A Review of Essential Oils in Edible Films and Coatings for Seafood Preservation: Functional Roles, Safety, and Regulatory Considerations

Karthikeyan Venkatachalam[1], Narin Charoenphun[2,*],
Sutee Wangtueai[3,4], Wiyada Kwanhian Klangbud[5], Kitisart Kraboun[6],
Sayomphoo Hanpakdeesakul[7] and Jittimon Wongsa[8,9]

[1]Faculty of Innovative Agriculture, Fisheries and Food, Prince of Songkla University, Surat Thani Campus, Surat Thani 84000, Thailand

[2]Faculty of Science and Arts, Burapha University Chanthaburi Campus, Chanthaburi 22160, Thailand

[3]School of Agro-Industry, Faculty of Agro-Industry, Chiang Mai University, Chiang Mai 50100, Thailand

[4]Cluster of Innovation for Sustainable Seafood Industry and Value Chain Management, Chiang Mai University, Chiang Mai, 50200, Thailand.

[5]Medical Technology program, Faculty of Science, Nakhon Phanom University, Nakhon Phanom 48000, Thailand

[6]Division of Food Safety Management and Technology, Faculty of Science and Technology, Rajamangala University of Technology Krugthep, Bangkok 10120, Thailand

[7]Faculty of Gems, Burapha University Chanthaburi Campus, Chanthaburi 22170, Thailand

[8]Faculty of Industrial Technology and Management, King Mongkut's University of Technology North Bangkok (Prachinburi Campus), Prachinburi 25230, Thailand

[9]Food and Agro-Industry Research Center, King Mongkut's University of Technology North Bangkok, Bangkok 10800, Thailand

(*Corresponding author's e-mail: narinch@buu.ac.th; narinch@go.buu.ac.th)

Abstract

Seafood deteriorates rapidly after harvest, leading to significant economic losses and driving the need for advanced, natural preservation strategies. This review explores the incorporation of essential oils (EOs) into edible films and coatings (EFCs) for seafood applications, focusing on their functional roles, antimicrobial efficacy, and regulatory considerations. Biopolymers such as chitosan, gelatin, soy protein isolate, and starch are evaluated as carriers for EOs including clove, cinnamon, oregano, garlic, and pomelo. These systems exhibit potent antimicrobial and antioxidant activities against spoilage microorganisms such as *Pseudomonas* spp., *Listeria monocytogenes*, and *Shewanella* spp. Specific formulations, such as chitosan-gelatin films with 1% clove oil, successfully extended the shelf life of shrimp and salmon by inhibiting microbial growth and oxidative degradation. The review also compares EO concentrations (0.3-2%) relative to their minimal inhibitory concentrations (MICs), discusses performance variations among EFC types, and addresses challenges like EO volatility and sensory alterations. Regulatory frameworks in the EU and USA, including GRAS designation and migration limits, are critically reviewed. Overall, EO-enriched EFCs represent a sustainable and commercially promising alternative to synthetic preservatives, aligning with the global demand for cleaner and greener food packaging solutions.

Keywords: Essential oil, Edible films, Coatings, Fish and seafood, Antimicrobial activities, Antioxidant activities, Nanoemulsion, Food packaging regulations

Abbreviations

ADI	Acceptable daily intake
ADP	Adenosine diphosphate
AMP	Adenosine monophosphate
ATP	Adenosine triphosphate
CFR	Code of Federal Regulations
DHA	Docosahexaenoic acid
DMPT	Dimethyl-β-propiothetine
DMS	Dimethyl sulfide
EFCs	Edible films and coatings
EOs	Essential oils
EPA	Eicosapentaenoic acid
FDA	Food and Drug Administration
GRAS	Generally recognized as safe
IMP	Inosine monophosphate
MIC	Minimal inhibitory concentrations
PPO	Polyphenol oxidase
PUFA	Polyunsaturated fatty acid
SFA	Saturated fatty acid
STEC	Shiga toxin-producing *Escherichia coli*
TMA	Trimethylamine
TMAO	Trimethylamine oxide

Introduction

EOs are volatile, aromatic compounds extracted from various plant parts, including flowers, leaves, fruits, bark, seeds, and roots [1]. They are composed of complex mixtures of bioactive compounds, primarily terpenes (monoterpenes, sesquiterpenes, and their oxygenated derivatives) and phenylpropanoids [2]. Additional components such as alcohols, esters, aldehydes, phenols, ketones, and acids contribute to their unique functionalities [3]. Terpenes, including pinene, limonene, and myrcene, are simple hydrocarbons, while terpenoids represent oxygenated forms, offering enhanced antimicrobial and physiological activities. Specific terpenes such as carvacrol, eugenol, and thymol have demonstrated antibacterial effects by disrupting cellular functions and inhibiting protein and DNA synthesis, making EOs valuable in addressing antibiotic-resistant bacteria [2-4]. Fish and seafood are critical sources of nutrition, providing essential proteins, omega-3 fatty acids, and micronutrients [5]. However, they are highly perishable, with spoilage driven by enzymatic reactions, oxidative processes, and microbial activity. Upon death, aquatic animals undergo biochemical and physical changes such as internal tissue digestion by gastric juices, discoloration, swelling, and softening, which accelerate microbial growth and quality degradation [6,7]. These rapid deteriorative processes cause substantial economic losses and emphasize the need for effective preservation strategies beyond traditional methods. EFCs have emerged as innovative solutions to enhance food preservation while addressing environmental concerns. EFCs are composed of biopolymers like proteins, polysaccharides, and lipids, offering biodegradable alternatives to petroleum-based packaging [8]. They act as physical barriers against environmental factors and, when infused with EOs, enhance functionality by inhibiting microbial growth and lipid oxidation. Several studies have demonstrated the efficacy of EO-enriched coatings in preserving seafood. For example, EOs combined with bacteriocins effectively suppressed *Listeria monocytogenes* in ready-to-eat seafood products [9]. EO-based vacuum packaging extended the freshness of rainbow trout [10], and chitosan coatings enriched with EOs preserved shrimp and tambaqui fillets under cold or frozen storage conditions [11,12]. This review aims to compile and present current

knowledge on the application of EOs in EFCs for seafood preservation. It focuses on the functional roles of different EOs, the performance of various biopolymer matrices, antimicrobial and antioxidant mechanisms, and relevant regulatory considerations. Challenges such as off-flavor formation, EO volatility, and regulatory constraints are also discussed, providing insights for future research and broader commercial applications.

Spoilage mechanisms in seafood and relevance to edible coating application

Lipid oxidation

Lipid oxidation, the primary cause of rancidity in fatty foods, severely impacts seafood quality, leading to undesirable odors, flavors, and nutritional losses. This chemical reaction occurs between oxygen and unsaturated fatty acids, generating unstable fatty acid hydroperoxides. These hydroperoxides decompose into volatile compounds, directly causing rancidity [13]. Several factors influence lipid oxidation, including the type of fatty acids, free fatty acid content, oxygen levels, temperature, water activity, the presence of minerals or metals, antioxidants, light exposure, and radiation [14]. Foods rich in unsaturated fats are particularly susceptible, as oxidation not only causes rancidity but also reduces nutritional quality by degrading essential components such as polyunsaturated fatty acids (PUFA). Building upon this understanding of lipid oxidation, it is important to note the unique composition of fish fats compared to mammalian fats. Fish fats are richer in long-chain fatty acids (14-22 carbon atoms) with 5 or 6 double bonds, making them highly unsaturated [16-17]. In contrast, mammalian fats typically consist of fatty acids with up to 2 double bonds. Essential fatty acids like eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are abundant in fish oil and are crucial for human nutrition. The rate of lipid oxidation varies among anatomical regions of fish. For example, studies on herring have shown that the head region experiences the highest oxidation rates, while internal organs and the abdominal wall oxidize more slowly [18]. This variability is primarily influenced by hemoglobin levels, lipoxygenase activity, and α-tocopherol concentration rather than total lipid or PUFA content. In addition to anatomical factors, processing methods can further accelerate oxidation. For instance, hot air drying of shrimp progressively increases lipid oxidation, leading to the formation of compounds such as 4-hydroxynonenal, a toxic by-product of fatty acid oxidation [19]. Extended drying times exacerbate this effect by promoting free radical formation and accelerating PUFA degradation. Addressing lipid oxidation is critical for maintaining seafood's sensory quality, nutritional value, and shelf life. **Table 1** summarizes the lipid and fatty acid composition across various seafood species, highlighting their vulnerability to oxidative deterioration.

Table 1 Example of lipid and fatty acid composition of fish and seafood.

Lipid and fatty acid	Seawater fish species (*Sparus auratus*) [5]	Freshwater fish species (*Clarias gariepinus*) [5]	Oyster (*Crassostrea lugubris*) [13]	Crab (*Eriphia verrucosa*) [15]	Squid (*Loligo edulis*) [20]	Shrimp (*Plesionica edwardsi*) [21]
Lipid content (g/100g)	12.4	3.21	2.54	1.11	3.50	2.46
Saturated fatty acid (SFA) (%)	25.5	29.8	35.82	25.0	17.69	29.58
MUFA (%)	28.0	22.7	17.60	21.0	1.65	38.89
PUFA (%)	34.5	23.2	43.08	46.1	38.71	31.53
PUFA/SFA	1.35	0.78	1.20	1.84	2.19	1.07
DHA/EPA	2.56	3.2	0.64	0.56	3.87	1.57

Proteolytic changes

Proteolytic activity is one of the major factors driving the spoilage of fish and seafood, leading to texture softening, loss of structural integrity, and the development of undesirable odors and flavors. This process involves the enzymatic breakdown of proteins and nitrogenous compounds, both from endogenous and microbial sources. Factors such as processing methods, salting procedures, marination, and brine composition significantly influence the extent of proteolytic changes. After harvest, post-mortem reactions in seafood muscle tissues result in the degradation of proteins and non-protein nitrogen compounds, causing notable changes in color, flavor, and texture. The breakdown of nitrogenous compounds, particularly non-protein compounds, generates unpleasant odors and putrid-smelling by-products, which serve as key spoilage indicators. Understanding these biochemical processes is critical for developing strategies to manage seafood freshness and quality during storage. Enzymatic activity significantly contributes to the degradation of muscle proteins. Endogenous enzymes such as lysosomes, cathepsins, calpains, and collagenases play critical roles in breaking down myofibrillar proteins, which are primarily responsible for maintaining the structural integrity of muscle tissue. These enzymatic actions lead to muscle softening, structural weakening, and a progressive decline in seafood quality after death [1,6,7]. To mitigate these proteolytic changes, frozen storage is commonly employed to inhibit enzymatic activity and microbial growth. Freezing helps preserve aroma, flavor, color, and nutritional value; however, prolonged storage can moderately impact the texture due to protein denaturation and aggregation. These changes occur because protein molecules gradually lose their functional properties during extended freezing periods, thereby affecting overall seafood quality [1,6]. Experimental evidence further illustrates the impact of proteolysis during frozen storage. A study monitoring enzymatic activities, including trypsin, calpain, and catechin, in intact and decapitated shrimp during 120 days of frozen storage revealed critical insights. The results showed that the content of myofibrillar proteins and Ca^{2+}-ATPase activity decreased over time in both groups. However, the decline was significantly more pronounced in intact shrimp, as decapitation appeared to inhibit enzymatic activity by preventing the transfer of trypsin enzymes from the shrimp head to the muscle tissue through the first abdominal segment [22,23]. Myofibrillar proteins, such as actin and myosin, are essential for maintaining seafood muscle texture and water-holding capacity. Ca^{2+}-ATPase activity is a valuable biochemical marker of freshness and quality, with its reduction signaling ongoing protein degradation. The myofibrillar fragmentation index also demonstrated that decapitated shrimp exhibited less muscle protein dissociation compared to intact shrimp. By limiting the enzymatic action of trypsin, calpain, and catechin, decapitation effectively extended the shelf life and preserved the textural quality of shrimp products. Overall, understanding the enzymatic processes and their effects on muscle proteins is crucial for optimizing seafood storage methods and maintaining quality during extended storage periods. **Figure 1** illustrates the typical proteolytic changes observed in fish muscle during postmortem deterioration.

Off-flavor formation

Unpleasant tastes and odors in fish and seafood products are significant challenges for the fishing industry, significantly affecting consumer acceptance and economic viability. These undesirable flavors often result from compounds such as hexanal, heptanal, nonanal, and trimethylamine, which are generated through various biochemical and environmental processes. The disparity in flavor profiles between aquaculture-raised and wild-captured fish further underscores the need for managing odorous volatile compounds to meet consumer preferences and maintain market value [23]. Several factors contribute to developing off-flavors in fish (**Figure 2**). Environmental conditions, feed composition, and contamination during rearing can lead to undesirable tastes and odors. Post-mortem changes exacerbate these issues, as spoilage processes driven by microbial growth, enzymatic activity, and lipid oxidation produce distinct off-flavors [24]. These mechanisms highlight the importance of understanding the formation and sources of off-flavor compounds to implement effective mitigation strategies in seafood processing. Identifying the causes of undesirable flavors before and after fish death is crucial for the industry to adopt corrective

measures, maintain product quality, and ensure consumer satisfaction. **Tables 2** and **3** show fish and

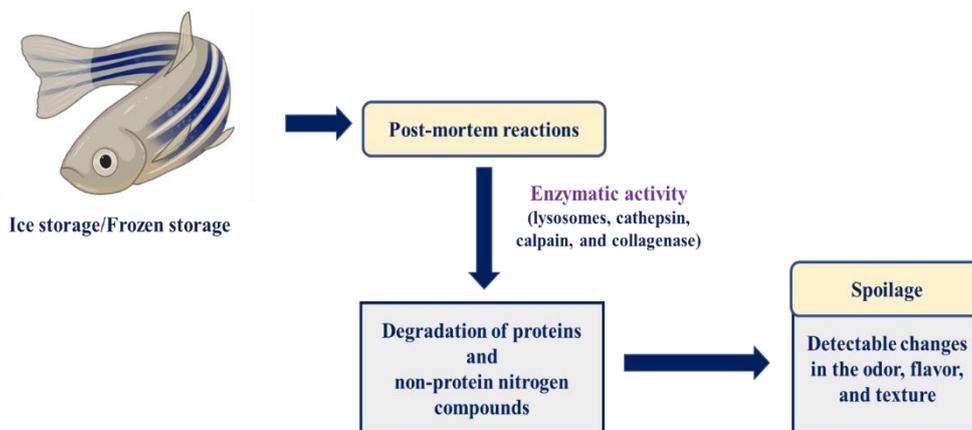seafood's pre-hunting and post-hunting off-flavor compounds.

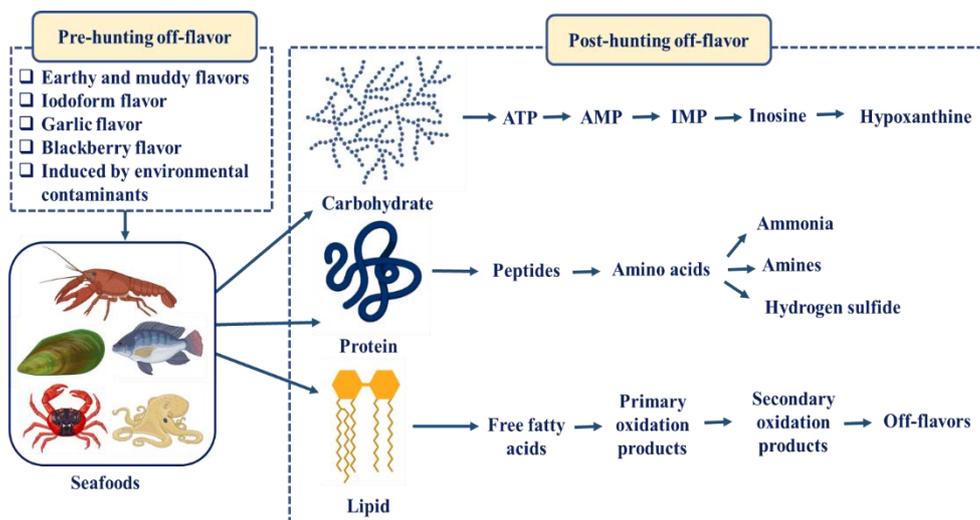**Figure 1** Proteolytic changes of fish.

Figure 2 A mechanism or reaction of off-flavor formation in seafoods.
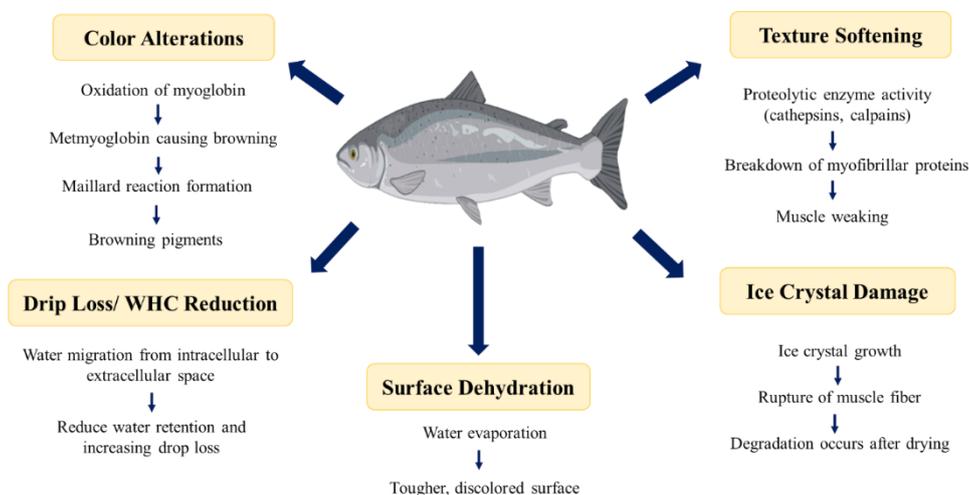

Figure 3 Physical and biochemical changes in seafood during storage.

Table 2 Pre-hunting off-flavor in fish and seafood.

Pre-hunting off-flavor	Compound	Source of off-flavor	References
Earthy and muddy flavors	Geosmin and 2-methylisoborneol	Actinomycetes and cyanobacteria	[25]
	2-methoxy-3-isopropylpyrazine	Streptomyces	[26]
Iodoform flavor	2,6-dibromophenol	Tyrosine/4-hydroxybenzoic acid biosynthesis (algae, polychaete worms).	[27]
Garlic flavor	bis-(methylthio)-methane	Methanethiol (from cysteine) and trimethylamine oxide (TMAO) are converted by enzymes or bacteria (marine organisms).	[28]
Blackberry flavor	Dimethyl sulfide (DMS)	Dimethyl-β-propiothetine (DMPT) is cleaved by algal enzymes or during cooking of contaminated muscle.	[29]
Off-flavors induced by environmental contaminants	petroleum, phenolic, sulfurous, chlorine, etc.	Petroleum, mineral oils, and environmental contaminants.	[24]

Table 3 post-hunting off-flavor in fish and seafood.

Post-hunting off-flavors	Compound	Sources	References
Microbial off-flavors			
Specific spoilage flavors *(Alcaligenes (achromobacter) spp.)*	Methanethiol, dimethyl disulfide, 1-penten-3-ol, 3-methyl-butanal, and trimethylamine (TMA)	Amino acids, TMAO, and lipid decomposition products.	[30]
Putrid odors *(Pseudomonas fluorescens)*	Methanethiol and dimethyl disulfide	Fish spoilage and blue-green fluorescence	[30]
Fruity and onion-like flavors *(Pseudomonas fragi)*	Sulfide, ethanol, ethyl acetate, ethyl butanoate, and ethyl hexanoate	Early spoilage is linked to methanethiol, DMS, and dimethyl disulfide formation.	[30]
Musty and potato-like odors *(Pseudomonas perolens)*	2-methoxy-3-isopropylpyrazine, possibly 2-methoxy-3-sec-butylpyrazine, methanethiol, dimethyl disulfide, dimethyl trisulfide, 3-methylbutanol, and 2-butanone	Endogenous valine, glycine, and methionine in pyruvate media (sole carbon source).	[30]

Post-hunting off-flavors	Compound	Sources	References
Ammoniacal, rotten, and hydrogen sulfide odors *(Shewanella putrefaciens)*	Sulfurous compounds, 3-methylbutanol, 1-penten-3-ol, and TMA	Sulfurous compounds from the metabolism of methionine, cysteine, cystine, and possibly glutathione.	[30]
Lipid oxidation off-flavors			
Plant-like odor and rancid flavors	Hexanal, (E)-2-hexenal, (E,E,Z)- and (E,Z,Z)-2,4,7-decatrienal	Fish lipid oxidation by autoxidation.	[31]
Some of the off-flavor-generating compounds produced during storage			
Old-fishy or fish house-like	Trimethylamine and related compounds	TMAO is reduced during microbial spoilage.	[31]
Pungent odor	Urea and related compounds	Ammonia and CO_2 by bacterial urease.	[26]
Stale cabbage, mercaptan-like sulfide, and hydrogen sulfide	Sulfurous compounds (methyl mercaptan, hydrogen sulfide, and dimethyl sulfide)	Microbial decomposition of free cysteine and methionine in fish muscle.	[26]
Putrid flavor, pungent flavor, and fishy flavor	Biogenic amines (putrescine, cadaverine, histamine, and phenylethylamine)	The bacterial decarboxylation of amino acids during storage.	[32]
Undesirable and extreme sweaty odors	Volatile acids	Fish oil	[26]
Off-flavors (cold-boiled potato, burnt, fishy, stale, and cold-like oil-like flavors)	Carbonyls (TMA, methyl propanal, 2- and 3-methyl butanal, and butane-2,3-dione in cod, and the acetaldehyde, propionaldehyde, butane-2,3-dione, pentane-2,3-dione, and C6, C8, and C9 carbonyl)	Retroaldol condensation of (E,Z)-2,6-nonadienal by water; (Z)-4-heptenal production accelerated at high pH and temperatures.	[26]

K-value

The K-value is a key index used to evaluate the freshness of fish and aquatic animals by measuring the progression of nucleotide degradation post-mortem. It reflects the biochemical changes in fish immediately after death, while endogenous enzymes remain active before significant microbial spoilage occurs [33]. Following the death of fish and aquatic animals, adenosine triphosphate (ATP) in the muscles undergoes enzymatic dephosphorylation, converting into adenosine diphosphate (ADP) and adenosine monophosphate (AMP). Subsequently, deamination transforms AMP into inosine monophosphate (IMP), which occurs rapidly due to enzymatic activity. Over time, microbial enzymes further degrade IMP into hypoxanthine, xanthine, and uric acid, signaling a decline in freshness [34]. The K-value is calculated as the ratio of nucleotide breakdown products (inosine and hypoxanthine) to the total nucleotide pool. A low K-value indicates freshness, whereas a high K-value signifies advanced spoilage.

For example, in studies monitoring rainbow trout (*Oncorhynchus mykiss*), the initial K-value was approximately 8% but increased to 50% after 24 h of storage and 73% after 28 h, signifying significant freshness loss over time [35]. Temperature plays a critical role in K-value progression. Research on Sebastes thompsoni revealed that refrigeration at 0°C significantly slowed the increase in K-value compared to storage at 10°C, underscoring the importance of precise temperature control during storage [36]. However, inaccuracies in temperature management during transportation often lead to accelerated spoilage. A study on yellow croaker (*Pseudosciaena crocea*) stored at 5, 10, and 15°C demonstrated that a lower storage temperature (5°C) resulted in a slower K-value increase and extended shelf life. Interestingly, the K-value at 10°C provided a more accurate shelf-life prediction under practical conditions [37]. The relationship between K-value and storage conditions has also been observed in shrimp, such as whiteleg shrimp (*Litopenaeus vannamei*). The K-value showed a linear correlation with storage time in whole shrimp and shrimp meat stored at 25°C, making it a reliable indicator for tracking freshness loss over extended periods [38]. These findings highlight the utility of the K-value as an essential tool for assessing the quality and shelf life of seafood, with its effectiveness influenced by storage temperature and handling practices.

Microbiological issues

Microorganisms in fish and seafood play both beneficial and detrimental roles, significantly influencing these products' quality, shelf life, and safety. Beneficial organisms, such as those found in the gastrointestinal tracts of aquatic species like lobsters, include *Vibrio*, *Pseudomonas*, *Bacillus*, *Micrococcus*, *Flavobacterium*, *Acinetobacter*, *Aeromonas*, *Alteromonas*, *Clostridium*, *Marinobacter*, *Pelagibacter*, *Photobacterium*, *Psychrobacter*, *Pseudoalteromonas*, *Shewanella*, and *Synechococcus*. These microorganisms vary in composition and abundance depending on the environment, and they contribute positively by aiding digestion through the secretion of enzymes like lipase, protease, and cellulase. They also play a role in nutrient absorption, vitamin synthesis, and enhancing host immunity by stimulating immune responses in the gastrointestinal tract [39-41]. However, microorganisms can also play a detrimental role in seafood spoilage. After the organism's death, biochemical changes in the tissues create an environment conducive to the growth of spoilage bacteria, particularly those in the gums, mucus, and digestive tract. Spoilage microorganisms commonly associated with fish and seafood include *Pseudomonas*, *Acinetobacter*, *Moraxella*, and *Flavobacterium*. When refrigeration is inadequate or temperatures rise slightly, other bacteria such as *Micrococcus, Bacillus, Proteus, Serratia, Sarcina,* and *Clostridium* may also proliferate. These bacteria can hydrolyze seafood proteins via protease, forming ammonia, hydrogen sulfide, organic acids, unpleasant aromas, undesirable tastes, and an unsatisfactory texture [40,41]. Many of these bacteria grow rapidly at room temperature and can even grow to some extent under refrigeration, leading to significant quality degradation [42]. Some microorganisms are linked to specific spoilage phenomena. For example, *Bacillus* sp. and *Acinetobacter* sp., in shrimp, produce the enzyme tyrosinase, which triggers oxidation reactions that lead to black spot formation in shrimp [43]. Additionally, certain microbes in seafood pose serious health risks to consumers. Foodborne pathogens, such as bacteria,

viruses, or parasites, are responsible for food poisoning [42,43]. They, such as *Vibrio vulnificus, Vibrio parahaemolyticus, Vibrio cholerae, Salmonella enterica*, Shiga toxin-producing *Escherichia coli* (STEC), *Listeria monocytogenes*, and *Clostridium botulinum,* can cause severe infections or intoxications. Notably, *Vibrio vulnificus*, *Vibrio parahaemolyticus*, *Vibrio cholerae*, *Listeria monocytogenes*, and Salmonella enterica are associated with severe and potentially fatal outcomes [44]. The scombroid toxin, or histamine poisoning, is another significant health concern linked to consuming scombroid fish species such as tuna, mahi-mahi, and bluefish. Spoilage bacteria producing decarboxylase enzymes convert free histidine in fish tissues into histamine in toxic amounts. Additionally, toxins produced by *Salmonella* spp. and *Clostridium botulinum* are highly neurotoxic and linked to numerous outbreaks and illnesses in the United States. Contaminated fish products, especially raw fish like tuna, mahi-mahi, barracuda, and salmon, are familiar sources of these toxins, underscoring the need for stringent microbial control during seafood processing and storage [45]. **Table 4** provides the occurrence of spoilage bacteria in seafood products.

Table 4 Occurrence of spoilage bacteria in seafood products.

Seafood	Spoilage bacteria	References
Fresh shrimp (*Litopenaeus vannamei*)	*Staphylococcus, Carnobacterium, Shewanella Psychrobacter, Carnobacterium* spp., *Psychrobacter, Brochothrix, Shewanella*	[39]
Fresh farmed Atlantic cod (*Gadus morhua*)	*Photobacterium phosphoreum, Pseudomonas* spp., *Shewanella baltica,* and *Shewanella putrefaciens*	[40]
Fresh lobster tails and whole lobster (*Homarus gammarus*)	*Psychrobacter* spp., *Pseudoalteromonas* spp., *Pseudomonas* spp., *Luteimonas* spp., *Aliivibrio* spp., *Psychrobacter, Planococcus, Exiguobacterium, Carnobacterium, Pseudomonas,* and *Chryseobacterium*	[41]
Fresh oyster (*Saccostrea commercialis)*, fish, raw salmon (*Salmo salar*), fish fillet, catfish (*Pangasianodon hypophthalmus*), sea bass (*Lates calcarifer*), and sea bream (*Anodontostoma chacunda*)	*Arthrobacter bergerei, Shewanella putrefaciens, Brochothrix thermosphacta, Vagococcus salmoninarum, Shewanella, Pseudomonas, Psychrobacter, Carnobacterium, Serratia liquefaciens, Buttiauxella noackia, Escherichia coli, Enterococcus* spp., *Serratia phymutica, Enterobacter agglomeran, Hafnia alvei, Flavobacterium damsel, Acinetobacter baumanii,* and *Aeromonas salmonicida*	[39]
Peeled cooked brown shrimp (*Crangon crangon*)	*Pseudomonas* spp., *Photobacterium* spp., *Shewanella putrefaciens,* and *Pseudomonas* spp.	[40]
Half-shell Pacific oyster (*Magallana gigas*)	*Chryseobacterium, Flavobacterium, Prosthecomicrobium, Arcobacter, Pseudoalteromonas, Mycoplasma, Vibrio, Helicobacter,* and *Terasakiella*	[6]
Refrigerated shrimp, cold smoked salmon (*Salmo salar*), and sea beam (*Anodontostoma chacunda*)	*Streptococcus parauberis, Vagococcus penaei, Serratia proteamaculans, Photobacterium phosphoreum, Brochothrix thermosphacta, Yersinia intermedia, Hafnia alvei, Carnobacterium maltaromaticum, Carnobacterium divergens, Lactococcus piscium, Serratia quinivorans, Acinetobacter baumanii,* and *Aeromonas salmonicida*	[7]
Vacuum-packed salmon (*Salmo salar*)	*Chryseobacterium piscicola*	[46]

Physical changes

The physical changes in fish and aquatic animals during storage significantly impact their sensory attributes and consumer acceptance. Among these changes, color alterations are often noticeable and result from various biochemical and enzymatic processes. The oxidation of myoglobin to metmyoglobin, which is brown, is a primary cause of discoloration. Additionally, metmyoglobin acts as a pro-oxidant, accelerating lipid oxidation and contributing to further quality degradation. During cryopreservation, the Maillard reaction, involving reducing sugars and amino acids, can occur due to continued glycolysis even at low temperatures. The Maillard reaction is achieved at any temperature. The lower the temperature, the slower the reaction proceeds [47]. This reaction produces fluorescent intermediates and impacts the appearance of aquatic products [33]. Fish with high-fat content are particularly prone to browning due to interactions between proteins and lipid oxidation products. For instance, unsaturated carbonyl compounds generated from fish oil oxidation can react with proteins, leading to a brown discoloration. Enzymatic reactions also play a critical role in color changes. Polyphenol oxidase (PPO), for example, catalyzes the oxidation of phenolic compounds in the presence of oxygen, leading to melanosis or black spot formation in shrimp. This process involves the hydroxylation of phenols to diphenols and the subsequent oxidation to o-benzoquinones, which polymerize into melanin, reducing product acceptability [48]. Texture changes during storage also serve as indicators of fish quality deterioration. The initial loss of springiness and increased softness resulted from muscle digestion, weakening of connective tissues, and the separation of muscle myofibrils. Over time, these changes are exacerbated by protease enzymes originating from the fish itself and spoilage bacteria. These endogenous and bacterial proteinases progressively break down muscle proteins, leading to a paste-like texture in advanced stages of spoilage [1,6,7]. **Figure 3** illustrates the physical and biochemical changes in seafood during storage, including mechanisms of color alteration, texture softening, drip loss, surface dehydration, and ice crystal damage.

EOs: Composition, mechanisms, and antimicrobial functions

EOs are volatile, aromatic liquids extracted from various plant parts such as flowers, leaves, citrus peels, fruits, and herbs. These oils are typically obtained through steam or water distillation and are known for their pleasant aroma, insolubility in water, and broad applications, including food preservation. Common sources of EOs include garlic, cloves, chili, ginger, galangal, kaffir lime, and pomelo, which serve as raw materials for producing EOs with diverse biological and functional properties [8,9]. Beyond their role as flavor enhancers, EOs exhibit remarkable antimicrobial activity, which makes them effective in inhibiting or destroying microorganisms, particularly those responsible for spoilage and foodborne diseases. EOs are rich in bioactive compounds such as terpenes, terpenoids, and phenylpropanoids. Terpenes are composed of isoprene units (mono-, sesqui-, and diterpenes), while terpenoids include oxygenated derivatives such as alcohols, esters, aldehydes, ketones, ethers, and phenols. Notable terpenoids with antimicrobial properties include thymol, carvacrol, linalool, linalyl acetate, citronellal, piperitone, menthol, and geraniol. These compounds, present in sources like calamondin, pomelo, garlic, and cinnamon, contribute to the antimicrobial and antioxidant activity of EOs, particularly in seafood preservation [9-11]. The structural differences influence the antimicrobial action of EOs in the cell membranes of gram-positive and gram-negative bacteria. Gram-positive bacteria, such as *Staphylococcus aureus*, have hydrophobic cell membranes that are more susceptible to disruption by hydrophobic EOs components. For example, when combined with certain fatty acids, carvacrol increases cell membrane permeability and fluidity, leading to the leakage of compatible solutes and eventual microbial death [49].

Conversely, gram-negative bacteria, such as *Escherichia coli*, possess lipopolysaccharide-rich hydrophilic cell membranes, which provide more excellent resistance to hydrophobic compounds like phenolic antimicrobial agents (e.g., thymol, eugenol, and carvacrol) [2,3]. The antimicrobial mechanisms of EOs are complex and involve multiple pathways. These include disrupting cell wall integrity, altering

cytoplasmic membrane properties, inhibiting ergosterol biosynthesis (a key component of cell membranes), altering lipid profiles, and inhibiting ATPase activity and biofilm formation. The effectiveness of EOs depends on factors such as concentration, the type of bioactive compounds present, and their functional groups [3,4]. Numerous studies have investigated the antimicrobial effects of EOs derived from citrus, herbs, and spices on seafood products. For example, calamondin (*Citrus microcarpa Bunge*), commonly used in Southeast Asia, contains phenolic acids such as p-coumaric and ferulic acid and flavonoid hesperidin [50]. The peel EOs of calamondin exhibit significant antimicrobial activity against spoilage microorganisms and pathogens, including *Escherichia coli*, *Citrobacter freundii*, *Aeromonas hydrophila*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Yersinia enterocolitica* [50]. Similarly, pomelo (*Citrus grandis* L. Osbeck) peel EOs, rich in monoterpenes such as terpinyl acetate, α-pinene, β-pinene, and terpinolene, effectively inhibit spoilage microorganisms in saltwater fish fillets, targeting pathogens such as *Yersinia pestis*, *Bacillus cereus*, *Escherichia coli*, *Staphylococcus aureus*, *Listeria monocytogenes*, *Pseudomonas aeruginosa*, and *Candida albicans*.

These monoterpenes disrupt microbial membrane integrity and impair respiration [51]. EOs from herbs and spices also display significant antimicrobial activity. Garlic (*Allium sativum*), a well-known antimicrobial agent, contains organosulfur and phenolic compounds such as allicin, diallyl sulfide, diallyl trisulfide, diallyl disulfide, ajoene, and 2-vinyldithiins. Studies have shown that garlic EOs reduce total viable counts, coliform bacteria, and psychrophilic bacteria in seafood. For instance, rainbow trout treated with 1-2% garlic EOs showed a > 2 log CFU/g reduction in bacterial counts compared to untreated controls. This effect is attributed to the ability of garlic EOs to disrupt cell membranes, causing leakage of cellular solutes [52]. Cinnamon EOs have also been extensively studied for their antimicrobial effects. In comparative studies involving 9 EOs (including star anise, clove, basil, garlic, oregano, lemongrass, thyme, rosemary, and black pepper), cinnamon EOs demonstrated superior antimicrobial activity in Asian seabass fillets stored at 4 ± 1 °C. At a concentration of 488 mg/L, cinnamon EOs effectively inhibited *Escherichia coli*, *S. Typhimurium*,

Staphylococcus aureus, and *Vibrio parahaemolyticus*, exhibiting the widest inhibition zones among the tested oils [53]. The antimicrobial efficacy of EOs highlights their potential for preserving seafood, leveraging their bioactive compounds to combat spoilage and pathogenic microorganisms while maintaining product quality and safety. **Table 5** illustrates the EO's source, bioactive compounds, and antimicrobial activities.

EFCs: Types, properties, and biopolymer matrices

EFCs have emerged as an innovative and sustainable alternative within the food packaging industry, offering environmental and functional advantages. This approach aligns with global efforts to address sustainability and food security challenges while optimizing food quality and reducing waste. Unlike traditional packaging, EFCs provide a biodegradable and safe solution to extend the shelf life of perishable goods, particularly in combating the global issue of food waste [8]. EFC materials are made from natural polymers, are safe for direct consumption, and are adaptable to various forms, such as films and coatings. Films are used in wraps, pouches, bags, capsules, and casings, serving as protective barriers around food items. Coatings, on the other hand, are directly applied to the surface of food, acting as integral components that maintain their protective and functional properties during consumption [9]. These films and coatings play a vital role in preserving and enhancing the quality of food products. They provide effective barriers against gases and moisture, regulate gas exchange, minimize ethylene production, and prevent moisture loss, maintaining the weight, flavor, and appearance of packaged foods. When infused with antioxidants and antimicrobial agents, EFCs also help inhibit spoilage, browning, and microbial activity. Furthermore, the versatility of these materials allows them to serve as nano-carriers, enabling the controlled release of additives for advanced preservation techniques [58]. The selection of EFC materials is tailored to the specific requirements of food products, ensuring compatibility with sensory characteristics to meet consumer expectations. This careful selection protects food from external factors and enhances its overall quality. Additionally, EFCs serve as a matrix for functional additives, including antimicrobial and antioxidant compounds, prebiotics, and other nutrients,

improving packaged foods' shelf life and nutritional value. By incorporating these compounds, EFCs enhance their structural, mechanical, and handling properties, broadening their applications [59]. Fish and seafood products are particularly suited for EFCs due to their high perishability. These products have high water activity values (0.95-0.98) and are rich in nutrients, making them highly susceptible to spoilage. Consequently, nearly 35% of global fish production is lost before consumption. To address this issue, developing ecologically sustainable packaging materials that can effectively preserve the freshness and quality of fish and seafood is imperative [9]. EFCs thus offer a promising solution, combining sustainability with enhanced preservation techniques to reduce waste, maintain product quality, and cater to growing consumer demands for environmentally friendly packaging alternatives.

Table 5 EO and their bioactive compounds and antimicrobial activities.

EOs source	Major bioactive compounds	Key spoilage microorganisms inhibited	MIC value	Effectiveness	References
Garlic (*Allium sativum*)	Allicin, diallyl sulfide, and ajoene	*Pseudomonas*, *Candida*, *Listeria*, *E. coli*	0.0086 µg/mL	Very high	[54]
Cinnamon (*Cinnamomum sp.*)	Cinnamaldehyde, eugenol	*S. aureus*, *Salmonella*, *E. coli*	5 µg/mL	High	[55]
Clove (*Syzygium aromaticum*)	Eugenol, caryophyllene	*E. coli*, *S. aureus*	5 µg/mL	High	[55]
Pomelo Peel (*Citrus grandis*)	d-limonene, terpinyl acetate	*Listeria*, *B. cereus*, *P. aeruginosa*	5.44 mg/mL	Moderate	[51]
Lemongrass (*Cymbopogon citratus*)	Citral (neral, geranial)	*Candida*, *S. aureus*	30 ppm	High	[56]
Red Galangal (*Alpinia purpurata*)	Phenols, flavonoids, terpenoids	*E. coli*, *S. aureus*	250 µg/mL	Moderate	[2]
Ginger (*Zingiber officinale*)	Zingiberene, α-curcumene	*E. coli*, *S. aureus*	0.0657 µg/mL	Very high	[3]
Kaffir Lime Leaf (*Citrus hystrix*)	Citronellal, α-terpineol	*S. pneumoniae*, *H. influenzae*	0.89 mg/mL	Moderate	[57]

Note: MIC = Minimum Inhibitory Concentration. Lower MIC = Higher potency.

Types and properties of EFCs

EFCs are typically divided into 2 distinct types: edible films and edible coatings. This classification is primarily based on differences in their fabrication techniques and modes of application to food surfaces. Films are produced in a 2-step process, wherein they are first created separately and then applied to the food product. In contrast, coatings are directly formed and applied onto the food surface as a superficial covering or inter-compartmental layers within the same food item (**Figure 4**). Within the classification of edible films, a distinction based on thickness further refines their categorization. Thin, stand-alone layers with a thickness between 0.050 and 0.250 mm are referred to as films, while those exceeding 0.250 mm are termed sheets, representing a more robust and nuanced variation within EFCs [60]. The primary biopolymers fabricating EFCs are polysaccharides, proteins, and lipids. Polysaccharides, including starch derivatives and gums, are particularly valued for their mechanical strength and optical properties, such as transparency. Proteins like gelatin and gluten contribute to edible films' structural and functional integrity, offering impressive tensile strength and flexibility [61]. Despite these advantages, polysaccharide- and protein-based films exhibit high susceptibility to moisture, which can compromise their performance in preventing food deterioration under humid conditions. Lipid-based films, in contrast, are made from waxes, lipids, or their derivatives and excel in providing water vapor barrier properties. This characteristic makes them particularly effective in protecting foods with high moisture sensitivity. However, their application is not without challenges. Lipid-based films often lack transparency and

flexibility, limiting their aesthetic appeal and adaptability. Additionally, they are prone to rancidity, which can impact the quality and shelf life of the food product they are designed to protect [62]. By leveraging the strengths of these biopolymers while addressing their respective limitations, EFCs continue to evolve as an innovative solution for preserving food quality, extending shelf life, and reducing environmental impact.

Protein-based films and coatings

Protein-based films and coatings are widely recognized for their ability to form cohesive molecules through peptide bonds, providing a versatile platform for food packaging applications. Proteins, which are derived from various raw materials such as corn, wheat, soy, collagen, keratin, casein, and gelatin, exhibit diverse structural and functional properties that support their roles in biochemical reactions and tissue construction in plants and animals [58]. These properties make proteins valuable renewable resources for developing eco-friendly packaging materials with superior functionality. The mechanical strength and water resistance of protein-based films can be significantly improved through chemical, enzymatic, or physical modifications, often in combination with hydrophobic polymers. This adaptability allows researchers to tailor protein films for specific applications, enhancing their durability and performance [63]. Proteinaceous materials such as casein, gelatin, wheat gluten, soy protein, and zein are particularly cost-effective and sustainable options for creating liquid coatings or solid laminates tailored to specific food products. Incorporating natural antioxidants into these films enhances their ability to combat free radicals, further broadening their applications in food preservation. One notable example of a protein-based biopolymer is gelatin, which is derived from the partial hydrolysis of collagen. Gelatin is water-soluble and offers a biodegradable alternative for food packaging. Its properties, including molecular weight distribution and amino acid composition, are influenced by factors such as the source of collagen, extraction methods, and processing conditions [64]. While gelatin does not inherently possess antimicrobial properties, it can be fortified with antioxidants and antimicrobial agents like citrus EOs or carvacrol. These additives enhance the functionality of gelatin-based films, making them more effective in extending the shelf life and maintaining the quality of packaged foods. Protein-based films and coatings thus represent a promising solution in developing sustainable, functional, and efficient food packaging materials, leveraging their natural properties and the potential for modification to meet diverse industrial requirements.

Polysaccharide-based films and coatings

Polysaccharide-based films and coatings have gained prominence as biodegradable materials with extensive applications in the food industry and beyond. Derived from natural sources, polysaccharides such as cellulose, starch, chitosan, chitin, guar gum, locust bean gum, tara gum, glucomannan, xanthan, agar, carrageenans, pectins, algins/alginates, curdlan, dextrans, levans, arabinoxylans, and pullulan are widely used in developing sustainable and functional EFCs materials [65]. The abundance and renewable nature of polysaccharides make them attractive for eco-friendly packaging, offering both nutritional and structural benefits. Fruits and vegetables and their by-products have emerged as particularly intriguing sources for developing edible films. These natural materials provide essential nutrients, bioactive compounds, polysaccharides, and sugars, which act as film-forming agents and plasticizers. This dual functionality enhances polysaccharide-based films' mechanical and structural integrity, making them suitable for various food preservation applications [66]. Polysaccharides' unique structural and functional properties stem from variations in their molecular size, sugar composition, glycosidic linkages, molecular conformation, and functional groups. These characteristics contribute to their effective film-forming capabilities and impart biological benefits, such as anticancer and antidiabetic properties, which enhance the value of these materials in food packaging [65]. Polysaccharide-based films are particularly effective as gas barriers, restricting oxygen and carbon dioxide permeation. While their hydrophilic nature can reduce resistance to water vapor, this property also allows them to absorb moisture temporarily, thus protecting food surfaces against dehydration. Polysaccharides like alginate and carrageenan, known for their hygroscopicity, form thick coatings that delay moisture loss during storage. These films also help preserve food products' sensory qualities

by minimizing the loss of organic vapors, including aroma compounds [67]. In addition to controlling moisture and gas exchange, polysaccharide-based films act as barriers against solvent penetration, preventing toxicity or quality deterioration of the packaged food. Their versatility allows integration with synthetic materials, such as polyvinyl alcohol, to enhance mechanical properties and broaden their functional applications. Moreover, incorporating additives such as antioxidants, antimicrobials, or plasticizers can extend the shelf life of ready-to-eat and highly perishable foods, making polysaccharide-based films and coatings a promising solution for sustainable and advanced food packaging systems [68]. These materials represent a pivotal step toward environmentally responsible packaging alternatives, offering robust performance while addressing consumer and industry demands for sustainability and food quality.
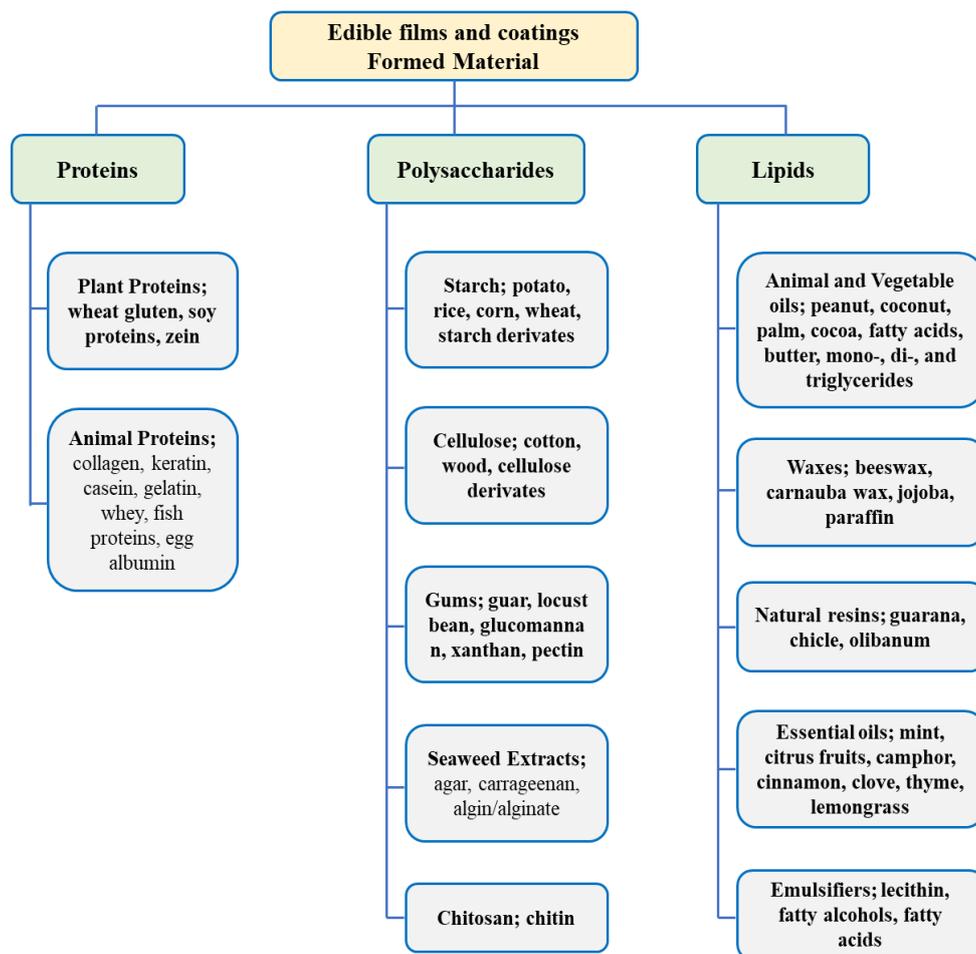

Figure 4 Classification of EFCs formed materials.

Lipid-based films and coatings

Lipid-based films and coatings are composed of hydrophobic compounds such as neutral lipids, natural oils and fats (from both animal and vegetable sources), fatty acids, mono-, di-, and triglycerides, natural waxes (vegetable and animal waxes), natural resins, emulsifiers, fat-soluble vitamins, and EOs. These small, hydrophobic molecules possess inherent water-vapor barrier properties, making them particularly effective in minimizing water loss and serving as mass transfer barriers to gases and vapors [62]. While lipid-based films have gained significant attention in recent years, their use in food preservation dates back centuries, when waxes were applied to fruits and vegetables to reduce moisture loss, prevent decay, and maintain quality during storage. Despite their advantages, traditional wax coatings faced issues such as the unintended buildup of carbon dioxide, which promoted microbial growth,

elevated acetaldehyde and ethanol levels, and contributed to anaerobic respiration that negatively impacted food quality [69]. Modern lipid-based films retain the advantages of traditional coatings, such as gloss enhancement and biodegradability, but address many of their historical limitations. However, they remain mechanically fragile compared to hydrocolloid-based films and are often brittle, making pure lipid films less common in practical applications. Lipid-based coatings are frequently used for meat, poultry, seafood, and other perishable foods to slow moisture loss and improve appearance. The overall properties of lipid-based films, including barrier performance, mechanical strength, thermal resistance, and optical clarity, depend significantly on the formulation and preparation methods used and external conditions like relative humidity, temperature, and storage duration [70]. Researchers have developed composite films by blending lipids with other biopolymers, such as proteins and polysaccharides, to overcome the inherent limitations of single-component films. Composite films integrate the unique characteristics of each material, resulting in films with enhanced mechanical, thermal, and barrier properties. For example, gelatin, which has poor thermal and mechanical performance, can be combined with hydroxypropyl methylcellulose to form a seamless matrix with superior film-forming capabilities.

Similarly, pectin and gelatin, which are known for their robust film-forming properties, can be combined to create biodegradable films that offer improved optical clarity, water resistance, and tensile strength. Athanasopoulou *et al*. [71] demonstrated the development of composite films using pectin, gelatin, and hydroxypropyl methylcellulose for biodegradable packaging of gilthead seabream fillet. These films exhibited excellent mechanical properties, optical qualities, and water resistance. Their hydrophobicity, evidenced by contact angles exceeding 90°, made them effective as barriers to moisture transfer while maintaining the freshness of the fish. This approach provides a sustainable alternative to traditional petroleum-based packaging materials, aligning with global environmental goals. Functional EFCs must meet specific criteria, including desirable color, appearance, barrier capabilities, mechanical strength, and rheological behavior. Films predominantly composed of

proteins often demonstrate favorable mechanical and optical properties but are limited by poor water vapor barrier capabilities due to their hydrophilic nature [72]. Lipid-based films, while excelling in water resistance, can be integrated with EOs and other additives to enhance their functionality. EOs derived from plants such as thyme, cinnamon, oregano, clove, lemongrass, and garlic are widely recognized for their strong antibacterial and antioxidant properties. Incorporating these oils into lipid-based films improves their performance by increasing their capacity to prevent water vapor transfer, inhibit microbial growth, and extend the shelf life of perishable food products [73]. For example, EOs can disrupt bacterial cell membranes, resulting in antimicrobial effects, while their antioxidant properties help mitigate lipid oxidation in packaged food. The seafood industry, in particular, offers significant potential for utilizing lipid-based films. By-products generated during seafood processing, such as myofibrillar and sarcoplasmic proteins, can produce protein-enriched films with enhanced structural and functional properties. When combined with EOs, these films form advanced packaging materials with superior antibacterial and antioxidant capabilities, ideal for preserving high-value seafood products [74]. Lipid-based films and coatings, primarily used with other biopolymers and active additives, are pivotal in developing sustainable, functional, and biodegradable food packaging materials. Their ability to reduce moisture loss, protect against microbial contamination, and extend the shelf life of perishable foods highlights their growing importance in addressing both environmental challenges and consumer demands for high-quality, sustainable packaging solutions.

Applications for EO-based EFCs in seafood

The application of EOs in EFCs offers a novel and effective strategy for addressing the challenges of preserving fish and seafood, among the most perishable food products [11]. Edible coatings are commonly applied to fish and seafood using dipping, brushing, and spraying methods, while edible films are typically used as wrappings [9]. Incorporating EOs into these EFC systems provides multiple benefits, including antimicrobial properties, antioxidant activity, and the ability to mitigate proteolytic changes, all contributing to maintaining product quality and extending shelf life.

Microbial spoilage poses a significant risk to the quality and safety of fish and seafood. Preventing microbial growth and ensuring consumer safety are critical to preserving these products [12]. Traditional synthetic preservatives and conventional packaging methods often fall short of meeting consumer demands for natural, sustainable, and clean-label solutions [9]. In this context, integrating EOs, extracted from various plant sources, into EFCs has emerged as an innovative alternative. This approach aligns consumer preferences for natural and eco-friendly packaging while addressing key challenges in seafood preservation [75]. Incorporating EOs in the EFCs enables the gradual release of bioactive compounds onto the food surface.

The EFC matrix acts as a carrier, controlling the diffusion rate of the essential oils depending on the polymer structure, thickness, and storage conditions. Upon contact with moisture, temperature fluctuations, or microbial activity, the encapsulated compounds are released, exerting antimicrobial and antioxidant effects by disrupting microbial cell membranes, inhibiting metabolic processes, and scavenging free radicals. This controlled release mechanism enhances food protection over extended storage periods and maintains product freshness. Schematic representation of bioactive compound release from EO-based EFCs and their antimicrobial action in packaged seafood products **(Figure 5)**.
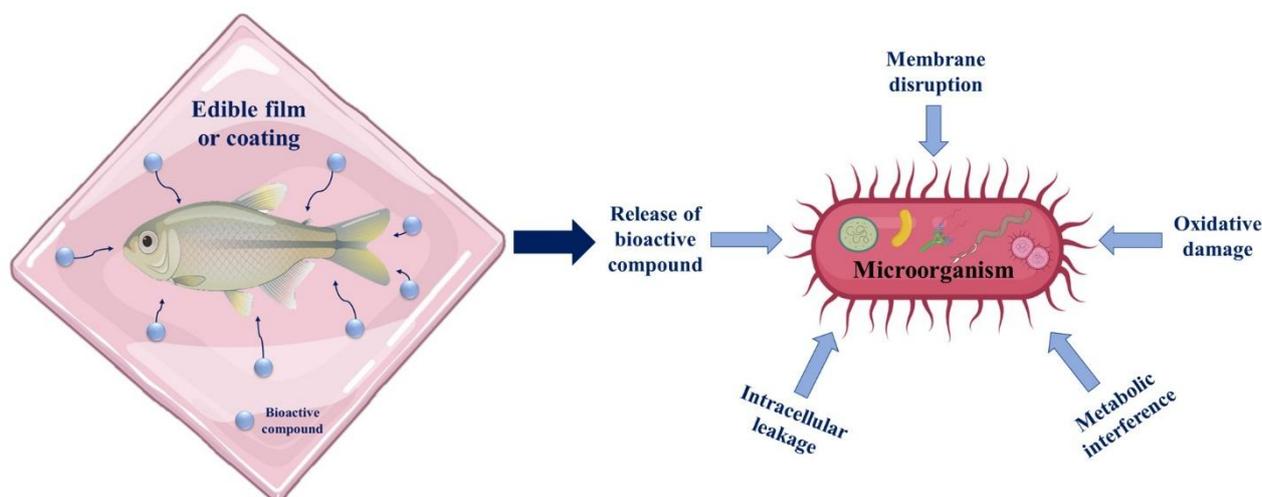

Figure 5 Schematic representation of the bioactive compound release from EO-based EFCs and their antimicrobial actions.

Table 6 illustrates the EO's applications in EFCs on fish and seafood. EOs exhibit strong antimicrobial properties, making them highly effective against a wide range of spoilage and pathogenic microorganisms commonly found in fish and seafood. Their antimicrobial efficacy is primarily attributed to bioactive compounds such as terpenoids, thymol, carvacrol, β-cubebene, β-eudesmol, β-ionone, dactylol, and pachydictol A, which are well-documented for their ability to inhibit microbial growth and activity [2-4]. EO-coated EFCs demonstrate bacteriostatic and bactericidal activities against common seafood pathogens, including *Salmonella* spp., *Escherichia coli*,

and *Listeria monocytogenes*. These properties are mainly due to the phenolic compounds in EOs, which are hydrophobic and disrupt microbial cell membranes by increasing permeability. This action targets lipid components in microbial cell membranes and mitochondria, impairing energy production by disrupting adenosine triphosphate synthesis and compromising the proton motive force. Such disruptions ultimately lead to cell death, further enhanced by the leakage of intracellular components caused by membrane destabilization [9,12]. Research has provided strong evidence supporting the effectiveness of EOs against pathogenic microorganisms in seafood

preservation. For instance, oregano and cinnamon EOs have been shown to inhibit the growth of *Salmonella spp.* and *Escherichia coli* through mechanisms such as disrupting microbial cell membranes, interfering with metabolic pathways, and preventing biofilm formation. These attributes make them powerful agents for enhancing food safety [76-79]. Various EOs have been incorporated into EFCs to preserve seafood products with notable success. Clove EOs, for example, have been added to soy protein isolate, gelatin, and chitosan-based films, which have been tested on tuna fillets and salmon slices with promising results [75]. Additionally, several combinations of biopolymers and EOs have demonstrated their potential in seafood preservation. Alginate, chitosan, and gelatin films enriched with sage EOs have been successfully used to wrap chilled fish burgers, while locust bean gum and sodium alginate coatings with lemon verbena EOs were applied to a large yellow croaker. Gelatin coatings enriched with orange leaf EOs were used for deep-water pink shrimp, and chitosan-gelatin films containing *Ziziphora clinopodioides* EOs were applied to peeled shrimp. These studies illustrate the versatility of EOs in enhancing the functional properties of EFCs across various seafood applications [7,11,80].

Incorporating EOs into EFCs offers a natural and effective approach to mitigating microbial contamination in fish and seafood. By addressing consumer preferences for natural and clean-label solutions while meeting industry demands for improved food safety and shelf life, EOs provide a sustainable and innovative solution for seafood preservation. The preservation of seafood quality is closely tied to controlling lipid oxidation, which leads to the development of rancid flavors and off-odors, compromising the sensory and nutritional attributes of seafood products [24,26,30]. EOs are rich in antioxidants, such as rosemary, thyme, and clove oils, and have shown significant efficacy in combating lipid oxidation. These EOs function by scavenging free radicals and chelating pro-oxidant metals, which effectively slow down the oxidative degradation of lipids in fish and seafood. Incorporating EOs into EFCs

is a promising strategy to maintain sensory quality and prolong the shelf life of seafood products [74,81]. In addition to their antioxidative effects, EOs have a masking impact on off-flavors, further enhancing product acceptability. Their antimicrobial properties complement these benefits, contributing to the overall improvement in seafood quality [2,4]. Studies have highlighted specific EOs compounds, such as carnosic acid, thymol, and eugenol, for their potent ability to inhibit lipid peroxidation and delay the development of off-flavors in seafood [82-85]. For example, seafood coated with films containing cinnamon leaf and clove EOs exhibited a delayed melanogenesis reaction, primarily due to the antioxidant activity of the EOs. This antioxidant function stabilized the product and improved its sensory acceptance among consumers [82]. The dual functionality of EOs as antioxidants and flavor enhancers positions them as a transformative solution in seafood preservation. Proteolytic changes, driven by enzymatic protein degradation, significantly alter the texture and overall quality of fish and seafood products [85]. These changes, often caused by endogenous and microbial proteases, result in undesirable softening and loss of structure in seafood. EOs have demonstrated notable potential in inhibiting proteolytic enzymes, thereby preventing the breakdown of proteins and preserving the integrity of seafood products [86,87]. Several EOs, including oregano, wild orange, tea tree, and clove leaf, have shown protease inhibitory activity, as evidenced in Pacific white shrimp studies (*Litopenaeus vannamei*). These EOs effectively reduce protein degradation, contributing to the retention of texture and quality in seafood [87]. For instance, Laorenza and Harnkarnsujarit [86] developed functional, active packaging films incorporating carvacrol, citral, and α-terpineol, inhibiting protease activity in Pacific white shrimp. Similarly, Liu *et al*. [83] utilized clove EOs in edible coatings to enhance white shrimp's texture and protein stability during storage. Both studies emphasize the importance of maintaining protein quality, as it directly impacts the texture, nutritional value, and overall consumer acceptance of seafood [83,86].

Table 6 Applications of EO-enriched EFS in seafood preservation.

Edible film/coating composition	EO used	Seafood products	Preservation effects	References
Soy protein isolate with montmorillonite nanocomposite	Clove EO	Bluefin tuna fillet	Reduced *Pseudomonas* spp. and Enterobacteriaceae delayed spoilage during 15 days at 2°C.	[76]
Gelatin blended with chitosan	Clove EO	Cod fillet	Inhibited microbial growth, including hydrogen sulfide-producing bacteria, *Pseudomonas* spp., and lactic acid bacteria during chilled storage	[77]
Gelatin and chitosan	Clove EO	Raw salmon slices	Extended shelf life by reducing *Listeria innocua*, *Escherichia coli*, and *Pseudomonas fluorescens*	[75]
Alginate, chitosan, and gelatin blend	Sage EO	Common carp burger	Controlled spoilage bacteria; preserved sensory quality at 4 °C	[78]
Locust bean gum and sodium alginate	Lemon verbena EO	Large yellow croaker (whole fish)	Maintained microbial quality, inhibited *Pseudomonas* spp. and lactic acid bacteria	[79]
Gelatin coating	Orange leaf EO	Deep-water pink shrimp	Shelf life extended by 10 days; reduced Enterobacteriaceae and total volatile basic nitrogen levels	[80]
Chitosan and gelatin films	Ziziphora clinopodioides EO	Peeled shrimp	Chitosan films + essential oil are most effective against Listeria monocytogenes, *Pseudomonas* spp., and lactic acid bacteria	[81]
Bombacaceae gum-based film	Cinnamon leaf EO	Salmon fillet	Strong antioxidant activity; reduced malondialdehyde and hydroperoxide levels during storage	[82]
Fully deacetylated chitosan	Clove EO + kojic acid	Whole shrimp	Inhibited melanosis; preserved texture and color stability	[83]
Rice starch film	Oregano EO	Marine catfish fillet	Lower thiobarbituric acid values; delayed lipid oxidation	[84]
Whey protein concentrate	Cinnamon EO	Beluga sturgeon fillet	Reduced total viable count, lipid oxidation, and enhanced sensory scores	[85]
Chitosan nanoparticles with collagen and anthocyanidin	Cinnamon-perilla EO	Red sea bream fillet	Lower total volatile basic nitrogen and thiobarbituric acid reactive substances; strong antioxidant effect	[8]
Polybutylene adipate terephthalate and polylactic acid composite	Carvacrol, citral, α-terpineol EO	Pacific white shrimp	Minimized proteolysis and melanosis; preserved muscle structure	[86]
Water-based dip treatment	Oregano + clove leaf EO	Pacific white shrimp	Inhibited protein degradation; preserved myofibrillar protein content	[87]

Limitations, regulatory issues, and consumer acceptance

EFCs as a sustainable alternative

EFCs made from natural polymers have gained traction as environmentally friendly and functional alternatives to synthetic cling films. These biodegradable materials, derived from proteins, polysaccharides, and lipids, offer effective barriers against contaminants and help preserve the freshness and quality of food. EOs have emerged as valuable additives to enhance the functionality of edible films, providing antimicrobial and antioxidant properties that extend shelf life and improve food safety [8,9]. Fruits and vegetables with edible coverings can inhibit respiration, lessen enzymatic browning, and postpone maturation. For instance, coated tomatoes remained firm and aesthetically pleasing for 15 days, and coated pineapples retained color and firmness for up to 9 days [88]. Coatings based on palm oil increased the shelf life of mangoes by 10 days, while active packaging further enhanced their freshness for an additional 15 days [89]. These natural coatings and films have many advantages. Adding natural antioxidants and antimicrobials improves food preservation and successfully extends shelf life. They are clean-label and environmentally friendly substitutes since their makeup satisfies consumer desire for natural and safe packaging options. They also offer practical advantages by enhancing food safety, preserving quality, and possibly even providing nutritional advantages. Their adaptability to various food varieties and packaging needs is made possible by their versatility and customizability. However, these materials also come with a few drawbacks. The flavor and aroma of food can be adversely affected by organoleptic problems, such as powerful essential oil scents. These films' antibacterial efficacy may vary depending on food interactions and outside environmental conditions. The expense of production and regulatory approval continues to hinder widespread adoption. Furthermore, acceptability may be constrained by customer hesitancy about edibility and safety. Significant technical problems include resolving storage issues and ensuring uniformity in film quality [90]. Additionally, the incorporation of EOs into EFC matrices often leads to structural fragility, primarily due to the incompatibility between hydrophobic EOs and hydrophilic polymer chains, resulting in reduced mechanical strength and flexibility [91]. The disruption of the polymer network caused by phase separation compromises film integrity, rendering EFCs brittle and less durable [92]. To address this challenge, the encapsulation of EOs within lipid-based nanocarriers, such as nanoemulsions, has proven effective in promoting homogeneous EO distribution and reinforcing the polymer matrix [93]. Moreover, encapsulation not only improves mechanical properties such as tensile strength and elongation at break but also protects bioactive compounds against volatilization and oxidation, thereby sustaining antimicrobial effectiveness over extended periods [94]. Notwithstanding these drawbacks, EFCs containing EOs are a promising development in food packaging that balances sustainability and practical advantages to improve food safety and preservation.

Consumer perception and cultural sensitivities

Since plant-derived EOs, including clove, thyme, oregano, and cinnamon, are known to have inherent antibacterial and antioxidant qualities, they are appealing for improving the performance of edible films and prolonging the shelf life of food. However, the stability, volatility, and potent sensory qualities of EOs make them difficult to incorporate into edible films, which may impact customer acceptability. By rupturing microbial cell walls, enhancing permeability, and inducing cell death, EOs have antibacterial action. Though their potent scents may restrict their use in culinary applications, chitosan films containing thyme and oregano EOs prevent *S. aureus, E. coli, and E. fecium* [95]. Encapsulation strategies have been investigated to address problems associated with EO stability and volatility. In food packaging applications, encapsulating EOs in polymers, liposomes, or solid lipid nanoparticles enhances their stability and regulates their release. For instance, it has been demonstrated that adding EOs to biopolymer films enhances their mechanical qualities and prolongs the shelf life of various food items [96]. Notwithstanding EOs' potent sensory qualities, these developments continue to be problematic. Consumer acceptability may be impacted by strong smells and scents that are added to food products by high doses required for antimicrobial

activity. For EO to be successfully used in edible films, it is therefore essential to maximize EO concentrations and create plans to conceal or lessen their sensory influence [97].

Navigating global regulations for EFCs containing EOs

The regulatory landscape for EFCs containing EOs varies considerably across global jurisdictions and must be carefully interpreted to ensure consumer safety and compliance. In the European Union, EFCs that are intended to be consumed as part of the food are explicitly excluded from the scope of materials regulated under food contact legislation, as defined in Regulation (EC) No 1935/2004, Article 1(3)(b) [98]. However, when EFCs contain active substances such as EOs with antimicrobial or antioxidant properties, they may be subject to the provisions of Regulation (EC) No 450/2009 on active and intelligent materials, which require manufacturers to ensure safety and evaluate the migration of active components into food [99]. The Food and Drug Administration (FDA) oversees using substances in edible coatings through its Code of Federal Regulations (CFR) in the United States. Components must be either approved food additives or classified as Generally Recognized as Safe (GRAS). The EOs such as clove, oregano, and cinnamon, are listed under 21 CFR §182.20 for flavoring use. However, when used as antimicrobials or antioxidants in EFCs, especially at higher concentrations or in novel delivery systems, additional safety evaluation may be required under 21 CFR parts 170 and 172 [100]. In China, while edible coatings can fall under food additive categories within GB 2760-2014, the country's regulatory framework for active food packaging is still developing. In Russia, efforts are being made to align national standards with Codex Alimentarius guidelines, but current laws do not explicitly address bioactive edible films, and regulatory clarity remains limited [101]. Moreover, although EOs are derived from natural sources, not all are safe for unrestricted use. Some contain compounds with known allergenic or cytotoxic properties, especially at elevated concentrations. Their volatility and strong sensory profiles also raise concerns regarding acceptable daily intake (ADI) and organoleptic compatibility. Therefore, migration testing, toxicological assessments, and encapsulation

technologies such as nanoemulsion or lipid carriers are increasingly recommended to control release rates and enhance safety. Given the complex and evolving legal context, researchers and product developers must consult regulatory authorities or legal advisors early in the development process to determine the appropriate classification of EO-based EFCs, whether as food, food additive, or packaging, and ensure compliance with toxicology, migration, and labeling requirements. Doing so will facilitate both regulatory acceptance and consumer trust.

Conclusions

The EOs have shown significant potential when incorporated into EFCs for seafood preservation. This review demonstrates that EO-infused films based on chitosan, gelatin, and composite polymers can effectively inhibit lipid oxidation, microbial growth, and proteolytic changes in seafood. Among the EOs reviewed, clove, cinnamon, and oregano oils consistently exhibited superior antimicrobial activity, with MIC values ranging from 0.0086 to 250 µg/mL against spoilage bacteria. The choice of matrix, whether protein-, polysaccharide-, or lipid-based, significantly influences the release and efficacy of EOs. For instance, chitosan-gelatin composite films containing 1% clove EO provided superior microbial inhibition and extended the shelf life of shrimp and salmon. The effectiveness of EO coatings also depends on concentration, food matrix compatibility, and environmental conditions such as temperature and humidity. Although regulatory and sensory issues pose limitations, especially concerning the volatility and aroma of EOs, encapsulation and nanoformulation techniques offer promising solutions. In conclusion, EO-enriched edible coatings and films represent a valuable strategy for replacing synthetic preservatives in seafood, aligning with consumer preferences for natural and sustainable food preservation solutions.

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Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that no generative AI or AI-assisted technologies were used in the writing, editing, or preparation of this manuscript. All content was developed solely by the authors.

CRediT Author Statement

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