

Do¨hler, N., Wellenreuther, C., & Wolf, A. (2022). Market dynamics of biodegradable bio- based plastics: Projections and linkages to European policies. EFB Bioeconomy Journal, 2, Article 100028.

Do¨rnyei, K. R., Uysal-Unalan, I., Krauter, V., Weinrich, R., Incarnato, L., Karlovits, I., … Corredig, M. (2023). Sustainable food packaging: An updated definition following a holistic approach. Frontiers in Sustainable Food Systems, 7, Article 1119052.

De Castro, R. J. S., Domingues, M. A. F., Ohara, A., Okuro, P. K., Dos Santos, J. G., Brex, R. P., & Sato, H. (2017). Whey protein as a key component in food systems: Physicochemical properties, production technologies and applications. Food Structure, 14, 17–29. https://doi.org/10.1016/j.foostr.2017.05.004

de Jong, S., Hoefnagels, R., Wetterlund, E., Pettersson, K., Faaij, A., & Junginger, M. (2017). Cost optimization of biofuel production–The impact of scale, integration, transport and supply chain configurations. Applied Energy, 195, 1055–1070.

De Silva, D. (2011). Value chain of fish and fishery products: Origin, functions and application in developed and developing country markets. Rome: FAO Value Chain Project Reports. FAO.

Devlieghere, F., Vermeulen, A., & Debevere, J. (2004). Chitosan: Antimicrobial activity, interactions with food components and applicability as a coating on fruit and vegetables. Food Microbiology, 21(6), 703–714. https://doi.org/10.1016/j. fm.2004.02.008

Di Pierro, P., Mariniello, L., Giosafatto, V. L., Esposito, M., Sabbah, M., & Porta, R. (2018). Dairy whey protein-based edible films and coatings for food preservation. In Food packaging and preservation (pp. 439–456). Amsterdam, The Netherlands: Elsevier.

Domínguez, R., Pateiro, M., Gagaoua, M., Barba, F. J., Zhang, W., & Lorenzo, J. M. (2019). A comprehensive review on lipid oxidation in meat and meat products. Antioxidants, 8(10), 429.

Donna, M., Henry, A. A., Laurie, H. M. C., Kathryn, R. M., Michael, M., Mineshi, S., & Alan, H. S. (2007). Methyl mercury exposure and health effects in humans: A worldwide concern. Ambio, 36, 1–11.

Duan, J., Cherian, G., & Zhao, Y. (2010). Quality enhancement in fresh and frozen lingcod (Ophiodon elongates) fillets by employment of fish oil incorporated chitosan coatings. Food Chemistry, 119(2), 524–532. https://doi.org/10.1016/j. foodchem.2009.06.055

Durmus, M. (2020). The effects of nanoemulsions based on citrus essential oils (orange, Mandarin, grapefruit, and lemon) on the shelf life of rainbow trout (Oncorhynchus mykiss) fillets at 4 2 C. Journal of Food Safety, 40(1), 1–10. https://doi.org/ 10.1111/jfs.12718

Dutta, P. K., Tripathi, S., Mehrotra, G. K., & Dutta, J. (2009). Perspectives for chitosan based antimicrobial films in food applications. Food Chemistry, 114(4), 1173–1182. https://doi.org/10.1016/j.foodchem.2008.11.047

Ebadi, Z., Khodanazary, A., Hosseini, S. M., & Zanguee, N. (2019). The shelf life extension of refrigerated Nemipterus japonicus fillets by chitosan coating incorporated with propolis extract. International Journal of Biological Macromolecules, 139, 94–102.

Echeverría, I., Lopez-Caballero, M. E., Gomez-Guillen, M. C., Mauri, A. N., & Montero, M. P. (2018). Active nanocomposite films based on soy proteins-montmorillonite- clove essential oil for the preservation of refrigerated bluefin tuna (Thunnus thynnus) fillets. International Journal of Food Microbiology, 266, 142–149. https://doi.org/10.1016/j.ijfoodmicro.2017.10.003

Ehsani, A., Hashemi, M., Afshari, A., Aminzare, M., Raeisi, M., & Zeinali, T. (2020). Effect of different types of active biodegradable films containing lactoperoxidase system or sage essential oil on the shelf life of fish burger during refrigerated storage. Lebensmittel-Wissenschaft und -Technologie, 117, Article 108633. https://doi.org/ 10.1016/j.lwt.2019.108633

El-Obeid, T., Yehia, H. M., Sakkas, H., Lambrianidi, L., Tsiraki, M. I., & Savvaidis, I. N. (2018). Shelf-life of smoked eel fillets treated with chitosan or thyme oil. International Journal of Biological Macromolecules, 114, 578–583. https://doi.org/ 10.1016/j.ijbiomac.2018.03.125

Emir Çoban, O¨ ., & Tuna Keles¸ temur, G. (2017). Qualitative improvement of catfish burger using Zataria multiflora Boiss. essential oil. Journal of Food Measurement and Characterization, 11, 530–537.

Engvang, K., & Nielsen, H. H. (2001). Proteolysis in fresh and cold-smoked salmon during cold storage: Effects of storage time and smoking process. Journal of Food Biochemistry, 25, 379–395.

Etxabide, A., Uranga, J., Guerrero, P., & De la Caba, K. (2017). Development of active gelatin films by means of valorisation of food processing waste: A review. Food Hydrocolloids, 68, 192–198.

European Commission. (2020). A new circular economy action plan for a cleaner and more competitive Europe (pp. 1–20). Brussels, Belgium: European Commission.

Fakhouri, F. M., Martelli, S. M., Caon, T., Velasco, J. I., & Mei, L. H. I. (2015). Edible films and coatings based on starch/gelatin: Film properties and effect of coatings on quality of refrigerated red crimson grapes. Postharvest Biology and Technology, 109, 57–64.

FAO. (2005). Post-harvest changes in fish. Retrieved September 25, 2020, from htt p://www.fao.org/fishery/topic/12320/en. (Accessed 18 October 2023).

FAO. (2011). Global food losses and food waste: Extent, causes, and prevention. Rome: FAO.

FAO. (2019). The state of food and agriculture. Moving forward on food loss and waste reduction. Rome: Food and Agriculture Organization.

Farajzadeh, F., Motamedzadegan, A., & Shahidi, S. A. (2016). The effect of chitosan- gelatin coating on the quality of shrimp (Litopenaeus vannamei) under refrigerated condition. Food Control, 67, 163–170. https://doi.org/10.1016/j. foodcont.2016.02.040

Farris, S., Unalan, I. U., Introzzi, L., Fuentes-Alventosa, J. M., & Cozzolino, C. A. (2014). Pullulan-based films and coatings for food packaging: Present applications, emerging opportunities, and future challenges. Journal of Applied Polymer Science, 131(13). https://doi.org/10.1002/app.40539

Farsanipour, A., Khodanazary, A., & Hosseini, S. M. (2020). Effect of chitosan-whey protein isolated coatings incorporated with tarragon Artemisia dracunculus essential oil on the quality of Scomberoides commersonnianus fillets at refrigerated condition. International Journal of Biological Macromolecules, 155, 766–771. https://doi.org/ 10.1016/j.ijbiomac.2020.03.228

FDA. (2005). US food and drugs administration. Center for Food Safety and Applied Nutrition. U.S. agency response letter GRAS notice no. GRN 170.

Febriana, I., Mashithah, E. D., & Pramono, H. (2021). Adding kaffir lime (citrus hystrix) leaf essential oil to gelatin coating for extending the shelf life of red snapper fillet. World Vet J, 11(4), 718–724. https://doi.org/10.54203/scil.2021.wvj91

Feng, X., Bansal, N., & Yang, H. (2016). Fish gelatin combined with chitosan coating inhibits myofibril degradation of golden pomfret (Trachinotus blochii) fillet during cold Storage. Food Chemistry, 200, 283–292. https://doi.org/10.1016/j. foodchem.2016.01.030

Feng, T., Du, Y., Li, J., Hu, Y., & Kennedy, J. F. (2008). Enhancement of antioxidant activity of chitosan by irradiation. Carbohydrate Polymers, 73(1), 126–132. https:// doi.org/10.1016/j.carbpol.2007.11.003

Fernandes, P. (2016). Enzymes in fish and seafood processing. Frontiers in Bioengineering and Biotechnology, 4. https://doi.org/10.3389/fbioe.2016.00059

Fernandes, L. M., Guimar˜aes, J. T., Pimentel, T. C., Esmerino, E. A., Freitas, M. Q., Carvalho, C. W. P., Cruz, A. G., & Silva, M. C. (2020). Edible whey protein films and coatings added with prebiotic ingredients. In Agri-food industry strategies for healthy diets and sustainability (pp. 177–193). Amsterdam, The Netherlands: Elsevier.

Fernandez-Saiz, P., Sanchez, G., Soler, C., Lagaron, J. M., & Ocio, M. J. (2013). Chitosan films for the microbiological preservation of refrigerated sole and hake fillets. Food Control, 34(1), 61–68. https://doi.org/10.1016/j.foodcont.2013.03.047

Fidalgo, L. G., Delgadillo, I., & Saraiva, J. A. (2020). Autolytic changes involving proteolytic enzymes on Atlantic salmon (Salmo salar) preserved by hyperbaric storage. Lebensmittel-Wissenschaft und -Technologie, 118, Article 108755. https://doi. org/10.1016/j.lwt.2019.108755

Firouz, M. S., Mohi-Alden, K., & Omid, M. (2021). A critical review on intelligent and active packaging in the food industry: Research and development. Food Research International, 141, Article 110113.

Florez, M., Guerra-Rodriguez, E., Cazon, P., & Vazquez, M. (2022). Chitosan for food packaging: Recent advances in active and intelligent films. Food Hydrocolloids, 124, Article 107328. https://doi.org/10.1016/j.foodhyd.2021.107328

Fraser, O., & Sumar, S. (1998). Compositional changes and spoilage in fish - an introduction. Nutrition & Food Science, 98(5), 275–279. https://doi.org/10.1108/ 00346659810224208

Friedly, E. C., Crandall, P. G., Ricke, S. C., Roman, M., O'Bryan, C., & Chalova, V. I. (2009). In vitro Antilisterial effects of citrus oil fractions in combination with organic acids. Journal of Food Science, 74(2), M67–M72. https://doi.org/10.1111/j.1750- 3841.2009.01056.x

Gagaoua, M., Bhattacharya, T., Lamri, M., Oz, F., Dib, A. L., Oz, E., … Tomasevic, I. (2021). Green coating polymers in meat preservation. Coatings, 11(11), 1379.

Galus, S., & Kadzin´ska, J. (2015). Food applications of emulsion-based edible films and coatings. Trends in Food Science & Technology, 45(2), 273–283.

Ganan, M., Carrascosa, A. V., & Martínez-Rodríguez, A. J. (2009). Antimicrobial activity of chitosan against Campylobacter spp. and other microorganisms and its mechanism of action. Journal of Food Protection, 72(8), 1735–1738. https://doi.org/ 10.4315/0362-028X-72.8.1735

Gautam, R. S., & Venugopal, V. (2021). Electron beam irradiation to control biohazards in seafood. Food Control, 130, Article 108320. https://doi.org/10.1016/j. foodcont.2021.108320

Goy, R. C., Britto, D. de, & Assis, O. B. G. (2009). A review of the antimicrobial activity of chitosan. Polímeros, 19(3), 241–247. https://doi.org/10.1590/S0104-14282009000300013

Gupta, B., Tummalapalli, M., Deopura, B. L., & Alam, M. S. (2014). Preparation and characterization of in-situ crosslinked pectin-gelatin hydrogels. Carbohydrate Polymers, 106, 312–318.

Hasanzati Rostami, A., Motallebi, A. A., Khanipour, A. A., Soltani, M., & Khanedan, N. (2010). Effect of whey protein coating on Physic-Chemical properties of gutted Kilka during frozen storage. Iranian Journal of Fisheries Sciences, 9, 412–421.

Hassoun, A., & Emir Çoban, O. (2017). Essential oils for antimicrobial and antioxidant applications in fish and other seafood products. Trends in Food Science & Technology, 68, 26–36. https://doi.org/10.1016/j.tifs.2017.07.016

Helander, I., Nurmiaho-Lassila, E.-L., Ahvenainen, R., Rhoades, J., & Roller, S. (2001). Chitosan disrupts the barrier properties of the outer membrane of Gram-negative bacteria. International Journal of Food Microbiology, 71(2–3), 235–244. https://doi. org/10.1016/S0168-1605(01)00609-2

Henriques, M., Gomes, D., & Pereira, C. (2016). Whey protein edible coatings: Recent developments and applications. In Emerging and traditional technologies for safe, healthy and quality food (pp. 177–196). Cham, Switzerland: Springer International Publishing, 978-3-319-24038-1.

Heu, M. S., Park, C. H., Kim, H. J., Lee, D. H., & Kim, S. J. (2010). Effects of a gelatin coating on the shelf life of salmon. Fisheries and Aquatic Sciences, 13(2), 89–95.

Heydari, R., Bavandi, S., & Javadian, S. R. (2015). Effect of sodium alginate coating enriched with horsemint (Mentha longifolia) essential oil on the quality of bighead carp fillets during storage at 4 C. Food Sciences and Nutrition, 3(3), 188–194. https:// doi.org/10.1002/fsn3.202

HLPE. (2014). Food losses and waste in the context of sustainable food systems. A report by the high level panel of experts on food security and nutrition of the committee. Rome: World Food Security.

Hosseini, S. F., Javidi, Z., & Rezaei, M. (2016). Efficient gas barrier properties of multi- layer films based on poly (lactic acid) and fish gelatin. International Journal of Biological Macromolecules, 92, 1205–1214.

Hosseini, S. F., Rezaei, M., Zandi, M., & Farahmand Ghavi, F. (2016). Effect of fish gelatin coating enriched with oregano essential oil on the quality of refrigerated rainbow trout fillet. Journal of Aquatic Food Product Technology, 25(6), 835–842.

Hu, Z., & Ganzle, M. G. (2019). Challenges and opportunities related to the use of chitosan as a food preservative. Journal of Applied Microbiology, 126(5), 1318–1331. https://doi.org/10.1111/jam.14131

Huang, T., Tu, Z.-c., Wang, H., Shangguan, X., Zhang, L., Zhang, N.-h., & Bansal, N. (2017). Pectin and enzyme complex modified fish scales gelatin: Rheological behavior, gel properties and nanostructure. Carbohydrate Polymers, 156, 294–302.

J¨aa¨skel¨ainen, E., Jakobsen, L. M., Hultman, J., Eggers, N., Bertram, H. C., & Bjo¨rkroth, J. (2019). Metabolomics and bacterial diversity of packaged yellowfin tuna (Thunnus albacares) and salmon (Salmo salar) show fish species-specific spoilage development during chilled storage. International Journal of Food Microbiology, 293, 44–52.

Jasour, M. S., Ehsani, A., Mehryar, L., & Naghibi, S. S. (2015). Chitosan coating incorporated with the lactoperoxidase system: An active edible coating for fish preservation. Journal of the Science of Food and Agriculture, 95(6), 1373–1378. https://doi.org/10.1002/jsfa.6838

Jayasena, D. D., & Jo, C. (2013). Essential oils as potential antimicrobial agents in meat and meat products: A review. Trends in Food Science & Technology, 34(2), 96–108. https://doi.org/10.1016/j.tifs.2013.09.002

Jeon, Y.-J., Kamil, J. Y. V. A., & Shahidi, F. (2002). Chitosan as an edible invisible film for quality preservation of herring and Atlantic cod. Journal of Agricultural and Food Chemistry, 50(18), 5167–5178. https://doi.org/10.1021/jf011693l

Jiang, X., Du, Z., Zhang, X., Zaman, F., Song, Z., Guan, Y., Yu, T., & Huang, Y. (2023). Gelatin-based anticancer drug delivery nanosystems: A mini review. Frontiers in Bioengineering and Biotechnology, 11, Article 1158749.

Jiang, M., Liu, S., Du, X., & Wang, Y. (2010). Physical properties and internal microstructures of films made from catfish skin gelatin and triacetin mixtures. Food Hydrocolloids, 24, 105–110. https://doi.org/10.1016/j.foodhyd.2009.08.011

Jiang, M., Liu, S., Du, X., & Wang, Y. (2011). Effects of antimicrobial coating from catfish skin gelatin on quality and shelf life of fresh white shrimp (Penaeus vannamei). Journal of Food Science, 76(3), M204–M209. https://doi.org/10.1111/j.1750- 3841.2011.02056.x

Kamil, J. Y. V. A., Jeon, Y.-J., & Shahidi, F. (2002). Antioxidative activity of chitosans of different viscosity in cooked comminuted flesh of herring (Clupea harengus). Food Chemistry, 79(1), 69–77. https://doi.org/10.1016/S0308-8146(02)00180-2

Kang, H. J., Kim, S. J., You, Y. S., Lacroix, M., & Han, J. (2013). Inhibitory effect of soy protein coating formulations on walnut (Juglans regia L.) kernels against lipid oxidation. LWT-Food Science & Technology, 51(1), 393–396.

Karaca, O. B., Oluk, C. A., Tas¸pinar, T., & Güven, M. (2019). New concept in packaging: Milk protein edible films. In Health and safety aspects of food processing technologies (pp. 537–565). Cham, Switzerland: Springer International Publishing.

Karoui, R., & Hassoun, A. (2017). Efficiency of rosemary and basil essential oils on the shelf-life extension of Atlantic mackerel (Scomber scombrus) fillets stored at 2◦C. Journal of AOAC International, 100(2), 335–344. https://doi.org/10.5740/ jaoacint.16-0410

Kearns, M. (2019). European frozen fish supplier introduces new compostable product packaging. Available online: https://www.seafoodsource.com/news/foodservice-re tail/european-frozen-fish-supplier-introduces-new-compostable-product-packaging. (Accessed 15 January 2024).

Khan, M. I., Adrees, M. N., Arshad, M. S., Anjum, F. M., Jo, C., & Sameen, A. (2015). Oxidative stability and quality characteristics of whey protein coated rohu (Labeo rohita) fillets. Lipids in Health and Disease, 14(58).

Khojah, S. M. (2020). Bio-based coating from fish gelatin, K-carrageenan and extract of pomegranate peels for maintaining the overall qualities of fish fillet. Journal of Aquatic Food Product Technology, 29, 810–822. https://doi.org/10.1080/ 10498850.2020.171826

Khwaldia, K., Perez, C., Banon, S., Desobry, S., & Hardy, J. (2004). Milk proteins for edible films and coatings. Critical Reviews in Food Science and Nutrition, 44(4), 239–251.

Koc, B., Akyuz, L., Cakmak, Y. S., Sargin, I., Salaberria, A. M., Labidi, J., … Kaya, M. (2020). Production and characterization of chitosan-fungal extract films. Food Bioscience, 35, Article 100545.

Kostaki, M., Giatrakou, V., Savvaidis, I. N., & Kontominas, M. G. (2009). Combined effect of MAP and thyme essential oil on the microbiological, chemical and sensory attributes of organically aquacultured sea bass (Dicentrarchus labrax) fillets. Food Microbiology, 26(5), 475–482. https://doi.org/10.1016/j.fm.2009.02.008

Kouhdasht, K. M., & Nasab, M. M. (2019). Shelf-life extension of whole shrimp using an active coating containing fish skin gelatin hydrolysates produced by a natural protease. Food Science and Nutrition, 8. https://doi.org/10.1002/fsn3.1293

Kulawik, P., & Dordevi´c, D. (2020). Sushi processing: Microbiological hazards and the use of emerging technologies. Critical Reviews in Food Science and Nutrition, 1270–1283. https://doi.org/10.1080/10408398.2020.1840332

Kulawik, P., Jamro´z, E., Zając, M., Guzik, P., & Tkaczewska, J. (2019). The effect of furcellaran-gelatin edible coatings with green and puerh tea extracts on the microbiological, physicochemical and sensory changes of salmon sushi stored at 4◦C. Food Control, 100, 83–91. https://doi.org/10.1016/j.foodcont.2019.01.004

Kumar, S., Mukherjee, A., & Dutta, J. (2020). Chitosan based nanocomposite films and coatings: Emerging antimicrobial food packaging alternatives. Trends in Food Science & Technology, 97, 196–209. https://doi.org/10.1016/j.tifs.2020.01.002

Kuuliala, L., Al Hage, Y., Ioannidis, A.-G., Sader, M., Kerckhof, F.-M., Vanderroost, M., et al. (2018). Microbiological, chemical and sensory spoilage analysis of raw Atlantic cod (Gadus morhua) stored under modified atmospheres. Food Microbiology, 70, 232–244. https://doi.org/10.1016/j.fm.2017.10.011

Lahreche, T., Durmus, M., Tümerkan, E. T. A., Hamdi, T. M., & O¨ zogul, F. (2020). Olive leaf extracts application for shelf life extension of vacuum packed frigate mackeral (Auxis thazard) fillets. Carpathian journal of food science and technology, 12(4), 70–83. https://doi.org/10.34302/crpjfst/2020.12.4.8

Li, T., Hu, W., Li, J., Zhang, X., Zhu, J., & Li, X. (2012). Coating effects of tea polyphenol and rosemary extract combined with chitosan on the storage quality of large yellow croaker (Pseudosciaena crocea). Food Control, 25(1), 101–106. https://doi.org/ 10.1016/j.foodcont.2011.10.029

Li, T., Sun, X., Chen, H., He, B., Mei, Y., Wang, D., et al. (2020). Effect of the combination of vanillin and chitosan coating on the microbial diversity and shelf-life of refrigerated turbot (Scophthalmus maximus) fillets. Frontiers in Microbiology, 11 (March), 1–10. https://doi.org/10.3389/fmicb.2020.00462

Li, X., Tu, Z., Sha, X., Li, Z., Li, J., & Huang, M. (2022). Effect of coating on flavor metabolism of fish under different storage temperatures. Food Chemistry:X, 13, Article 100256. https://doi.org/10.1016/j.fochx.2022.100256

Li, Y., Wu, C., Wu, T., Yuan, C., & Hu, Y. (2019). Antioxidant and antibacterial properties of coating with chitosan–citrus essential oil and effect on the quality of Pacific mackerel during chilled storage. Food Sciences and Nutrition, 7(3), 1131–1143. https://doi.org/10.1002/fsn3.958

Li, X. P., Zhou, M. Y., Liu, J. F., Xu, Y. X., Mi, H. B., Yi, S. M., Li, J. R., & Lin, H. (2016). Shelf-life extension of chilled olive flounder (Paralichthys olivaceus) using chitosan coatings containing clove oil. Journal of Food Processing and Preservation, 41(5), Article e13204. https://doi.org/10.1111/jfpp.13204

Li, J., Zhou, G., Xue, P., Dong, X., Xia, Y., Regenstein, J., Du, M., & Sun, L. (2021). Spoilage microbes' effect on freshness and IMP degradation in sturgeon fillets during chilled storage. Food Bioscience, 41, Article 101008. https://doi.org/10.1016/j. fbio.2021.101008

Liu, J., Shao, Y., Yuan, C., Takaki, K., Li, Y., Ying, Y., & Hu, Y. (2021). Eugenol-chitosan nanoemulsion as an edible coating: Its impact on physicochemical, microbiological and sensorial properties of hairtail (Trichiurus haumela) during storage at 4 ◦C. International Journal of Biological Macromolecules, 183, 2199–2204. https://doi.org/ 10.1016/j.ijbiomac.2021.05.183

Liu, W., Shen, Y., Li, N., Mei, J., & Xie, J. (2019). Application of gelatin incorporated with red pitaya peel methanol extract as edible coating for quality enhancement of crayfish (Procambarus clarkii) during refrigerated storage. Journal of Food Quality. , Article 1715946. https://doi.org/10.1155/2019/1715946

X., Zhang, Y., Li, D., & Luo, Y. (2017). Characterization of the microbiota in lightly salted bighead carp (Aristichthys nobilis) fillets stored at 4 C. Food Microbiology, 62, 106–111. https://doi.org/10.1016/j.fm.2016.10.007

Liu, X., Zhang, C., Liu, S., Gao, J., Cui, S. W., & Xia, W. (2020). Coating white shrimp (Litopenaeus vannamei) with edible fully deacetylated chitosan incorporated with clove essential oil and kojic acid improves

preservation during cold storage. International Journal of Biological Macromolecules, 162, 1276–1282. https://doi.org/ 10.1016/j.ijbiomac.2020.06.248

Lopez-Caballero, M. E., Gomez-Guillen, M. C., Perez-Mateos, M., & Montero, P. (2005). A chitosan–gelatin blend as a coating for fish patties. Food Hydrocolloids, 19, 303–311.

Losada, V., Barros-Vel´azquez, J., & Aubourg, S. P. (2007). Rancidity development in frozen pelagic fish: Influence of slurry ice as preliminary chilling treatment. LWT - Food Science and Technology, 40(6), 991–999. https://doi.org/10.1016/j. lwt.2006.05.011

Lu, Y., Luo, Q., Chu, Y., Tao, N., Deng, S., Wang, L., & Li, L. (2022). Application of gelatin in food packaging: A review. Polymers, 14(3), 436.

Møretrø, T., Moen, B., Heir Hansen, A., & Langsrud, S. (2016). Contamination of salmon fillets and processing plants with spoilage bacteria. International Journal of Food Microbiology, 237, 98–108. https://doi.org/10.1016/j.ijfoodmicro.2016.08.016

Ma, Z., Garrido-Maestu, A., & Jeong, K. C. (2017). Application, mode of action, and in vivo activity of chitosan and its micro- and nanoparticles as antimicrobial agents: A review. Carbohydrate Polymers, 176, 257–265. https://doi.org/10.1016/j. carbpol.2017.08.082

Mahmoud, B. S. M., Nannapaneni, R., Chang, S., Wu, Y., & Coker, R. (2016). Improving the safety and quality of raw tuna fillets by X-ray irradiation. Food Control, 60, 569–574. https://doi.org/10.1016/j.foodcont.2015.08.039

Manandhar, A., & Shah, A. (2020). Techno-economic analysis of bio-based lactic acid production utilizing corn grain as feedstock. Processes, 8(2), 199.

Maqsood, S., Benjakul, S., Abushelaibi, A., & Alam, A. (2014). Phenolic compounds and plant phenolic extracts as natural antioxidants in prevention of lipid oxidation in seafood: A detailed review. Comprehensive Reviews in Food Science and Food Safety, 13 (6), 1125–1140. https://doi.org/10.1111/1541-4337.12106

Masniyom, P., Benjama, O., & Maneesri, J. (2012). Effect of turmeric and lemongrass essential oils and their mixture on quality changes of refrigerated green mussel (Perna viridis). International Journal of Food Science and Technology, 47(5), 1079–1085. https://doi.org/10.1111/j.1365-2621.2012.02944.x

Mei, J., Ma, X., & Xie, J. (2019). Review on natural preservatives for extending fish shelf life. Foods, 8(10), 490. https://doi.org/10.3390/foods8100490

Mellinas, C., Vald´es, A., Ramos, M., Burgos, N., Garrigos, M. D. C., & Jim´enez, A. (2016). Active edible films: Current state and future trends. Journal of Applied Polymer Science, 133(2).

Mezhoudi, M., Salem, A., Abdelhedi, O., Fakhfakh, N., Mabrouk, M., Khorchani, T., Debeaufort, F., Jridi, M., & Zouar, N. (2022). Development of active edible coatings based on fish gelatin enriched with Moringa oleifera extract: Application in fish (Mustelus mustelus) fillet preservation. Food Science and Nutrition, 10(11), 3979–3992.

Milani, J. M., & Tirgarian, B. (2020). An overview of edible protein-based packaging: Main sources, advantages, drawbacks, recent progressions and food applications. Journal of Packaging Technology and Research, 4, 103–115.

Mohan, C. O., Ravishankar, C. N., Lalitha, K. V., & Srinivasa Gopal, T. K. (2012). Effect of chitosan edible coating on the quality of double filleted Indian oil sardine (Sardinella longiceps) during chilled storage. Food Hydrocolloids, 26(1), 167–174. https://doi. org/10.1016/j.foodhyd.2011.05.005

Mokrane, S., Buonocore, E., Capone, R., & Franzese, P. P. (2023). Exploring the global scientific literature on food waste and loss. Sustainability, 15(6), 4757.

Montero, M., & Acosta, O´ . G. (2020). Tuna skin gelatin production: Optimization of extraction steps and process scale-up. CyTA - Journal of Food, 18(1), 580–590.

Moradi, M., Tajik, H., Rohani, S. M. R., Oromiehie, A. R., Malekinejad, H., Aliakbarlu, J., & Hadian, M. (2012). Characterization of antioxidant chitosan film incorporated with Zataria multiflora Boiss essential oil and grape seed extract. LWT-Food Science & Technology, 46(2), 477–484.

Mukundan, M. K., Anthony, P. D., & Nair, M. R. (1986). A review on autolysis in fish. Fisheries Research, 4, 259–269. https://doi.org/10.1016/0165-7836(86)90007-X Muzzarelli, R. A. A., Jeuniaux, C., & Gooday, G. W. (1986). Chitin in nature and technology (Vol. 385). Springer.

Nair, M. S., Tomar, M., Punia, S., Kukula-Koch, W., & Kumar, M. (2020). Enhancing the functionality of chitosan- and alginate-based active edible coatings/films for the preservation of fruits and vegetables: A review. International Journal of Biological Macromolecules, 164, 304–320.

Nakazawa, N., Wada, R., Fukushima, H., Tanaka, R., Kono, S., & Okazaki, E. (2020). Effect of long-term storage, ultra-low temperature, and freshness on the quality characteristics of frozen tuna meat. International Journal of Refrigeration, 112, 270–280. https://doi.org/10.1016/j.ijrefrig.2019.12.012

Nanda, P. K., Das, A. K., Dandapat, P., Dhar, P., Bandyopadhyay, S., Dib, A. L., … Gagaoua, M. (2021). Nutritional aspects, flavour profile and health benefits of crab meat based novel food products and valorisation of processing waste to wealth: A review. Trends in Food Science & Technology, 112, 252–267.

Nawaz, T., Fatima, M., Shah, S. Z. H., & Afzal, M. (2020). Coating effect of rosemary extract combined with chitosan on storage quality of mori (Cirrhinus mrigala). Journal of Food Processing and Preservation, 44(10), Article e14833. https://doi.org/ 10.1111/jfpp.14833

Neetoo, H., Ye, M., & Chen, H. (2010). Bioactive alginate coatings to control Listeria monocytogenes oncold-smoked salmon slices and fillets. International Journal of Food Microbiology, 136(3), 326–331.

Nie, X., Zhang, R., Cheng, L., Zhu, W., Li, S., & Chen, X. (2022). Mechanisms underlying the deterioration of fish quality after harvest and methods of preservation. Food Control, 135. https://doi.org/10.1016/j.foodcont.2021.108805

Nisar, T., Yang, X., Alim, A., Iqbal, M., Wang, Z.-C., & Guo, Y. (2019). Physicochemical responses and microbiological changes of bream (Megalobrama ambycephala) to pectin-based coatings enriched with clove essential oil during refrigeration. International Journal of Biological Macromolecules, 124, 1156–1166. https://doi.org/ 10.1016/j.ijbiomac.2018.12.005

O'grady, M. N., Monahan, F. J., & Brunton, N. P. (2001). Oxymyoglobin oxidation and lipid oxidation in bovine muscle—mechanistic studies. JFS: Food Chemistry and Toxicology, 66(3), 386–392. https://doi.org/10.1111/j.1365-2621.2001.tb16115.x

Ojagh, S. M., Rezaei, M., Razavi, S. H., & Hosseini, S. M. H. (2010). Effect of chitosan coatings enriched with cinnamon oil on the quality of refrigerated rainbow trout. Food Chemistry, 120(1), 193–198. https://doi.org/10.1016/j.foodchem.2009.10.006

Olatunde, O. O., & Benjakul, S. (2018). Natural preservatives for extending the shelf-life of seafood: A revisit. Comprehensive Reviews in Food Science and Food Safety, 17(6), 1595–1612. https://doi.org/10.1111/1541-4337.12390

Ortiz-Zarama, M. A., Jim´enez-Aparicio, A. R., & Solorza-Feria, J. (2016). Obtainment and partial characterization of biodegradable gelatin films with tannic acid, bentonite and glycerol. Journal of the Science of Food and Agriculture, 96(10), 3424–3431.

Osheba, A., Sorour, M., & Abdou, S. (2013). Effect of chitosan nanoparticles as active coating on chemical quality and oil uptake of fish fingers. Journal of Agriculture and Environment Science, 2(1), 1–14.

Otoni, C. G., Espitia, P. J. P., Bustillos, R. J. A., & McHugh, T. H. (2016). Trends in antimicrobial food packaging systems: Emitting sachets and absorbent pads. Food Research International, 83, 60–73. https://doi.org/10.1016/j.foodres.2016.02.018

Ou, C. Y., Tsay, S. F., Lai, C. H., & Weng, Y. M. (2002). Using gelatin-based antimicrobial edible coating to prolong shelf-life of tilapia fillets. Journal of Food Quality, 25(3), 213–222.

Ozogul, F., & Ozogul, Y. (2006). Biogenic amine content and biogenic amine quality indices of sardines (Sardina pilchardus) stored in modified atmosphere packaging and vacuum packaging. Food Chemistry, 99(3), 574–578.

Ozogul, Y., Yuvka, ˙I., Ucar, Y., Durmus, M., Ko¨sker, A. R., Oz, M., et al. (2017). Evaluation of effects of nanoemulsion based on herb essential oils (rosemary, laurel, thyme and sage) on sensory, chemical and microbiological quality of rainbow trout (Oncorhynchus mykiss) fillets during ice storage. Lebensmittel-Wissenschaft und -Technologie, 75, 677–684. https://doi.org/10.1016/j.lwt.2016.10.009

Paarup, T., Sanchez, J. A., Pela´ez, C., & Moral, A. (2002). Sensory, chemical and bacteriological changes in vacuum-packed pressurised squid mantle (Todaropsis eblanae) stored at 4 ◦C. International Journal of Food Microbiology, 74, 1–12. https:// doi.org/10.1016/S0168-1605(01)00701-2

Pan, Z., Li, L., Shen, Z., Chen, Y., & Li, M. (2021). Effects of tea polyphenol treatments on the quality and microbiota of crisp grass carp fillets during storage at 4 C. Applied Sciences, 11(10), 4370. https://doi.org/10.3390/app11104370

Park, D. Y., Lee, S., Lee, J., Kim, E. J., Jo, Y., Kim, H., Choi, M., & Hong, G. (2021). Stepwise cooling mediated feasible supercooling preservation to extend freshness of mackerel fillets. Lebensmittel-Wissenschaft und -Technologie, 152, Article 112389. https://doi.org/10.1016/j.lwt.2021.112389

Parlapani, F. F., Mallouchos, A., Haroutounian, S. A., & Boziaris, I. S. (2014). Microbiological spoilage and investigation of volatile profile during storage of sea bream fillets under various conditions. International Journal of Food Microbiology, 189, 153–163. https://doi.org/10.1016/j.ijfoodmicro.2014.08.006

Pedreiro, S., Figueirinha, A., Silva, A. S., & Ramos, F. (2021). Bioactive edible films and coatings based in gums and starch: Phenolic enrichment and foods application. Coatings, 11(11), 1393.

Pei, J., Mei, J., Wu, G., Yu, H., & Xie, J. (2022). Gum tragacanth-sodium alginate active coatings containing epigallocatechin gallate reduce hydrogen peroxide content and inhibit lipid and protein oxidations of large yellow croaker (Larimichthys crocea) during superchilling storage. Food Chemistry, 397, Article 133792. https://doi.org/ 10.1016/j.foodchem.2022.133792

Perez-Gago, M. B., & Krochta, J. M. (2002). Formation and properties of whey protein films and coatings. In Protein-based films and coatings (pp. 159–180).

Punarvasu, T. P., & Prashanth, K. H. (2023). Acute and subacute in vivo safety assessment of developed chitosan derivatives for food applications. Food Hydrocolloids for Health, 4, 100145.

Qi, L., Xu, Z., Jiang, X., Hu, C., & Zou, X. (2004). Preparation and antibacterial activity of chitosan nanoparticles. Carbohydrate Research, 339(16), 2693–2700. https://doi. org/10.1016/j.carres.2004.09.007

Qin, Y., Li, P., & Guo, Z. (2020). Cationic chitosan derivatives as potential antifungals: A review of structural optimization and applications. Carbohydrate Polymers, 236, Article 116002.

Qiu, X., Chen, S., Liu, G., & Yang, Q. (2014). Quality enhancement in the Japanese sea bass (Lateolabrax japonicas) fillets stored at 4 C by chitosan coating incorporated with citric acid or licorice extract. Food Chemistry, 162, 156–160. https://doi.org/ 10.1016/j.foodchem.2014.04.037

Raafat, D., von Bargen, K., Haas, A., & Sahl, H.-G. (2008). Insights into the mode of action of chitosan as an antibacterial compound. Applied and Environmental Microbiology, 74(12), 3764–3773. https://doi.org/10.1128/AEM.00453-08

Racioppo, A., Speranza, B., Campaniello, D., Sinigaglia, M., Corbo, M. R., & Bevilacqua, A. (2021). Fish loss/waste and low-value fish challenges: State of art, advances, and perspectives. Foods, 10(11), 2725. https://doi.org/10.3390/ foods10112725

Raeisi, M., Hashemi, M., Aminzare, M., Bidkorpeh, F. G., Ebrahimi, M., Jannat, B., Tepe, B., & Noori, S. M. A. (2020). Effects of sodium alginate and chitosan coating combined with three different essential oils on microbial and chemical attributes of rainbow trout fillets. Journal of Aquatic Food Product Technology, 29, 253–563. https://doi.org/10.1080/10498850.2020.1722777

Ramezani, Z., Zarei, M., & Raminnejad, N. (2015). Comparing the effectiveness of chitosan and nanochitosan coatings on the quality of refrigerated silver carp fillets. Food Control, 51, 43–48. https://doi.org/10.1016/j.foodcont.2014.11.015

Ramos, O. L., Fernandes, J. C., Silva, S. I., Pintado, M. E., & Malcata, F. X. (2012). Edible films and coatings from whey proteins: A review on formulation, and on mechanical and bioactive properties. Critical Reviews in Food Science and Nutrition, 52(6), 533–552.

Reddy, M. B., Barka, E. A., Castaigne, F., & Arul, J. (1997). Effect of chitosan on growth and toxin production by Alternaria alternata f. sp. lycopersici. HortScience, 32(3), 467F–468F. https://doi.org/10.21273/HORTSCI.32.3.467F

Remya, S., Sivaraman, G. K., Joseph, T. C., Parmar, E., Sreelakshmi, K. R., Mohan, C. O., & Ravishankar, C. N. (2022). Influence of corn starch based bio-active edible coating containing fumaric acid on the lipid quality and microbial shelf life of silver pomfret fish steaks stored at 4◦ C. Journal of Food Science and Technology, 1–12. https://doi.org/10.1007/s13197-021-05322-y

Rezaeifar, M., Mehdizadeh, T., Mojaddar Langroodi, A., & Rezaei, F. (2020). Effect of chitosan edible coating enriched with lemon verbena extract and essential oil on the shelf life of vacuum rainbow trout (Oncorhynchus mykiss). Journal of Food Safety, 40 (3), Article e12781. https://doi.org/10.1111/jfs.12781

Robertson, G. L. (2016). Food packaging: Principles and practice. Boca Raton, Florida: CRC press.

Rodriguez-Garcia, I., Silva-Espinoza, B. A., Ortega-Ramirez, L. A., Leyva, J. M., Siddiqui, M. W., Cruz-Valenzuela, M. R., et al. (2016). Oregano essential oil as an antimicrobial and antioxidant additive in food products. Critical Reviews in Food Science and Nutrition, 56(10), 1717–1727. https://doi.org/10.1080/10408398.2013.800832

Rodriguez-Turienzo, L., Cobos, A., & Diaz, O. (2013). Effects of microbial transglutaminase added edible coatings based on heated or ultrasound-treated whey proteins in physical and chemical parameters of frozen Atlantic salmon (Salmo salar. Journal of Food Engineering, 119(3), 433–438.

Rodriguez-Turienzo, L., Cobos, A., Moreno, V., Caride, A., Vieites, J. M., & Diaz, O. (2011). Whey protein-based coatings on frozen Atlantic salmon (Salmo salar): Influence of the plasticiser and the moment of coating on quality preservation. Food Chemistry, 128(1), 187–194.

Rudi, K., Maugesten, T., Hannevik, S. E., & Nissen, H. (2004). Explorative multivariate analyses of 16S rRNA gene data from microbial communities in modified- atmosphere-packed salmon and coalfish. Applied and Environmental Microbiology, 70 (8), 5010–5018. https://doi.org/10.1128/AEM.70.8.5010-5018.2004

Sabu, S., Ashita, T., & Stephy, S. (2020). Chitosan and lemon peel extract coating on quality and shelf life of yellowfin tuna (Thunnus albacares) meat stored under refrigerated condition. Indian Journal of Fisheries, 67(1), 114–122.

Sahari, M. A., Farahani, F., Soleimanian, Y., & Javadi, A. (2014). Effect of frozen storage on fatty acid composition of the different tissues of four scombrid and one dussumeriid species. Journal of Applied Ichthyology, 1–11.

Sapper, M., & Chiralt, A. (2018). Starch-based coatings for preservation of fruits and vegetables. Coatings. https://doi.org/10.3390/coatings8050152

Schmid, M., & Müller, K. (2019). Whey protein-based packaging films and coatings. In Whey proteins (pp. 407–437). Academic Press.

Schrieber, R., & Gareis, H. (2007). Gelatine handbook: Theory and industrial practice. Weinheim, Germany: John Wiley & Sons.

Shahidi, F., Kamil, J., Jeon, Y., & Kim, S. (2002). Antioxidant role of chitosan in a cooked cod (Gadus morhua) model system. Journal of Food Lipids, 9(1), 57–64. https://doi. org/10.1111/j.1745-4522.2002.tb00208.x

Sheikha, A. F. E., Allam, A. Y., Oz, E., Khan, M. R., Proestos, C., & Oz, F. (2022). Edible xanthan/propolis coating and its effect on physicochemical, microbial, and sensory quality indices in mackerel tuna (euthynnus affinis) fillets during chilled storage. Gels, 8(7), 405. https://doi.org/10.3390/gels8070405

Shokri, S., Ehsani, A., & Jasour, M. S. (2015). Efficacy of lactoperoxidase system-whey protein coating onshelf-life extension of rainbow trout fillets during cold storage (4◦C). Food and Bioprocess Technology, 8(1), 54–62.

Silbande, A., Adenet, S., Smith-Ravin, J., Joffraud, J. J., Rochefort, K., & Leroi, F. (2016). Quality assessment of ice-stored tropical yellowfin tuna (Thunnus albacares) and influence of vacuum and modified atmosphere packaging. Food Microbiology, 60, 62–72.

Singh, A., Benjakul, S., Zhou, P., Zhang, B., & Deng, S. (2021). Effect of squid pen chitooligosaccharide and epigallocatechin gallate on discoloration and shelf-life of yellowfin tuna slices during refrigerated storage. Food Chemistry, 351, Article 129296. https://doi.org/10.1016/j.foodchem.2021.129296

Skovsgaard, L., & Jacobsen, H. K. (2017). Economies of scale in biogas production and the significance of flexible regulation. Energy Policy, 101, 77–89.

Soares, N. M. F., Oliveira, M. S. G., & Vicente, A. A. (2015). Effects of glazing and chitosan-based coating application on frozen salmon preservation during six-month storage in industrial freezing chambers. LWT - Food Science and Technology, 61(2), 524–531. https://doi.org/10.1016/j.lwt.2014.12.009

Song, Y., Liu, L., Shen, H., You, J., & Luo, Y. (2011). Effect of sodium alginate-based edible coating containing different anti-oxidants on quality and shelf life of refrigerated bream (Megalobrama amblycephala). Food Control, 22, 608–615. https://doi.org/10.1016/j.foodcont.2010.10.012

Srinivasan, T., & Saranraj, P. (2017). Isolation and identification of spoilage causing microorganisms in an Indian mackerel fish (Rastrelliger kanagurta). International Journal of Advanced Research in Biological Sciences, 4(7), 1–7. https://doi.org/ 10.22192/ijarbs.2017.04.07.001

Stuchell, Y. M., & Krochta, J. M. (1995). Edible coatings on frozen king salmon: Effect of whey protein isolate and acetylated monoglycerides on moisture loss and lipid oxidation. Journal of Food Science, 60(1), 28–31.

Suhag, R., Kumar, N., Petkoska, A. T., & Upadhyay, A. (2020). Film formation and deposition methods of edible coating on food products: A review. Food Research International, 136, Article 109582. https://doi.org/10.1016/j.foodres.2020.109582

Sun, X., Guo, X., Ji, M., Wu, J., Zhu, W., Wang, J., Cheng, C., Chen, L., & Zhang, Q. (2018). Preservative effects of fish gelatin coating enriched with CUR/βCD emulsion on grass carp (Ctenopharyngodon idellus) fillets during storage at 4 ◦C. Food Chemistry, 30, 643–652. https://doi.org/10.1016/j.foodchem.2018.08.040

Syafiq, R., Sapuan, S. M., Zuhri, M. Y. M., Ilyas, R. A., Nazrin, A., Sherwani, S. F. K., & Khalina, A. (2020). Antimicrobial activities of starch-based biopolymers and biocomposites incorporated with plant essential oils: A review. Polymers, 12(10), 2403.

Symons, J. (2022). Environmental & economic implications of biobased packaging. Available on line : https://content.vu.edu.au/sites/default/files/environmental-an d-economic-implications-of-biobased-packaging.pdf. (Accessed 15 January 2024).

Talo´n, E., Trifkovic, K. T., Nedovic, V. A., Bugarski, B. M., Vargas, M., Chiralt, A., & Gonza´lez-Martínez, C. (2017). Antioxidant edible films based on chitosan and starch containing polyphenols from thyme extracts. Carbohydrate Polymers, 157, 1153–1161.

Tanha, L. D., Khoshkhoo, Z., & Azizi, M. H. (2021). Application of edible coating made of sturgeon gelatin and Portulaca oleracea extract for improving the shelf life of fish sausages. Journal of Food Measurement and Characterization, 15, 4306–4313. https:// doi.org/10.1007/s11694-021-01013-6

Tavares, J., Martins, A., Fidalgo, L. G., Lima, V., Amaral, R. A., Pinto, C. A., … Saraiva, J. A. (2021). Fresh fish degradation and advances in preservation using physical emerging technologies. Foods, 10(4), 780. https://doi.org/10.3390/ foods10040780

Tavassoli-Kafrani, E., Shekarchizadeh, H., & Masoudpour-Behabadi, M. (2016). Development of edible films and coatings from alginates and carrageenans. Carbohydrate Polymers, 137, 360–374.

Tayel, A. A., Moussa, S., El-Tras, W. F., Knittel, D., Opwis, K., & Schollmeyer, E. (2010). Anticandidal action of fungal chitosan against Candida albicans. International Journal of Biological Macromolecules, 47(4), 454–457. https://doi.org/10.1016/j. ijbiomac.2010.06.011

Thiansilakul, Y., Benjakul, S., & Richards, M. P. (2011). The effect of different atmospheric conditions on the changes in myoglobin and colour of refrigerated Eastern little tuna (Euthynnus affinis) muscle. Journal of the Science of Food and Agriculture, 91(6), 1103–1110.

Tkaczewska, J., Jamro´z, E., Kasprzak, M., Zając, M., Pająk, P., Grzebieniarz, W., … Juszczak, L. (2023). Edible coatings based on a Furcellaran and gelatin extract with herb addition as an active packaging for carp fillets. Food and Bioprocess Technology, 16(5), 1009–1021.

Tongnuanchan, P., & Benjakul, S. (2014). Essential oils: Extraction, bioactivities, and their uses for food preservation. Journal of Food Science, 79(7), R1231–R1249. https://doi.org/10.1111/1750-3841.12492

Trigo, M., Nozal, P., Miranda, J. M., Aubourg, S. P., & Velazquez, J. B. (2022). Antimicrobial and antioxidant effect of lyophilized Fucus spiralis addition on gelatin film during refrigerated storage of mackerel. Food Control, 131, Article 108416. https://doi.org/10.1016/j.foodcont.2021.108416

Trombetta, D., Castelli, F., Sarpietro, M. G., Venuti, V., Cristani, M., Daniele, C., et al. (2005). Mechanisms of antibacterial action of three monoterpenes. Antimicrobial Agents and Chemotherapy, 49(6), 2474–2478. https://doi.org/10.1128/ AAC.49.6.2474-2478.2005

Tsironi, T., Gogou, E., Velliou, E., & Taoukis, P. S. (2008). Application and validation of the TTI based chill chain management system SMAS (Safety Monitoring and Assurance System) on shelf life optimization of vacuum-packed chilled tuna. International Journal of Food Microbiology, 128(1), 108–115.

Unalan, I˙. U., Arcan, I., Korel, F., & Yemeniciog˘lu, A. (2013). Application of active zein- based films with controlled release properties to control Listeria monocytogenes growth and lipid oxidation in fresh Kashar cheese. Innovative Food Science & Emerging Technologies, 20, 208–214.

Unalan, I˙. U., Korel, F., & Yemeniciog˘lu, A. (2011). Active packaging of ground beef patties by edible zein films incorporated with partially purified lysozyme and Na2EDTA. International Journal of Food Science and Technology, 46(6), 1289–1295.

Vala, M., Augusto, A., Horta, A., Mendes, S., & Gil, M. M. (2017). Effect of tuna skin gelatin-based coating enriched with seaweed extracts on the quality of tuna fillets during storage at 4 C. International Journal of Food Studies, 6(2), 201–221.

Venugopal, V., & Sasidharan, A. (2021). Seafood industry effluents: Environmental hazards, treatment and resource recovery. Environmental Chemical Engineering, 9(2). https://doi.org/10.1016/j.jece.2020.104758

Vieira, B. B., Mafra, J. F., da Rocha Bispo, A. S., Ferreira, M. A., de Lima Silva, F., Rodrigues, A. V. N., & Evangelista-Barreto, N. S. (2019). Combination of chitosan coating and clove essential oil reduces lipid oxidation and microbial growth in frozen stored tambaqui (Colossoma macropomum) fillets. Lebensmittel-Wissenschaft und -Technologie, 116, Article 108546. https://doi.org/10.1016/j.lwt.2019.108546

Vinsova, J., & Vavrikova, E. (2011). Chitosan derivatives with antimicrobial, antitumour and antioxidant activities - a Review. Current Pharmaceutical Design, 17(32), 3596–3607. https://doi.org/10.2174/138161211798194468

Wang, H., Ding, F., Ma, L., & Zhang, Y. (2021). Edible films from chitosan-gelatin: Physical properties and food packaging application. Food Bioscience, 40, Article 100871. https://doi.org/10.1016/j.fbio.2020.100871

Wang, C., Killpatrick, A., Humphrey, A., & Guo, M. (2019). Whey protein functional properties and applications in food formulation. In Whey protein production, chemistry, functionality, and applications (pp. 157–204). Chichester, UK: John Wiley & Sons, Ltd., 9781119256052.

Wang, H., Liao, Y., Wu, A., Li, B., Qian, J., & Ding, F. (2019). Effect of sodium trimetaphosphate on chitosan-methylcellulose composite films: Physicochemical properties and food packaging application. Polymers, 11(2), 368.

Wang, Y., Liu, L., Zhou, J., Ruan, X., Lin, J., & Fu, L. (2015). Effect of chitosan nanoparticle coatings on the quality changes of postharvest white leg shrimp, Litopenaeus vannamei, during storage at 4◦C. Food and Bioprocess Technology, 8(4), 907–915. https://doi.org/10.1007/s11947-014-1458-8

Wei, P., Cao, J., Shen, X., & Li, C. (2019). The preservation effect and mechanism of gelatin on golden pompano (Trachinotus blochii) fillets during cold storage. Food Sci. Technol, Campinas, 39(2), 626–631. https://doi.org/10.1590/fst.28718

Wong, L. W., Loke, X. J., Chang, C. K., Ko, W. C., Hou, C. Y., & Hsieh, C. W. (2020). Use of the plasma-treated and chitosan/gallic acid-coated polyethylene film for the preservation of tilapia (Orechromis niloticus) fillets. Food Chemistry, 329, Article 126989. https://doi.org/10.1016/j.foodchem.2020.126989

Wongwichian, C., Klomklao, S., Panpipat, W., Benjakul, S., & Chaijan, M. (2015). Interrelationship between myoglobin and lipid oxidations in oxeye scad (Selar boops) muscle during iced storage. Food Chemistry, 174, 279–285. https://doi.org/ 10.1016/j.foodchem.2014.11.071

Wu, C., Fu, S., Xiang, Y., Yuan, C., Hu, Y., Chen, S., … Ye, X. (2016). Effect of Chitosan Gallate coating on the quality maintenance of refrigerated (4 C) silver pomfret (Pampus argentus). Food and Bioprocess Technology, 9, 1835–1843.

Wu, T., Ge, Y., Li, Y., Xiang, Y., Jiang, Y., & Hu, Y. (2018). Quality enhancement of large yellow croaker treated with edible coatings based on chitosan and lysozyme. International Journal of Biological Macromolecules, 120, 1072–1079. https://doi.org/ 10.1016/j.ijbiomac.2018.08.188

Wu, C., Li, Y., Wang, L., Hu, Y., Chen, J., Liu, D., et al. (2016). Efficacy of chitosan-gallic acid coating on shelf life extension of refrigerated pacific mackerel fillets. Food and Bioprocess Technology, 9(4), 675–685. https://doi.org/10.1007/s11947-015-1659-9

Xiong, Y., Kambo, M., Ajlouni, S., & Fang, Z. (2021). Incorporation of salmon bone gelatine with chitosan, gallic acid and clove oil as edible coating for the cold storage of fresh salmon fillet. Food Control, 125, Article 107994. https://doi.org/10.1016/j. foodcont.2021.107994

Xu, F., Yan, Y., Yong, H., Yun, D., Chen, D., & Liu, J. (2022). Comparison of the physical and functional properties of food packaging films containing starch and polyphenols from different varieties of wolfberry. Journal of Food Measurement and Characterization, 16(6), 4444–4456.

Yadav, J. S. S., Yan, S., Pilli, S., Kumar, L., Tyagi, R. D., & Surampalli, R. Y. (2015). Cheese whey: A potential resource to transform into bioprotein, functional/ nutritional proteins and bioactive peptides. Biotechnology Advances, 33(6), 756–774.

Yen, M.-T., Yang, J.-H., & Mau, J.-L. (2008). Antioxidant properties of chitosan from crab shells. Carbohydrate Polymers, 74(4), 840–844.

Yildiz, P. O., & Yangilar, F. (2016). Effects of different whey protein concentrate coating on selectedproperties of rainbow trout (Oncorhynchus mykiss) during cold storage (4◦C). International Journal of Food Properties, 19(9), 2007–2015.

Younes, I., Sellimi, S., Rinaudo, M., Jellouli, K., & Nasri, M. (2014). Influence of acetylation degree and molecular weight of homogeneous chitosans on antibacterial and antifungal activities. International Journal of Food Microbiology, 185, 57–63. https://doi.org/10.1016/j.ijfoodmicro.2014.04.029

Yu, D., Jiang, Q., Xu, Y., & Xia, W. (2017). The shelf life extension of refrigerated grass carp (Ctenopharyngodon idellus) fillets by chitosan coating combined with glycerol monolaurate. International Journal of Biological Macromolecules, 101, 448–454. https://doi.org/10.1016/j.ijbiomac.2017.03.038

Yu, D., Li, P., Xu, Y., Jiang, Q., & Xia, W. (2017). Physicochemical, microbiological, and sensory attributes of chitosan-coated grass carp (Ctenopharyngodon idellus) fillets stored at 4 C. International Journal of Food Properties, 20(2), 390–401. https://doi. org/10.1080/10942912.2016.1163267

Yuan, G., Lv, H., Tang, W., Zhang, X., & Sun, H. (2016). Effect of chitosan coating combined with pomegranate peel extract on the quality of Pacific white shrimp during iced storage. Food Control, 59, 818–823. https://doi.org/10.1016/j. foodcont.2015.07.011

Zanetti, M., Ternus, Z., Dalcanton, F., De Mello, M. M. J., De Oliveira, D., Araujo, P. H. H., et al. (2015). Microbiological characterization of pure geraniol and comparison with bactericidal activity of the cinnamic acid in gram-positive and gram-negative bacteria. Journal of Microbial & Biochemical Technology, 7(4), 186–193.

Zhao, X., Chen, L., Wongmaneepratip, W., He, Y., Zhao, L., & Yang, H. (2021). Effect of vacuum impregnated fish gelatin and grape seed extract on moisture state, microbiota composition, and quality of chilled seabass fillets. Food Chemistry, 354, Article 129581. https://doi.org/10.1016/j.foodchem.2021.129581

Zhao, Y., Li, Z., Yang, W., Xue, C., Wang, Y., Dong, J., & Xue, Y. (2016). Modification of gelatine with galla chinensis extract, a natural crosslinker. International Journal of Food Properties, 19(4), 731–744. https://doi.org/10.1080/10942912.2015.1013633

Zhao, X., Zhou, Y., Zhao, L., Chen, L., He, Y., & Yang, H. (2019). Vacuum impregnation of fish gelatin combined with grape seed extract inhibits protein oxidation and degradation of chilled tilapia fillets. Food Chemistry, 294, 316–325. https://doi.org/ 10.1016/j.foodchem.2019.05.054