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REVIEW

REVIEWS IN Aquaculture

Advancements in edible films for aquatic product preservation and packaging

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Abstract

This review focuses on the incorporation of various bioactive compounds into edible films/coatings, improving their properties using novel techniques, and discussing their applications in aquatic food products. Aquatic food products with a high nutritional value play an important role in the market. However, these products are susceptible to microbiological spoilage, chemical oxidation, and physical deterioration. Therefore, the use of functional edible films and coating layers for shelf life extension is a critical issue. In this review, marine-based biopolymers, peptides, biodegradable polymers, and their conjugates as edible film/coating materials are summarised, and commonly applied methods are explained. Polysaccharide and/or protein films enriched with plant extracts, phenolic compounds, and essential oils (EOs) have also been presented. Recent studies have indicated that nanostructures, such as nanofibers, nanoparticles, and nanoemulsions, have gained interest for the nanoencapsulation of bioactive ingredients or antimicrobial agents in edible films to preserve freshness. Therefore, nanocomposite packaging film materials with improved moisture barriers have a strong impact on oxidation and microbial delay. The combination of various compounds or synergistic treatment of edible films with other nonthermal methods such as ozonation, high hydrostatic pressure, and irradiation, are recommended as alternative edible film modification methods. Finally, the enrichment of edible films with microorganism-based additives, bacteriophages, and enzymes is discussed. This review reports that the integration of natural antioxidants, phenolic compounds, probiotics, and bacteriocins with antioxidant and antimicrobial activities in edible films and their packaging applications has the potential to prolong the shelf life of aquatic products.

KEYWORDS
antimicrobial film, aquatic food quality, edible coating, edible packaging, shelf life extension

1 | INTRODUCTION

It is widely known that aquatic food products spoil more easily than other meat products and should be transported and delivered fresh.[1–3] Packaging materials protect a product from external influences, keep the product together, and facilitate its distribution and marketing. Packages containing antimicrobial substances can delay the growth of microorganisms and increase the shelf life and quality of food products.[4] Edible film

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packages protect aquatic food products because they reduce the rates of moisture and gas transfer between food and the surrounding environment and may also serve as carriers for aroma/flavouring compounds for better sensory quality.[5] Furthermore, edible films may reduce the negative environmental impacts of non-biodegradable plastic coating materials with carcinogenic properties.[6]

Edible films have been in use since the 16th century. Earlier, meat products were coated with fats to preserve colour and brightness, and to reduce water loss.[1,7] Fewer water changes in edible film-applied samples may be due to the inhibition of protein denaturation, leading to retention of their hydration capacity. Therefore, one of the most important features of edible films is their resistance to water vapour absorbency, thereby reducing weight loss that may occur in food, fat oxidation, and rancidity, and preserving the freshness of the product.[1] Deterioration of texture, water retention, and colour also affect appearance and have a great economic impact. Texture degradation and lipid oxidation, which can change flavour and colour, can be inhibited in aquatic products using edible films.

Edible films and packaging have various applications for aquatic food products. They can be applied directly to the surface of a product by brushing, spraying, dipping the product into a film-forming solution, or panning with the aid of drying.[5] Edible film packages used as coating or wrapping materials have also been reported.[8]

The material used in edible films should be safe, allow slow but controlled product respiration, provide structural integrity, improve mechanical processing, act as a binder for food additives, and prevent or delay microbial spoilage during storage.[1,9] Therefore, edible films potentially contain compounds that protect against spoilage bacteria or moisture. Various food-grade plasticisers such as glycerin, ethylene glycol, sorbitol, mannitol, and polyethylene glycol are added to the structures of edible films to improve their mechanical properties. These substances are generally small molecules with low molecular weights and boiling temperatures suitable for polymers.[1,5,10]

Plant extracts, antioxidants, phenolic compounds, and EOs positively affect the stability of aquatic food products.[11] Antioxidants can prevent oxidation by slowing the generation of free radicals, whereas antimicrobial agents can inhibit bacterial growth.[12–14] Moreover, pre- or post-treatment with ozonation, microwave irradiation or gamma irradiation methods can be novel alternatives for the modification of edible films.[12,15,16] Nanoencapsulation of antimicrobial substances, such as metals, in edible films and the development of nanocomposite film materials are also gaining interest.[5,17,18]

Recently, increased interest in healthy diets has led to the research and development of new functional foods containing probiotics, prebiotics, and natural antimicrobials.[19,20] Probiotics are live microorganisms that exert beneficial health effects.[21,22] *Lactobacillus* and *Bifidobacterium* including films cause damage to the total bacterial counts and H_2S-producing microorganisms when combined with high-pressure treatment.[23] Therefore, probiotic strains incorporated into biopolymer films pass to the muscle, increase beneficial lactic acid bacteria (LAB) in aquaculture products, and contribute to preservation.

The purpose of this review is to provide an overview of the published research on edible film types, application methods in aquaculture products, their combination with auxiliary materials and nonthermal treatments, and their effects on the quality of aquatic food products.

2 | EDIBLE FILM TYPES

Polysaccharides and proteins are the main components of edible films used as wall materials.[5] Their conjugates and the incorporation of other auxiliary materials, such as EOs, nanostructures, plant extracts, microorganism-based compounds, and enzymes, have been reported in previous literature (Figure 1). This section discusses the main components of the edible films.

2.1 | Protein-based Films

Protein-based edible films used in aquaculture products can be prepared from whey, collagen, gelatin, soy, corn, or wheat.[1,24] Fish gelatine is another source of animal-based proteins. Özyürt et al.[25] investigated the effects of fish proteins, extracted using acid- and alkali-assisted processes, as a biodegradable coating material on rainbow trout (*Oncorhynchus mykiss*) during cold and frozen storage. They stated that the total viable and psychrophilic bacterial counts improved faster in uncoated fillets than in the coated fillets. They also reported that protein-based coatings prevented the deterioration of the pH, Total Volatile Basic Nitrogen (TVB-N), and free fatty acid values. However, edible films of fish water-soluble proteins have lower water vapour permeability than many other protein films.[1,26] Several studies have been published on the quality of fish-protein films.[1,10,27–29] Some production methods and aquatic food product-based film materials are presented in Table 1. Edible films can be produced directly from fish meat or water-soluble proteins in the surimi washing water.[1,30,36] Fish mince is washed several times with cold water to remove sarcoplasmic proteins in order to make the surimi tasteless and odourless. This surimi washing water contains water-soluble proteins that are nutritious and highly functional.[1,29] Weng et al.[36] prepared film-forming solution using frozen Alaska cod surimi, and heated them to 45, 70, and 100°C to induce denaturation of protein molecules. Solubility, surface hydrophobicity, and reactive sulfhydryl content of surimi proteins increased, myosin heavy chain degradation was more effectively inhibited at higher temperatures (70°C, 100°C), and mechanical properties improved with the reduction of film solubility and protein solubility of films. These results indicate that the mechanical properties of surimi films can be improved by preventing myosin heavy chain degradation through heat treatment.

Amino acids have been used as protective agents. ε-Polylysine, a natural peptide, has antimicrobial effects against gram-positive and gram-negative bacteria.[37,38] Hamaguchi et al.[34] investigated changes in

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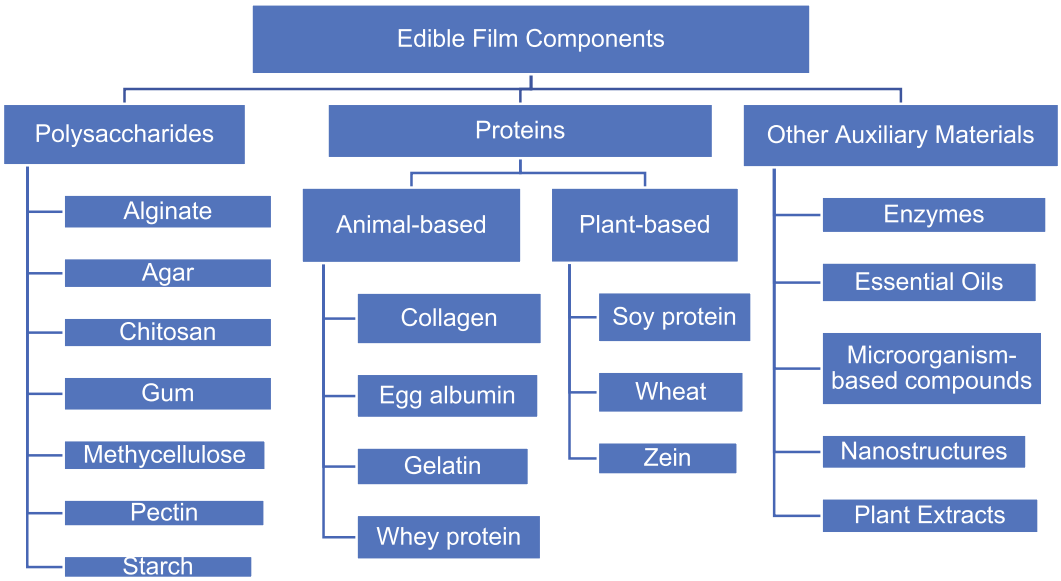


FIGURE 1 Schematic representation of edible film components.

TABLE 1 Marine-based edible film components and their properties.

Film components	Production method	Aim	Properties	Ref.
Alaska pollack (*Theragra chalcogramma*) surimi containing sorbitol, sucrose, and sodium triphosphate	Casting technique	Mechanical properties and intentional denaturation of surimi to investigate affect	Slight protein denaturation caused decreased elongation at break of the films and the complete denaturation gave rise to reduction of tensile strength and elongation at break.	30
3% fish gelatin, 0, 2, 5, 10 wt% (based on the gelatin) alginate dialdehyde	Solution dialyzing with sodium periodate	Mechanical properties	The mechanical strength and Young's modulus of the film increased significantly with an increase in the content of the alginate. Adding 10% alginate increased tensile strength and Young's modulus by 400% and 600%, respectively, and film remained stable for 30 days under wet environment.	31
Fish protein isolate/fish skin gelatin film containing basil leaf EO and ZnO nanoparticles (ZnOP)	Casting and drying	Mechanical properties and antimicrobial effect	ZnONP resulted in higher tensile strength but lower elongation at break. The lowest water vapour permeability was observed for the film incorporated with 100% basil leaf EO and 3% ZnONP. ZnONP exhibited strong antibacterial activity against pathogenic bacteria.	32
0, 1 and 4 wt% aloe vera added fish skin gelatin 8 wt%	Casting technique	Antimicrobial and mechanical properties	Hydrophilicity, solubility thermal properties increased. Microbial growth of *S. aureus* inhibited with the aloe vera addition. Better total phenolics content, and antioxidant activity.	33
2% blue marlin protein, 50% (w/w) glycerol, ϵ-polylysine	Casting and drying	Mechanical properties and intentional denaturation	Water vapour permeability of films was not affected by either the quality of the fish meat or the pH.	34
0, 1:20, 4:20, and 8:20 vitamin C/fish oil ratios	Electrospinning	Mechanical and antioxidant properties	Vitamin C/gelatin ratios 4:20 and 8:20 increased the nanofiber adhesiveness during the storage. Adding Vitamin C decreased loading capacity and prevented lipid oxidation.	35

fish meat quality by applying fish protein-based edible films. Enrichment of the film solutions with ϵ-polylysine reduced the microbial load of the films during storage of blue marlin fish meat at 30°C. The mechanical properties of the films were slightly affected by the acidic and alkaline pH values, and the water vapour permeability of the protein films was not affected by the fish meat quality or the pH of the film-forming

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TABLE 2 Biodegradable films containing proteins and polysaccharides and their effect on aquaculture products.

Film composition	Sample	Application	Storage	Results	Ref.
Chitosan-based edible film	Sea bass (*Dicentrarchus labrax*) fillets	Wrapped and vacuum packaged using polyethylene bags	4°C	Vacuum packaging with reduced trimethylamine (TMA), TVB-N, and growth of microorganisms ($p \leq 0.05$). Shelf life increased to 30 days.	40
1% and 2% chitosan solution, egg albumin, soy protein concentrate	Pink salmon fillets (*Oncorhynchus gorbuscha*)	Dipped for 5 min then packed in polyethylene bags	−20°C, 3 months	2% chitosan coating showed higher yield. No significant effects of coating on L^*, a^*, b^*. Lipid oxidation inhibited.	41
1%, 3%, and 5% chitosan (w/w) incorporated in low density polyethylene	Tilapia (*Oreochromis mossambicus*)	Heat sealed film	2°C, 30 days	Peroxide value (PV), free fatty acids (FFA), TVB-N and aerobic plate count revealed good antibacterial property. Longer shelf life compared to control film.	42
Round scad protein film including palm oil and chitosan	Dried fish powder	Covered	28–30°C, 21 days	Lipid oxidation inhibited more effectively than control film. No reduction regarding water migration into the sample.	43
Sodium alginate with concentrations of 0/25%, 1/25%, 0/75%, and 1/75% (w/v)	Kilka	Soaked for 1 h then packed in polyethylene utensils	Frozen storage up to 6 months	Total bacteria and *Staphylococcus* bacteria count in coated samples showed a decrease. FFA, thiobarbituric acid reactive substances (TBARS), PV, TVN and pH in coated samples showed a decrease ($p < 0.05$).	44
Gums, zein, rennet casein, wheat, and corn flour in different ratios	Prefried trout fillets	Breading and battering produced a film during the frying process	−18°C, 7 months	Spoilage delayed, and the sensorial features improved. Lower levels of pH, TVB-N, and TBA compared to control.	2

solution. Recently, Ala-Tyr dipeptide-added furcellaran/gelatin films have been used for the preservation of aquatic food products.[39]

These studies and the data in Table 2 indicate that protein-based films may be produced from seafood products and have a positive effect on the quality of aquatic food products during storage.

2.2 | Polysaccharide-based films

The primary sources of polysaccharide films are wheat, cellulose, gum, starch, pectin, and chitin/chitosan.[1] Chitosan, a polymer obtained by deacetylation of chitin, has no toxic effects, and shows antimicrobial activity. Therefore, it is one of the main polysaccharides widely used in films for aquatic food preservation. Lee et al.[45] reported that chitosan and ascorbic acid coatings had positive effects on tilapia (*Oreochromis niloticus*) fish shelf life during cold storage. They reported that uncoated fillets had a shelf life of 6 days less than that of coated fillets with higher lipid oxidation and the pH value, and 2% chitosan coatings with 5% ascorbic acid were effective in increasing the shelf life. Günlü and Koyun[40] determined the microbial and chemical quality of rainbow trout (*Oncorhynchus mykiss*) fillets under cold storage conditions (4°C) treated with chitosan-based edible film and hydrostatic pressure. Both hydrostatic pressure and chitosan-based edible film samples increased the shelf life by 24 days. Fadıloğlu et al.[46] treated chitosan films, enriched with sumac, on rainbow trout (*O. mykiss*) fillets. The shelf life of cold-stored fillets was extended by 6 days compared to that of the controls. In another study, a chitosan coating was applied to silver carp to determine its quality and shelf life during frozen storage. It was reported that 2% chitosan coatings preserved the chemical and sensory characteristics of the fish at −3°C and extended the shelf life.[47]

Cellulose-based films are used as oxygen and water barriers in high-fat food. These films reduce the loss of crispness in deep-fried foods by reducing oxidation and preventing water reabsorption.[1,48] Methylcellulose is a cellulose ether formed by the reaction of cellulose with methyl chloride followed by alkali treatment. Thermal gelling of methylcellulose results in excellent film-forming properties and is widely used in the preparation of edible films.[1,49] Cellulose absorbs most of the water in a product because of its large polymeric structure. Owing to this feature, cellulose-containing films have positive effects on rancidity.[1] Methylcellulose or hydroxy methyl cellulose minimises loss during cooking, reduces fat intake, and reduces moisture loss when applied as glazes in aquatic food products.[1,50]

Alginate, which is mainly derived from brown algae, can also be used to form film coatings on aquatic food products. Hamzeh et al.[51]

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coated rainbow trout fillets with 3% sodium alginate solution and stored them under cold storage conditions (4°C) for 20 days. Coating with sodium alginate contributed positively to the quality characteristics of the processed fresh fish fillets and extended their shelf life. Other polysaccharides, such as starch, pectin, and agar alginates, have also been reported to improve the mechanical properties.[52,53]

2.3 | Protein/polysaccharide conjugates

Because polysaccharides are hydrophilic, their water-barrier properties are poor. Proteins are more hydrophobic than polysaccharides. Waxes and triglycerides form thinner and more fragile film structures. The films can be modified using these substances to improve their structural properties. With the integration of oil, the films absorb less water vapour, resulting in better water vapour and barrier properties. The barrier properties of these films depend on the degree of saturation, melting point, and hydrophobicity of oil. Therefore, the properties of some conjugate films can be improved by combining polysaccharides and proteins. For instance, pink salmon (*Oncorhynchus gorbuscha*) coated with chitosan, egg albumin, and soy protein concentrate had higher moisture content than the control group during 3 months of frozen storage.[41] López-Caballero et al.[54] applied a chitosan/gelatine-based coating to cod patties and examined their colour, hardness, flexibility, stickiness, chewing, TVB-N, thiobarbituric acid (TBA) values, total bacteria, Pseudomonas, LAB, and *Staphylococcus aureus* counts. According to the results, the coating increased elasticity and prevented chemical and microbial spoilage.

Notably, coating and wrapping film application may have different effects on the physicochemical and microbiological properties of aquatic food products.[55–57] In a study by Nowzari et al.[58] chitosan/gelatine-based films showed slower rancidity development on rainbow trout fillets in a period of 16 days at 4°C. Edible coatings (prepared by immersion/dipping fillets into a solution) were superior to films (prepared by wrapping) in terms of retaining the lipid oxidation. Alemán et al.[55] used a chitosan–gelatin–shrimp concentration-based coating and wrapping film to preserve surimi sausages during chilled storage. The film inhibited microbial growth more than the coating did.

The abovementioned results and the studies presented in Table 2 indicate that a mixture of proteins and polysaccharides and their different applications (coatings or films) are promising for the preservation of aquatic food products.

3 | EDIBLE FILM APPLICATION METHODS

Edible films are generally applied to aquatic foods using methods, such as immersing/dipping, spraying, brushing, or wrapping of the film material (Figure 2). These methods vary according to the surface and properties of the aquaculture products and the properties of the edible film solution used.

Dipping is one of the most common methods used to coat foodstuffs.[59,60] This is based on the principle that the product to be coated is immersed in an edible film solution and the product absorbs the solution. The immersion process consists of three steps. In the first step, the product is immersed in an edible film solution. The excess surface fluid is filtered and removed.[59,61] Subsequently, the solvent and excess liquid on the surface of the product are evaporated by heating and drying.[59,62] When the excess coating solution is removed, the solution will either be dried at room temperature or using a dryer.[59,63] This method is simple and inexpensive.[59,64] As it provides good uniformity on the surface, it is suitable for the complete coating of aquatic food products.[59,65]

Spraying is another common method used to coat surfaces.[59,66,67] By creating droplets, the surface area of the liquid is increased and distributed over the food through a series of nozzles. Air-blast and pressure atomization are some of the commonly used spraying techniques.[59,68] Pouring is another commonly used method. This is based on the principle that an edible film solution

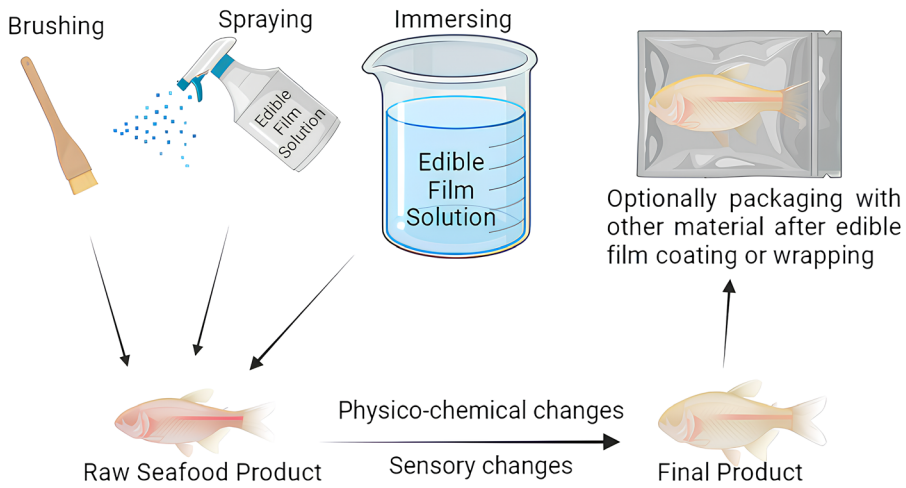


FIGURE 2 Application methods of edible films on aquaculture products.

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is poured onto a generally flat product surface and the solution forms a layer on this surface. Dissolving the biopolymer in an appropriate solvent, transferring the solution into a mould, and forming an edible film solution are the three main steps in film preparation.[59,69] Air dryers, such as hot air ovens, tray dryers, microwaves, and vacuum dryers, facilitate the drying of the edible film solution and the removal of the film from the mould.[59,70] The rapid drying of the film negatively affects its physical and structural properties.[59,71] On the other hand, the brushing method is based on the application of the edible film solution with a brush without leaving any gaps on the product surface. Packaging film materials can also be developed by uniformly embedding polymers into composites. Reesha et al.[42] developed a chitosan-incorporated antimicrobial polyethylene film using blown film extrusion and applied it to fish products. Other applications, such as nanocoating by rubbing, wrapping, or coating of film solutions, have also been studied in previous literatures.[3,17,72–74]

4 | INCORPORATION OF OTHER MATERIALS FOR EDIBLE FILM IMPROVEMENT

In addition to film-forming high-molecular-weight polymers, plasticisers, and solvents are the main components of edible films.[75] Plasticiser agents reduce the intermolecular forces and increase the mobility of the biopolymer chains, thereby improving the mechanical properties of the film. Plasticisers are also necessary to provide gloss to the polysaccharide film and generally increase the passage of gases, water vapour, and solid materials dissolved in the film.[1,48] When a solvent is added to protein films, partial denaturation of polypeptide chains occurs because of pH changes, the addition of an electrolyte that provides crosslinking, or the application of heat.[1,76] Films in the protein structure depend on various factors such as the pH of the protein solution, plasticiser, thickness of the prepared film, preparation conditions, and structures included in the solution forming the film.[1,27] Other auxiliary materials, such as EOs, plant extracts, nanostructures, and microorganism-based compounds, are explained in this section.

4.1 | Plant extracts or phenolic compounds

Plant-derived extracts have been extensively used as film enhancers to improve antibacterial and antioxidant activities. Recent publications on plant extracts, natural antioxidants, and phenol-added films for aquaculture products are summarised in Table 3. These extracts significantly delayed lipid oxidation and microbiological degradation during storage.[81] For instance, Raeisi et al.[101] covered semi-fried rainbow trout (*O. mykiss*) fillets with shallot berry (*Allium ascalonicum*) and corn anise (*Trachyspermum ammi*) seed extracts. Similarly, Bazargani-Gilani[102] developed resveratrol-loaded alginate to protect rainbow trout fillets during cold storage for 15 days. These films were more effective in inhibiting the growth of LAB, yeasts, and moulds than alginate films without resveratrol. Other compounds, such as *Jacaranda cuspidifolia* anthocyanin[16] polyphenols from tea,[92] and gingerol,[87] have also been reported to enhance the antibacterial properties of films. Therefore, plant-derived fruit polysaccharides can be utilised as a new source of pectic polysaccharides in edible films.[13,14] All these studies prove that herbal extracts, anthocyanins extracted from plants, or polyphenols are alternative natural preservatives that improve the mechanical, moisture resistance, thermal, and antimicrobial properties when included in edible films.

4.2 | Essential oils

In recent years, EOs with phenolic and nonphenolic components have attracted significant attention because of their antimicrobial and antioxidant properties in aquatic food products.[103] EOs obtained from plants can be used to preserve aquatic food products. Furthermore, in the film-forming process, the incorporation of oils may reduce the surface roughness because they occupy tiny surface voids. Lemon,[104] marjoram,[105] carvacrol,[106] cinnamon,[107,108] garlic,[109] estragon,[110] clove,[111] ginger,[112,113] laurel,[114] turmeric, orange peels,[115] rosemary, thyme, oregano,[116,117] and basil[117,118] have all been successfully used as film materials. For instance, chitosan films enriched with thyme (*Origanum minutiflorum*) and rosemary (*Rosmarinus officinalis*) EO improved quality characteristics and shelf life of smoked rainbow trout at 4°C.[119] Lu et al.[120] investigated the quality and shelf life effects of composite films consisting of chitosan, polyvinyl alcohol, and thyme EO on snakehead (*Channa argus*). They stated that the samples treated with the edible film have 4 days longer shelf life. The properties of the edible films containing EOs and their effects on the physicochemical properties of aquatic food products are presented in Table 4. As shown in this table, non-thermal treatments have also been applied to EO-added films. Cold plasma and high-pressure treatments improve the thermomechanical, physical, and structural properties of edible packaging films.[137] These treatments can also slow down the release of active compounds included into the edible films through the process of cross-linking between biopolymer and active compound. This allows for a controlled release of bioactives into aquatic food products, thereby reducing the microbial load.[15,121,126,138] So pre- or post-treatment with cold plasma, ozonation, and high hydrostatic pressure should be further investigated to obtain a synergistic effect on EO-incorporated films.

4.3 | Nanostructures

One of the most exciting and promising research areas in the field of edible film improvement is nanostructures.[3,5] In Table 5, various nanomaterials such as nanofibers, nanoparticles, and nanoemulsions, have been reported in the literature for the preservation of aquatic food products. Nanomaterials enhance surface area, increase the loading

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TABLE 3 Biodegradable films containing plant extracts, natural antioxidants or phenolic compounds and their effect on aquaculture products.

Composition	Sample	Application	Storage	Results	Ref.
Chitosan-young apple polyphenol films	Grass carp (*Ctenopharyngodon idellus*) fillets	Wrapping	Cold storage, 8 days	Microbial growth delayed, PV, TBARs, TVB-N, and pH values, water holding capacity decreased.	77
Chitosan film incorporated with ginger extract Chitosan + ginger coatings	Silver Carp (*Hypophthalmichthys molitrix*) fillets	Packaged with film and then in polyethylene plastic Immersing	4°C for 12 days	Chitosan film containing 10% ginger extract showed the lowest levels of peroxide, TBA, TVC, and PTC compared to the coating and controls.	78
Anthocyanin extracted from the *Jacaranda cuspidifolia* petal was incorporated into chitosan and polyvinyl alcohol	Fish fillet	Coating	Room temperature, 52 h	UV–Vis light transmission reduced ($p < 0.05$). Increasing anthocyanin concentration showed improved oxygen permeability and moisture retention capacity. Antibacterial activities determined against *S. aureus*, and *E. coli*.	16
Collagen hydrolysate-chitosan film loaded with red cabbage extracts	Shrimp	Immersing in coating solution	4°C for 6 days	Good barrier ability, antioxidant, and antibacterial activities.	72
Chitosan films with conjugated or incorporated chlorogenic acid	Pacific white shrimp (*Penaeus vannamei*)	Wrapped then was put into zip-lock bag	4°C for 8 days	Enhanced opacity, water solubility, antioxidant, and antibacterial activities.	79
1.5% chitosan, 12.5% sea fennel plant and sea fennel extracts	Atlantic horse mackarel (*Trachurus trachurus*) burgers	Coating by placing on burgers	4°C, 12 days	Extract produced a better pH than sea fennel plant and enhanced the antioxidant properties and lipid oxidation. Plant had better acceptability than extract.	80
Chitosan films enriched with seaweeds (*Himanthalia elongata* and *Palmaria palmata*) and seaweed extracts	Rainbow trout (*Oncorhynchus mykiss*) burgers	Coated, placed in trays covered with aluminium	4°C, 7 days	Both seaweed extract films reduced the antioxidant loss better than seaweed films. A minor antimicrobial activity in films with extracts observed. *H. elongata* exhibited higher total phenol content and antioxidant capacity than *P. palmata*.	81
Citric acid (0.5% w/v), 1.5% (w/v) chitosan, 0.6% (v/v) acetic acid and 1% (w/v) licorice extract	Frozen farmed ovate Pompano (*Trachinotus ovatus L.*)	Dipping	−18°C, 6 months	Citric acid and licorice extract enhanced the antioxidant effects. Chitosan and licorice extract showed the best antioxidant effects, reducing PV, TBARS.	82
Gelatin-water soluble chitosan film	Bluefin tuna (*Thunnus thynnus*) slices	Wrapping	4 ± 1°C for 10 days	Lipid oxidation retarded and microbial growth slowed. Shelf life increased 6 days more.	83

(Continues)

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TABLE 3 (Continued)

Composition	Sample	Application	Storage	Results	Ref.
infused with 0.5 mg/mL squid Maillard peptides					
Chitosan-gelatin film with grape seed extract (1% and 2%) and Ziziphora clinopodioides EO (1% and 2%)	Rainbow trout mince	Wrapping	4°C, 11 days	pH, TVBN, PV decreased. *Pseudomonas fluorescens*, *Shewanella putrefaciens*, *Listeria monocytogenes*, *Enterobacteriaceae* growth delayed.	84
Resveratrol and coating with chitosan and alginate edible films	Brined and smoked sea bass (*Dicentrarchus labrax*) fillets	Immersing, 1 min	4 ± 0.5°C, 4 weeks	Resveratrol antioxidant effect was enhanced when coated with alginate or chitosan.	85
Alginate-calcium coating containing *Citrus wilsonii* Tanaka extract	White shrimps (*Litopenaeus vannamei* Boone)	Immersing, 2 min	4°C, 6 days in polyethylene bags	*C. wilsonii* exhibited significant antimicrobial activity against *L. sphaericus*, TVC of the treated shrimps was 10 times lower than the control, rate of the increase in pH and TVB-N slowed. Higher sensory score observed.	86
Sodium alginate coating enriched with 6-gingerol (0.5%)	Red sea bream (*Pagrosomus major*)	Immersing	4°C, 20 days	Lipid oxidation, protein degradation, nucleotide breakdown delayed, microbial growth inhibited. Combination showed better sensory and textural results.	87
ε-polylysine (0.4% w/v) in combination with alginate coating	Japanese sea bass (*Lateolabrax japonicas*)	Coating	4°C, 16 days	Nucleotide breakdown, lipid oxidation, microbial growth retarded. Better texture and sensory results observed.	37
Olive leaf powder and different levels (0, 1.88, 3.75 and 5.63 w/w) of olive leaf extract incorporated gelatin films	Inoculated cold-smoked salmon	Wrapped to cover the entire top surface	23°C, 58% RH for 6 days	Films with extract at 5.63% (w/w) reduced *L. monocytogenes* growth. Extract concentrations over 3.75% (w/w) increased film water vapour permeability. Extract has significantly higher phenolic content, antimicrobial and antioxidant activity than powder.	88
Epigallocatechin gallate–gelatin biofilm treatment	Tilapia fillets	Immersing, 30 min	4°C for 21 days	Lipid and protein oxidation were significantly delayed. Shelf life was extended by 6 days.	89
Propolis extract (2%, 8%, and 16% by volume per mass of gelatin) added gelatin films	Rainbow trout (*Oncorhynchus mykiss*) fillets	Wrapping	4°C for 15 days	Antioxidant and antimicrobial properties enhanced. Using 8% and 16% extract in gelatin films longer shelf life.	90
Oregano or rosemary extract-enriched edible films based on	Cold-smoked sardines (*Sardina pilchardus*)	Wrapped then placed in ethylene vinyl alcohol copolymer matrix	5°C for 21 days in dark conditions	Oregano or rosemary extract was able to retard lipid oxidation. Combinations of high pressure and coating with film added with an oregano extract, microorganism	91

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TABLE 3 (Continued)

Composition	Sample	Application	Storage	Results	Ref.
gelatin or gelatin–chitosan				counts, and oxidation indices were kept well below.	
1.2%, 2.4%, and 3.6% (w/v) gelatin and 0.4% (w/v) tea polyphenol	Golden pomfret	Immersed for 30 min then packed in polyethylene bags	4°C, 17 days	0.4% tea polyphenol + 1.2% gelatin treatment showed the best effect on reducing the weight loss, lowering pH and microbial growth, slowing down the myofibril degradation and rate of PUFA oxidation.	92
Polyethylene films coated with (p-coumaric and ferulic acids) obtained from barley husk extract	Farmed coho salmon (*Oncorhynchus kisutch*)	Polyphenol vacuum package combined coating	18°C, for 3, 9, 15, and 18 months	Combination of vacuum and polyphenol extracts showed lower ($p < 0.05$) peroxide and anisidine values and to an inhibitory effect ($p < 0.05$) on α- and γ-tocopherol losses. A partial inhibitory effect on rancidity was observed. No effect observed on FFA.	93
Low-density polyethylene film with barley husk antioxidants	Frozen cod (*Gadus morhua*)	Packaging with low-density polyethylene film	12 months of frozen storage at −20°C	Control samples were more susceptible to lipid hydrolysis and lipid oxidation. The antioxidants were shown to increase oxidative stability.	94
Low-density polyethylene film two different antioxidants from with barley husk extract	Hake (*Merluccius merluccius*) muscle			Lipid hydrolysis slowed and oxidative stability increased compared to controls.	95
Phenolic compounds were extracted from barley husk	Atlantic salmon (*Salmo salar* L.)			Efficacy in delaying the hydrolysis of lipids and increasing the oxidative stability.	96
Ethylene-vinyl alcohol copolymer film containing ascorbic acid, ferulic acid, quercetin, and green tea extract	Salted sardines (*Sardina pilchardus*)	Vacuum packaged in aluminium/low-density polyethylene bag in contact with both sides	4°C for 13 days in dark conditions	Reduction of the peroxide index and the content of malondialdehyde. The film with green tea extract showed the best protection against lipid oxidation. Films containing green tea extract and quercetin showed a decrease in permeability values.	97
Basil seed gum-based film enriched with *Echinophora platyloba* extract (0%–2%/dry matter)	Silver carp (*Hypophthalmichthys molitrix*) fillets	Wrapping	4°C for 16 days	The film loaded with 2% extract overall showed optimum acceptable physicochemical properties. Lower pH, TVB-N, and TBA, PV, and microbial load after 16 days of storage for 2% EPE added film.	98
Catechin-kradon (*Careya sphaerica Roxb*) extract (0.9%)	Bluefin tuna slices (*Thunnus thynnus*)	Wrapping	4°C for 10 days	Decreased the formation of primary and secondary lipid oxidation products, delayed PV, TBARS and TVB-N. Shelf life increased for 6 days.	99
Cowpea (*V. unguiculata*) starch/maqui berry extracts	Salmon	Wrapping	4°C for 6 days	Maqui berry extract increased solubility and water vapour permeability. Lipid oxidation delayed.	100

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capacity of bioactive compounds, and improve the stability and mechanical properties of films and coatings. Nanomaterials are generally considered to have a particle size <100 nm.[156] Nanofibers produced by electrospinning have attracted interest for encapsulation of bioactive ingredients in edible films. As nanofiber production does not require heating, it is more appropriate for the nanoencapsulation of heat-sensitive compounds.[74,155] Nanoparticles are submicron-sized solid carriers in the form of nanospheres, and have been also employed alone or with bioactives. Their antimicrobial action is associated with triggering local stress on the bacterial cell wall, resulting in bacteria membrane deformation.[17,157] Films containing ZnO,[52,57,153] silica,[146] and chitosan nanoparticles[144] with antimicrobial functions have been successfully applied to aquaculture products. Nanocomposite materials consisting of polymer matrices can be reinforced using nanoparticles or nanofillers.[105] Composite films enriched with nanochitosan,[158] chitosan–lignin nanoparticles,[143] ZnO,[154] and nanoclays[105,151] have also been reported.

Nanoemulsions mostly cover a size range of 100–600 nm that exhibit a milky appearance. Nanoemulsions can increase the transport of active compounds across biomembranes.[149] Thus, edible films containing nanoemulsions may exhibit improved properties.[139]

These studies indicate that the use of nanofibers, nanoparticles, nanoemulsions, and nanocomposite films with high antimicrobial and barrier functions have the potential to improve the stability of aquaculture products during storage.

4.4 | Additives of microorganism origins and enzymes

Increased consumer interest in health and nutrition has led to improved research on the film-forming properties of biopolymers containing microorganism-based compounds.[6] Studies on aquaculture products used in combination with microorganism-based antimicrobial agents and enzymes are summarised in Table 6.

Products targeting intestinal health have led to research and development in the functional food market. Probiotics, mainly *Lactobacillus* and *Bifidobacterium* groups, are living cells with beneficial properties, and their use in edible films has attracted interest.[170] For instance, strains grown on agar containing green tea extract films exhibited antimicrobial properties against *Escherichia coli*, *Listeria monocytogenes*, and *S. typhimurium*, inoculated with hake fillets.[164]

Bacteriocins are extracellular bioactive peptides or peptide complexes that exert bactericidal and bacteriostatic effects. They form a diverse family of proteins that exhibit a broad spectrum of antimicrobial activity.[171] They are degraded by proteases in the gastrointestinal tract; LAB are generally recognised as safe microorganisms. The application of bacteriocins as aquaculture food preservatives can be achieved using the bacteriocin strain as a starter culture, preservative culture, or bacteriocin as an additive. Nisin, a natural polypeptide isolated from *Lactococcus lactis* subsp. has been approved as a bacteriocin by the Food and Drug Administration and plays an important role in preserving seafood quality. The antibacterial activity of nisin in cooked and raw silver carp (*Hypophthalmichthys molitrix*) or tilapia (*O. niloticus*) fillets has been previously reported.[159,165,172]

LAB provide taste and texture and increase the nutritional value of meat products. Concha–Meyer et al.[162] isolated *Carnobacterium maltaromaticum* from smoked salmon and incorporated into alginate films to reduce *L. monocytogenes* growth in the inoculated salmon. Other researchers have stated that adding sodium lactate or sodium diacetate to chitosan-based films can effectively control *L. monocytogenes* contamination on the surfaces of smoked salmon.[56]

Bacteriophages are ubiquitous viruses and natural antagonists of bacteria which only kill certain bacteria. Phages are extremely specific to their hosts; therefore, they do not kill normal and beneficial microflora, unlike traditional chemical antimicrobials.[173] Kalkan[174] applied an edible film-based methylcellulose and encapsulated phages to raw fish fillets to evaluate their antibacterial activity against *V. parahaemolyticus*. Results showed that fillets had a bacterial reduction by about 6.46 $\log_{10}$ CFU cm^{-2} with respect to the control. Although the application of edible films for aquatic food preservation via the incorporation of bacteriophages is rare, the use of phages should be further investigated in the future.

Enzymes, such as lysozyme and lactoperoxidase, have also been used in edible films. Lysozyme is a food-grade antimicrobial enzyme with bacteriostatic activity that efficiently controls the growth of pathogens, particularly gram-positive bacteria.[160,166] Datta et al.[161] investigated the antimicrobial effects of calcium alginate and oyster lysozyme, with or without the addition of nisin, on smoked trout, against *L. monocytogenes* and *Salmonella anatum*. They indicated that calcium alginate coatings containing lysozyme, with and without nisin, could be used to reduce the growth of *L. monocytogenes* and *S. anatum* on the surface of ready-made smoked trout. Therefore, the encapsulation or integration of lysozymes or bacteriosins into films is promising for reducing the growth of pathogenic bacteria. Lactoperoxidase, a single polypeptide chain found in milk, saliva, and tears secreted in the mammary tissue, when incorporated into whey protein films shows antimicrobial, antifungal, and antiviral properties.[167,168] The combination of lactoperoxidase and α-tocopherol was found to impart antioxidant and antibacterial features to whey protein coating for pike perch fillets.[168]

These results indicate that edible films enriched with microbial compounds have potential applications in next-generation aquaculture packaging.

5 | CONCLUSION

Aquatic products are one of the most traded products in the global food sector. Therefore, there is a great demand for preservation and packaging. The industrial production and commercialization of biodegradable and non-toxic film materials with good barrier properties make them suitable for these purposes. Edible films based on

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TABLE 4 Biodegradable films containing essential oils and their effect on aquaculture products.

Composition	Sample	Application	Storage	Results	Ref.
Chitosan film coating combined with orange peel EO (2%)	Deepwater pink shrimp	Coated with film by both sides, then vacuum packed	4°C, 15 days	Lipid oxidation and microbial growth inhibited. The shelf-life of shrimps extended for nearly 8 days more when compared to the non-coated group.	115
Cold plasma-treated chitosan–wampee seed EO films	Golden pompano fillets	Coated then modified atmosphere packed	4°C, 13 days	Cold plasma and modified atmosphere packaging, exhibited the lowest total bacterial count, TVB-N, PV and TBA. Minimal colour changes, drip loss, and texture deterioration observed.	121
Flaxseed chitosan film with *Ziziphora clinopodioides* EO, and sesame oil	Raw minced trout fillets	Wrapping	4°C, 14 days	Reduced growth of *L. monocytogenes*, *S. aureus*, *E. coli* O157:H7, and *S. typhimurium*	122
Chitosan-ginger (*Zingiber officinale Rosc.*) EO	Cobia (*Rachycentron canadum*) fish steak	Wrapping	2°C, 30 days	pH, TVB-N, TBA increase delayed inhibition of *Pseudomonas*, *Brochothrix thermosphacta*.	123
Gelatine–chitosan edible films incorporated with clove EO	Cod (*Gadus morhua*) fillets	Covered and vacuum-packed in bags	2°C, 11 days	The growth of H_2S-producers, *Pseudomonas* sp. Enterobacteriaceae, lactic acid bacteria (LAB) inhibited. The occurrence of TVB-N delayed.	124
Chitosan blended with gelatine (from catfish skin) and clove EO	Raw sliced salmon	Covered and vacuum-packed in bags	2°C, 11 days	Good antimicrobial results against *P. fluorescens*, *Lactobacillus acidophilus*, *L. innocua*, and *E. coli* in vitro and on (in the latter case, the total bacterial counts were delayed by 2 log cycles).	125
Clove EO added gelatine-chitosan films with high-pressure treatment	Salmon (*Salmo salar*) carpaccio	Covering	5°C, 12 days	Chitosan and clove EO had a significant effect on water solubility, puncture force and deformation ($p \leq 0.05$), causing a reduction in water solubility. Clove components improved oxidative stability.	126
Locust bean gum and sodium alginate containing lemon verbena (*Lippa citriodora* Kunth) EO	Large yellow croaker (*Larimichthys crocea*)	Dipping	4°C, 3 days	0.30% or 0.60% LVEO incorporation inhibited the growth of mesophile bacteria, *Pseudomonas* spp., H_2S-producing bacteria, LAB, and psychrophilic bacteria ($p < 0.05$), and reduced the TMA, TVB-N values.	104
Carvacrol incorporated in flaxseed gum-sodium alginate	Chinese sea bass (*Lateolabrax maculatus*)	Coating	−4.0 ± 0.1°C, 12 days	Carvacrol has good antibacterial activity against *V. parahemolyticus*, *S. putrefaciens*, *S. aureus*, and *P. fluorescens*. FSG-SA films containing carvacrol presented better antimicrobial and antioxidant activities compared to the control film; however, their tensile strength was lower.	106
Fish gelatin films added with carvacrol (blended and grafted)	Prefried breaded hake medallions	Wrapped into films then heat sealed	−4 ± 1°C, 49 days	TVB-N and the total psychrotrophic bacteria counts were significantly lesser for FG-0.6CRV than in the other samples. The total oxidation index, PV, and p-anisidine value were reduced by 18%, 30%, and 16%, respectively.	127
Gelatin film incorporated with lemongrass EO	Sea bass slices	Placed in polystyrene-trays, then wrapped	4°C, 12 days	Growth of LAB, psychrophilic bacteria, and Enterobacteriaceae retarded. Changes of colour, K value, TVB-N and TBARS value were decreased.	128

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TABLE 4 (Continued)

Composition	Sample	Application	Storage	Results	Ref.
Furcellaran–gelatine coatings incorporated with herb extracts (Nutmeg, rosemary, thyme, milfoil, marjoram, parsley, turmeric, basil, and ginger)	Carp fish	Dipping	4°C, 12 days	Colour of the fillets treated with the rosemary and thyme extracts became slightly darker and had a propensity towards redness and yellowness. Rosemary extract effectively slowed the lipid oxidation processes. Rosemary showed better appearance, smell, texture, and overall acceptability attributes.	129
Gelatin-based edible films enriched with laurel EO (1% by volume per mass)	Rainbow trout (*Oncorhynchus mykiss*)	Wrapped then vacuum packaged	4°C, 26 days	Laurel EO showed quality characteristics at an acceptable level up to 22 days of storage, while the control and gelatin film without EO reached an unacceptable level at 15 and 20 days, respectively.	114
Polypropylene/low-density polyethylene composite films containing attapulgite loaded with *Allium sativum* EO	Large yellow croaker (*Pseudosciaena crocea*) fillets	Vacuum packed by film	4 ± 1°C, 10 days	The lipid oxidation of fish was delayed due to the slow release of EO. Lower TBA, TVB-N, and pH values observed compared to controls.	109
Poly (butylene adipate co-terephthalate) with oregano EO	Fish fillets	Wrapped with the films then heat sealed	7°C, 12 days	Higher EO concentration in the films showed the greater antioxidant activity. Lower growth of total coliforms, *Staphylococcus aureus*, and psychrotrophic microorganisms.	130
Bombacaceae gum films (2.5%, w/v) containing cinnamon leaf EO (0.75%, 1.00%, and 1.25%)	Fresh salmon fillets	Wrapped and stored in low-density polyethylene bags	4°C, 15 days	Cinnamon leaf EO caused a decrease in tensile strength, whereas film stretching ability and water barrier properties increased. 1.25% cinnamon leaf was particularly effective for inhibiting lipid oxidation. Antioxidant and antimicrobial activities observed.	107
Quince seed (1%) mucilage film incorporated with 0%–2% (V/V) thyme or oregano EO	Rainbow trout	Wrapping	4°C, 18 days	The lowest PV was obtained in fillets wrapped with film. A significant reduction observed in pH after 12 days ($p < 0.05$).	117
Quince seed mucilage films incorporated with oregano or thyme EOs	Rainbow trout fillets	Wrapping	4°C, 18 days	1%, 1.5%, 2% Oregano, 1%, 1.5%, and 2% Thyme resulted shelf life extension by 3, 5, 9, 6, 10 and 11 days, respectively.	131
Soy protein-based films containing 5% (v/v) EOs (*Thymus* sp., *Mentha piperita*, *Foeniculum vulgare*, *Laurus nobilis*, *Fructus cumini*)	African catfish (*Clarias gariepinus*)	Applied to surfaces then vacuumed with plastic bags	4°C, 15 days	Lower TBA, peroxide value, free fatty acidity compared to controls.	132
Sage seed gum film incorporating *Zataria multiflora Boiss* EO on the storage	*Otolithes ruber* fillets	Wrapping	5°C, 15 days	Effect of sage quality and biogenic amine content of microbial growth, lipid oxidation, biogenic amine accumulation decelerated. Alterations pH, TVB-N, and TBARS compared with oil addition.	133
Whey protein concentrate with 1.5% cinnamon EO	Beluga sturegeon (*Huso huso*)	Dipped into the coating solution for 30 s	4°C, 20 days	PV, TBA, TVC increase slowed, lipid oxidation retarded. Better sensory scores compared to controls	134

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TABLE 4 (Continued)

Composition	Sample	Application	Storage	Results	Ref.
Potato peel waste-based edible films with oregano EOs	Inoculated cold-smoked salmon	Covered and vacuum packed	4°C, 28 days	*L. monocytogenes* growth inhibited. Incorporation of oil into the films reduced the film strength and increased their water vapour permeability.	135
Agar film protein hydrolysate and clove EO (0.5 g/g)	Flounder fillets (*Paralichthys orbignyanus*)	Wrapping	5°C, 15 days	TVC, LAB, *Enterobacteriaceae*, H_2S-producer microorganisms, and *Pseudomonas* spp. growth delayed. Shelf life increased from 10 to 15 days.	136

TABLE 5 Biodegradable films containing nanostructures and their effect on aquaculture products.

Composition	Sample	Application	Storage	Results	Ref.
Anthocyanidin/chitosan nanocomposite-based edible films containing cinnamon-perilla EO nanoemulsions	Red sea bream (*Pagrus major*) fillets	Wrapping	4°C, 14 days	Edible films showed excellent antioxidant activity. Tle lowest TVB-N value was for the packaged film that contained anthocyanidins. 1% (v/v) blending film was extended shelf life by 6–8 days.	139
The gelatin-based film with cellulose nanofibers, epigallocatechin gallate and carvacrol	Sea bass (*Lateolabrax japonicus*)	Wrapping	4°C, 15 days	The shelf life extended to more than 15 days. Carvacrol and epigallocatechin gallate complex had synergistic antioxidant effects.	73
Chitosan films incorporated with Montmorillonite (0 and 1 g/100 g) clay and α-tocopherol (0, 10, 15 g/100 g)	Salmon	Wrapping	4°C, 8 days	Lower TBARS at 8 days indicated reduced lipid oxidation The magnesium content in salmon increased after 8 days showing potential nanoparticle migration.	140
Cellulose nanofiber/deacetylated quaternary chitosan composite	Raw salmon	Packed with nanofiber and nanofiber/composite 5% films and sealed with PET	4, 10, and 15°C for 12 days	Shelf life extended more than 1 day. Antimicrobial activity observed against *L. monocytogenes*.	141
Spirulina-loaded chitosan nanoparticles	Pike-perch (*Sander lucioperca*) fillet	Coating	4°C, 14 days	Higher overall consumer acceptability and the lowest values for TVB-N and TBA at the end of storage compared to control	142
Chitosan–lignin nanoparticles films (0, 1, 5, and 10 wt% based on chitosan)	Grass carp	Wrapped	4°C for 14 days	A significant decrease in TVC and TBARS observed. Shelf life extended 5 days. Even 1 wt% lignin nanoparticles improved UV-blocking, antibacterial, and antioxidant activity.	143
Cinnamaldehyde-loaded chitosan nanoparticles	Rainbow trout fillets	Wrapped	4°C for 16 days	Higher antibacterial activities against (*S. aureus*, *L. monocytogenes*, *E. coli*, and *S. enteritidis*). Antioxidant capacity enhanced, lipid oxidation delayed. The shelf-life was extended from	144

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TABLE 5 (Continued)

Composition	Sample	Application	Storage	Results	Ref.
				8 to 12 days compared to the control.	
Four different solutions; 1% chitosan, 0.1% gallic acid, chitosan/gallic acid, 1% chitosan nanoparticle and gallic acid	Horse mackarel (*Trachurus Trachurus*) fillets	Dipping	4°C, 13 days	Chitosan reduced microbial growth more than 2 log cycles. The lowest TVB-N, TBARS, and pH values were found with chitosan nanoparticle coating. Adding gallic acid delayed lipid oxidation	145
Chitosan-based film impregnated with turmeric EO-loaded magnetic-silica nanocomposites	Inoculated fresh surimi	Wrapping	Refrigerated for 14 days	Bionanocomposite-incorporated film had a stronger antibacterial effect against *B. cereus* than the film containing only turmeric EO. Physical and mechanical properties of film were significantly improved after adding nanoparticles.	146
Composite film based on chitosan nanoparticle, cinnamon EO and perilla EO/anthocyanidin	Red sea bream fillets (*Pagrus major*)	Wrapping	4°C, 14 days	Sensory evaluation, microbiological analyses, pH, TVB-N, TBARS values, colour and texture revealed the shelf life of fillets extended to 6–8 days Plant EO added film was better than that of the other groups.	147
Chitosan/clay bionanocomposite activated with rosemary EO	Fresh silver carp	Immersing for 30 s 2 times	4°C, 16 days	Lipid oxidation retarded and lower peroxide, FFA, and TBA values observed. Acceptability of the fillets improved by about 8 days in comparison with the control.	148
Fish sarcoplasmic protein/chitosan composite films containing ginger EO emulsions and nanoemulsions	Red sea bream (*Pagrus major*)	Wrapping	4°C, 10 days	TBARS and other physicochemical results demonstrated that nanoemulsions prolonged the shelf life. Light transmittance, water vapour permeability, and water solubility for nanoemulsion decreased.	112
Zataria multiflora Boiss EO, alginate coarse/nanoemulsions	Trout	Immersing	4°C, 16 days	The highest reduction rates of TVC, TPC, HSC, and ENC were observed in the nanoemulsion of alginate-containing samples, compared with alginate and control samples. The microbial growth was significantly inhibited in all treatments, compared with that in the control ($p < 0.05$).	149
High methoxyl pectin/gelatin/TiO_2/curcumin nanocomposite films	Salmon fillet	Wrapped	4°C for 12 days	Shelf life extended up to 12 days for 5 wt% TiO_2 nanoparticle addition. Significant differences ($p < 0.05$) with increasing TiO_2 nanoparticles, except on Day 0.	150

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TABLE 5 (Continued)

Composition	Sample	Application	Storage	Results	Ref.
Tilapia and squid skin gelatin film/nanoclay/ethanolic extract from coconut husk	Mackerel meat powder	Wrapping	28–30°C, 30% RH, 30 days	Retarded lipid oxidation, better sensory quality.	151
Zinc oxide nanorods/clove EO incorporated Type B gelatin	Peeled shrimp	Packaged in gelatin-based films	4°C, 20 days	The oxygen and UV barrier property increased, and porosity prevented by incorporating ZnO nanorods. Combination with ZnO nanorods, showed maximum antibacterial activity against *Listeria monocytogenes* and *Salmonella typhimurium*.	152
Fish protein isolate/fish skin gelatin–ZnO nanocomposite film incorporated with basil leaf EO	Sea bass	Wrapping	4°C, 12 days	Film had the lowest growth of psychrophilic bacteria, LAB, Pseudomonas, H_2S-producing bacteria and Enterobacteriaceae compared to controls. pH, TVB, PV, and TBARS value increase delayed were found in film-wrapped samples, compared with others ($p < 0.05$). Film showed longest shelf life.	153
Nanocomposite film based on PLA/ZnO nanoparticle/*Zataria multiflora Boiss*. EO and *Menthe piperita L*. EOs (both at 0.5%, 1%, and 1.5%)	*Otolithes ruber* fillets	Wrapping	4°C, 16 days	Improved phenolic content, antioxidant potential and antimicrobial activity Increased shelf life from 8 to 16 days	154
Gracilaria vermiculophylla extract films with and without ZnO nanoparticles (3%)	Inoculated smoked salmon	Wrapping	4°C, 8 days	The UV–visible light transmittance and elongation at break were decreased by the addition of ZnO. The antimicrobial activity against *Listeria monocytogenes* and *Salmonella typhimurium* decreased and degree of lipid oxidation decreased with increasing nanoparticle concentration.	52
Soy protein isolate-montmorillonite-clove EO nanocomposite film	Bluefin tuna (*Thunnus thynnus*)	Pouring after wrapping	2°C, 17 days	Pseudomonas growth and lipid autooxidation and TVB index decreased. Nanoclay minerals (Si and Al) did not diffuse from nanocomposite films to fish muscle.	111
Ziziphora clinopodioides EO (0.5%), apple peel extract (1%), and zinc oxide nanoparticle (0.5%)	Silver carp fillet	Wrapped then packed in sterile polyethylene bag	4°C for 14 days	TVC, *Pseudomonas* spp., *P. fluorescens*, H_2S-producing bacteria, and *Enterobacteriaceae* growth delayed	57
Collagen/zein electrospun films incorporated with gallic acid	Tilapia (*Oreochromis niloticus*) fillets	Wrapping	4°C for 10 days	The shelf life prolonged by at least 2 days	155

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TABLE 6 Biodegradable films containing microorganism-based compounds and their effect on aquaculture products.

Composition	Sample	Application	Storage	Results	Ref.
1% chitosan, 1% chitosan combined with 0.2% nisin, and 1% chitosan combined with 0.6% nisin	Large yellow croaker (*Pseudosciaena crocea*)	Treated by deionized water and packed in sterile bags	4°C, 8 days	Nisin-treated samples showed better quality preservation effects than chitosan alone. 1% chitosan + 0.6% nisin presented optimal quality enhancement effects (>4 days prolonged shelf life). Better volatile spoilage inhibition, lower TVB-N and TVC growth compared to controls.	159
Chitosan, alginate, and gelatin films containing lactoperoxidase system, sage EO	Common carp fish burger	Wrapping	4°C, 20 days	Chitosan films containing lactoperoxidase system were the most effective in terms of microbiological (TVC, psychrotrophic bacterial count, *Pseudomonas* spp., and *Shewanella* spp.) and TBARS results (5 days longer shelf life) The alginate and chitosan films containing lactoperoxidase system and age EO) had the higher pH ($p < 0.05$).	160
Lysozyme with or without nisin added to calcium alginate	Inoculated smoked salmon	Dipping	4°C, 35 days	Hen egg white and oyster lysozymes inhibited the growth of *L. monocytogenes* and *S. anatum* Nisin enhanced the antimicrobial activity	161
Starch, sodium alginate, and glycerol-containing *Carnobacterium maltaromaticum* strains and nisin	Vacuum packed cold smoked salmon inoculated with *L. monocytogenes*	Covering	4°C, 28 days	Films with either LAB strain or a combination of both strains and nisin had a bacteriostatic effect on *L. monocytogenes*	162
Thermoplastic starch/polybutylene adipate terephthalate film coated with gelatin containing nisin Z and lauric arginate	Inoculated Bigeye snapper (*Lutjanus lutjanus*) and tiger prawn (*Penaeus monodon*)	Coated then vacuum-packed	−20°C for up to 2 months and 4°C for up to 28 days	*S. typhimurium* and *V. parahaemolyticus* counts reduced.	163
Gelatin films containing glucose (2%) and cysteine (0.05%), incorporated with *Lactobacillus acidophilus* and *Bifidobacterium bifidum*	European hake (*Merluccius merluccius*)	Covering	4°C, 15 days	High pressure combined treatments reduced the content of volatile bases, total viable counts (<2 log cycles) and lowered the pH by more than 1 unit.	23
Agar, green tea extract and *Lactobacillus paracasei* L26 and *Bifidobacterium lactis* B94	Inoculated defrosted hake (*Merluccius capensis*)	Covered then vacuum-packed	4°C, 15 days	H_2S-producing bacteria, total viable bacteria count, TVB-N, TMA-N, and pH decreased. The total viable counts, H_2S-producing microorganisms and TVB-N were maintained below the limits of acceptability for 15 days. Green tea and probiotic were extended the shelf life at least for a week.	164
Tartary buckwheat polysaccharide; (5, 10, and 15 g kg^{-1}) combined with nisin	Nile tilapia (*Oreochromis niloticus*)	Dipping	4°C for 12 days	Combination with nisin-treated groups improved the bacteriological, physicochemical, and sensory properties. Better quality preservation effects observed compared to nisin coating alone. Nisin with TBP-coated fillets increased shelf life 4–6 days.	165

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TABLE 6 (Continued)

Composition	Sample	Application	Storage	Results	Ref.
Collagen–lysozyme	Salmon (*Salmo salar*)	Immersing	4°C, 15 days	No obvious differences in the colour and pH between the control and the treated samples ($p > 0.05$). 0.7% lysozyme + 4% collagen (w/v) decreased the TVB-N values and inhibited the growth of bacterial growth better than other treatments 0.5% lysozyme + 4% collagen had the best effect on reducing the weight loss.	166
Lactoperoxidase-system (LPOS) incorporated 0 (control), 1.25%, 2.5%, 5%, and 7.5% (v/v) into whey protein	Rainbow trout (*Oncorhynchus mykiss*)	Immersing	4°C, 16 days	Control and 1.25% LPOS treated samples reached undesirable levels of rancidity ($p < 0.05$) at 12th and 16th days, respectively, Higher concentrations showed better results ($p < 0.05$) in sensory, TVB-N, pH, and microbiological analysis. Shelf life extended 4 days.	167
Lactoperoxidase and α-tocopherol incorporated whey protein films	Pike-Perch *S. lucioperca*) fillets	Immersing	4°C, 16 days	Treated batches with α-tocopherol showed lower changes in colour, odour, and TBA compared with WPS (whey protein coating solution) batches ($p < 0.05$). WPS + 2.5% LPOS (lactoperoxidase system) treatment exhibited better quality about bacterial load, TVB-N, texture, and overall acceptability compared to WPS ($p < 0.05$), while colour, odour, and TBA were not significantly affected by LPOS ($p > 0.05$). WPS + 2.5% LPOS + 1.5% α-tocopherol and WPS + 2.5% LPOS + 3% α-tocopherol treatments had higher qualities than other treatments.	168
Probiotic carboxymethyl cellulose-sodium caseinate films containing *Lactobacillus acidophilus*, *L. reuteri*, *L. casei*, *L. rhamnosus*, and *Bifidobacterium bifidum*	Rainbow trout (*Oncorhynchus mykiss*) fillets	Packing with designated films and in sterile bags	4°C, 14 days	PV, TBARS, TVB-N changes in all treated fillets were significantly lower than controls ($p < 0.05$). Probiotic films extended shelf life by at least 2 weeks.	169

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proteins, polysaccharides, and their conjugates, which act as buffers between products, have positive effects on moisture loss, microbial growth, and lipid oxidation of aquaculture products. In recent years, the enrichment of edible films with various plant- and microorganism-based materials as active components has gained attention. The integration of EOs, plant extracts, and phenolic compounds into films contributes to slower deterioration and a protective effect when applied to aquatic food products. Such applications will be developed and applied for industrial purposes. To ensure a higher shelf life of aquaculture products, pre- or post-treatment with nonthermal methods such as irradiation, ozonation, cold plasma applications, high hydrostatic pressure, and their combined effects should be investigated in further studies. Strategies involving the nanoencapsulation of active components, antimicrobial agents, and antioxidants have shown improved sensory and quality characteristics of aquaculture products compared with conventional film materials. Owing to the enhanced polymer-nanofiller interfacial interactions, the nanocomposite films exhibited improved mechanical and barrier properties and thermal stability. Increasing consumer demand for natural food additives has focused on the incorporation of probiotics, prebiotics, bacteriocins, and enzymes. Therefore, novel multifunctional edible films with inexpensive processing materials and natural healthy components can be widely used in aquaculture packaging.

AUTHOR CONTRIBUTIONS

Turgay Çetinkaya: Conceptualization; investigation; writing – original draft; writing - review and editing; methodology; visualization. **Aydın Aytaç Gürdal:** Writing – original draft; investigation.

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CONFLICT OF INTEREST STATEMENT

No potential competing interest was reported by the authors.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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