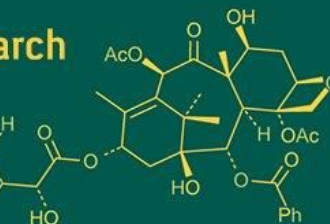


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Advanced edible packaging systems for the seafood preservation: Innovative technologies for waste utilization and extended freshness

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Abstract

Fishery products are highly perishable, experiencing rapid quality decline due to biochemical reactions and microbial activity. This review examines the role of edible coatings in extending the shelf life and enhancing the quality of seafood. Studies show that coatings from chitosan, alginate, and whey protein significantly inhibit microbial growth, improve moisture retention, and reduce oxidative spoilage. They also lower harmful nitrogenous compounds, thereby enhancing safety and sensory attributes. Despite existing research focusing on physicochemical changes, further studies are needed to explore the mechanisms of action and the potential of using fish processing waste to create sustainable coatings. Investigating active substance diffusion and industrial-scale application techniques is crucial for maximizing their benefits. Overall, edible coatings represent a promising approach to improve fishery product preservation while aligning with sustainability goals in the food industry.

Keywords: Fishery products, edible coatings, shelf life extension, seafood preservation, chitosan

1. Introduction

Packaging plays a crucial role in modern consumption, offering various functionalities and benefits, especially in the consumer packaged goods (CPG) sector. Here, packaging is vital for preserving product quality, minimizing losses, aiding in transportation and storage, and differentiating products in the marketplace. Typically, packaging is created to endure beyond its contents, often becoming unnecessary after use. With the frequent buying and discarding of CPG items, this contributes significantly to environmental issues, such as global warming, depletion of raw materials, acidification, and high energy use (Steenis *et al.*, 2017) ^[19]. Packaging is a crucial necessity for nearly every product, whether it's food or manufactured items. It plays a key role in selling the product, requiring an appropriate container for delivery to customers. Beyond this sales function, packaging also serves several important purposes. For food items, it helps conserve and preserve the product, ensuring that the inherent qualities remain intact. The packaging needs can vary significantly depending on the type of product. In particular, the packaging requirements for food products—especially fish—are quite complex due to their unique characteristics and the need to maintain their quality while stored (Balachandran, 2001) ^[1].

Packaging serves as an external method to protect products from spoilage, damage, or loss due to external factors. Most packaged foods undergo some form of preservation prior to packaging, and the materials used can help extend their shelf life. A food package is designed to safeguard against contamination, loss, and mishandling while also preventing damage and degradation. Additionally, packaging facilitates convenient dispensing and selling, as well as safer transport. These functional requirements indicate that packaging must fulfill roles beyond mere protection and preservation. It should also attract consumers through appealing aesthetics. Key concepts in packaging include protection and preservation, containment, performance on packaging machines, communication, convenience, and economic factors (Balachandran, 2001) ^[1].

Packaging materials play a crucial role in preserving food products and ensuring their safe transportation and storage.

A variety of materials are commonly used in food packaging, each offering unique benefits. These include paper and coated paper products, which provide versatility and recyclability; cellulose products like cellophane, known for their moisture resistance; metals such as tinplate and aluminum, which offer durability and protection from light and air; ceramics and glass, valued for their non-reactive properties; rubber, which is used for seals and closures; and plastics, which are lightweight and customizable. Additionally, materials like wood and fiber are also utilized, contributing to sustainable packaging solutions. Each of these materials plays a vital role in meeting the diverse needs of the food industry (Balachandran, 2001) ^[1].

Early fish packaging primarily involved wooden crates, woven bamboo or palm baskets, and wooden pickling barrels. Over time, in response to commercial demands and consumer preferences, significant changes have been made to fish packaging. Today, materials such as metal, glass, paper, and especially plastics have gained popularity. Fish is marketed either fresh or iced and transported long distances, as well as processed into various products for retail and wholesale. The specific packaging needs vary depending on the inherent qualities of the fish and the type of processed product. Plastics are the predominant material used for many fish and seafood packaging applications. Understanding the properties and limitations of different plastic materials is essential, and it is important to develop packaging solutions that cater to the specific characteristics of each product (Balachandran, 2001) ^[1].

Waste management is a significant challenge in modern industries, especially in seafood processing, where a large volume of both biodegradable and non-biodegradable waste is generated. With increasing consumer demand for fish, the seafood industry faces growing concerns regarding quality and safety, as a substantial amount of waste—such as heads, viscera, and scales—is typically discarded. This not only contributes to environmental pollution but also wastes valuable nutrients. However, there are opportunities to convert this waste into valuable products, like fish meal, gelatin and biodegradable packaging. Innovative solutions can transform seafood waste into wealth, benefiting both the environment and the industry. The development of edible films and coatings from seafood waste represents a promising approach to enhancing food safety and sustainability (Majumder & Balange, 2023) ^[11].

Edible packaging technology is an eco-friendly solution that holds great promise in food packaging by ensuring the delivery of safe and stable food products. With the global trend towards "Green consumerism" on the rise, there has been a significant increase in demand for edible coatings (ECs) and films due to their biodegradable and non-toxic

properties. Edible packaging improves the quality and shelf life of fresh fish and seafood by acting as a primary protective layer. Additionally, it addresses environmental and health concerns associated with the excessive use of non-biodegradable synthetic packaging materials.

This technology offers a more environmentally friendly, easily degradable, and safer alternative to conventional plastic packaging materials (Majumder & Balange, 2023) ^[11].

2. Seafood waste

The growth of fisheries and aquaculture production and processing has led to a rise in by-products and waste, which adversely affects both the environment and the economy (Ozogul *et al.*, 2021) ^[15]. Additionally, because of low-value discards, storage issues, and spoilage, 30% of captured fish go unused. The fish that are harvested move on to processing facilities, where only 30-50% are turned into consumable products, while the remaining 50-70% are discarded as by-products or leftovers (Tao *et al.*, 2022) ^[24]. Moreover, processing crustaceans generates a significant amount of underutilized by-products. These wastes, which include shells and heads, make up about 35-40% of the total wet weight (Caba *et al.*, 2019) ^[2].

3. Waste generation from processing

Food processing waste is a major contributor to environmental pollution, with over 50% of raw fish captured ending up as waste during harvesting and processing. In India alone, more than 2 million metric tons of seafood waste is generated annually, which is costly to dispose of due to its nutritional value. The improper disposal of this waste not only harms the environment but also wastes valuable nutrients. However, solid waste from seafood, such as heads, shells, and bycatches, is increasingly sought after for creating high-value products and nutraceuticals. By finding marketable byproducts, industries can reduce waste and generate additional revenue. Approximately 50-80% of the raw material results in waste rich in proteins and other nutrients. This waste is crucial for fish meal production and can also benefit the poultry and pet food industries. Additionally, skin and bone waste can be used for gelatin and collagen, while prawn and crab shells can produce chitin and chitosan for nutraceutical uses. In Europe, liquefied fish, known as fish silage, is effectively used as feed for livestock. Fish oils derived from seafood waste are rich in beneficial fatty acids, providing numerous nutraceutical applications. Overall, transforming seafood waste into valuable products offers significant advantages for both the environment and the seafood industry.

Table 1: The percentage of waste generated (w/w) for various seafood products, including shrimp, fish fillets, fish steaks, whole and gutted fish, surimi, cuttlefish, and squid

Products	Percentage of Waste Generated (w/w)	Products	Percentage of Waste Generated (w/w)
Shrimp products	50	Cuttlefish whole	30
Fish fillets	65	Cuttlefish fillets	50
Fish steaks	30	Squids whole	20
Whole and gutted fish	10	Squid tubes	50
Surimi	70	Squid rings	55
Cuttlefish rings	50		

Industries and researchers are increasingly exploring biodegradable and edible packaging made from seafood processing waste. Edible films (EFs) and coatings (ECs) are innovative solutions that enhance food quality and shelf-life. EFs serve as wraps and packages, while ECs form protective liquid layers on food surfaces, preventing moisture loss and controlling gas exchange. This eco-friendly technology improves food safety and stability by providing a semi-permeable barrier to oxygen, CO₂, and water vapor. Additionally, EFs and ECs can incorporate antimicrobials, antioxidants, and flavoring agents, further enhancing food quality and safety.

4. History of edible packaging

The origins of edible films (EFs) date back to ancient times when films made from edible polymers were utilized for espionage. Spies would write secret information on these films, allowing them to easily destroy the information by eating it if they were captured. Edible films and coatings, particularly waxes, have been employed since ancient times to prevent fruits from wilting and to give them a glossy appearance. The practice of using wax coatings to preserve citrus fruits in China goes back to the 12th century. In the 15th century in Japan, the first edible film used for food preservation was created from soy milk, known as Yuba (Dehghani *et al.*, 2018) [3]. Until 1967, the use of edible packaging in food applications was mostly confined to wax coatings on fruits and vegetables. However, nowadays, edible films and coatings are applied to a wide range of foods in various forms to improve their quality and safety.

5. Meaning of edible packaging!

Edible packaging can be described as a primary package made from edible materials that can be consumed along with the food or separately. This packaging encases the food to improve its quality and extend its shelf life. Edible packaging comes in two forms: coatings and films.

5.1 Edible coatings (ECS)

Coatings are thin layers of edible material applied directly to the surface of the food. They are typically applied in liquid form, usually through dipping or spraying.

5.2 Edible Films (EFS)

Edible films are created separately as thin sheets and then placed over the product or between food components. Initially molded into solid sheets, these films can be used as wraps or as stand-alone pouches. Typically, the thickness of these films and coatings should be less than 0.3 mm (Pavlati, & Ors, 2009) [17]. The mechanical strength and moisture and gas barrier properties of these coatings and films largely depend on the compatibility and strength of the bonds formed between the coating-forming polymer chains, such as covalent bonds, ionic bonds, and hydrogen bonding. A key advantage of edible packaging is the ability to incorporate bioactive compounds like antioxidants, antimicrobials, flavors, colorants, and probiotics into the polymer matrix to improve the quality and safety of food products. These coatings and films can also extend the shelf life of seafood by protecting it from mechanical damage and spoilage.

6. Principle of Edible Packaging

Edible packaging can serve as a barrier, a carrier, or an

enhancer for the product.

6.1 Barrier

As a barrier, it controls the movement of gases and moisture, minimizes the loss of flavor and aroma from the food, and safeguards it against microbial contamination.

6.2 Carrier

The coating functions as a carrier for active compounds such as antioxidants, antimicrobials, flavors, colors, and nutraceuticals. These compounds are released into the food to help slow chemical and microbial spoilage while improving or preserving the product's appearance and nutritional quality.

6.3 Enhancer

The use of edible films or coatings enhances the appearance and mechanical properties of delicate food items, particularly fruits. For instance, wax coatings are applied to certain citrus fruits and apples to give them a glossy finish, which can also help reduce dehydration and wilting. Additionally, chitosan coatings have been utilized to minimize mechanical damage to strawberries (Resende *et al.*, 2018) [18].

7. Components of edible packaging

- Edible packaging is created from biomacromolecules that can form a continuous and cohesive network. Structurally, these films and coatings consist of two key components: the matrix and additives.
- The matrix is a cohesively structured polymer network made from any type of bio macromolecule.
- Additives are substances that can be incorporated into the material matrix, either individually or in combination, to improve the functionality of the biopolymer.
- The matrix and additive components can be either hydrophilic or hydrophobic. To ensure the packaging material remains edible, only water or ethanol should be used as solvents for preparing the edible polymer solution.

7.1 Matrix material

The matrix is usually based on hydrocolloids (polysaccharides and proteins) or lipids (waxes), which may be used alone or in combination as composites.

7.1.1 Hydrocolloid matrix

Polysaccharides and proteins are considered hydrocolloids. These large biopolymers contain numerous hydroxyl groups that attract water. Hydrophilic polymer coatings, particularly polysaccharides like alginates and starch, function as sacrificial moisture agents for the product. In this case, moisture evaporates from the film rather than the product's surface, helping to protect the food from dehydration (Majumder & Balange, 2023) [11]. In contrast, protein-based packaging offers excellent mechanical stability due to improved interactions between polymer chains. Hydrocolloid films and coatings have a neutral taste, are colourless, and have an oil-free appearance. They can be applied to extend the shelf life of fish and fishery products by significantly reducing dehydration and oxidative rancidity.

7.1.1.1 Polysaccharide Based Films and Coatings

Polysaccharides are naturally occurring carbohydrate polymers made up of monomeric units linked by glycosidic bonds, resulting in long polymer chains. They are commonly used to create edible films or coatings, sourced from marine algae (such as alginate and carrageenan), various plants (including starch, pectin, and cellulose), animals (like chitosan), and microorganisms (such as bacterial cellulose and Pullulan). Notably, chitosan and alginate have been extensively researched for use in edible packaging for fruits, meat, and dairy products (Sánchez *et al.*, 2024) [23]. Typically, the formation of a polysaccharide matrix involves two key processes: disrupting the original interactions between polymer chains during the melting or dissolution phase, and cross-linking adjacent chains through newly formed covalent or hydrogen bonds during the drying phase.

The major advantages of polysaccharide films/coatings are

1. Readily accessible and generally affordable;
2. Clear, oil-free look that contributes minimal calories to the product;
3. Exceptional gas barrier and mechanical properties resulting from a well-structured hydrogen-bonded network;
4. Provides a barrier against fats and oils.

However, the hydrophilic characteristics of these coatings offer minimal resistance to water vapour, making their effectiveness largely reliant on the humidity levels during storage. Below are the primary polysaccharide films assessed for the preservation of fish and fishery products:

1) Chitosan

Chitosan ($C_8H_{13}N_5O_8$) is a natural polysaccharide derived from crustacean shells and fungi, making it a renewable, eco-friendly material with significant potential in the food industry. It's non-toxic, biodegradable, and is primarily used as films and coatings that enhance food shelf life by acting as barriers to oxygen, carbon dioxide, and microbes. Although the exact mechanism of its antimicrobial action isn't fully understood, it's believed that its positive charge interacts with negatively charged microbial membranes. Chitosan films are smooth and adhesive but sensitive to humidity, which limits their use. To improve their properties, modifications such as adjusting deacetylation, pH, and adding plasticizers like glycerol can be made. Additionally, factors like molecular weight and antimicrobial concentration affect performance, while cross-linking with agents like glutaraldehyde helps enhance stability and prevent dissolving (Majumder & Balange, 2023) [11]. Chitosan films have been enhanced with active and bioactive compounds to boost their antimicrobial and antioxidant properties, thereby extending the shelf life and improving the sensory qualities of food. This enhancement helps preserve the intrinsic quality of meat, poultry, and seafood. Chitosan, a cationic polysaccharide derived from the deacetylation of chitin, is recognized as an eco-friendly packaging material due to its biodegradable, biocompatible, and non-toxic nature. Additionally, studies have demonstrated its antimicrobial effectiveness (Merlo *et al.*, 2019) [12].

2) Alginate

Alginates ($C_{12}H_{20}O_{12}P$) are salts from alginic acid found in brown seaweeds, known for their hydrophilic properties and abilities to thicken, suspend, stabilize, and form films. They can react with di- and trivalent cations to create films that enhance mechanical and barrier properties while controlling the release of active materials. Alginates improve food quality by retaining moisture and texture, extending shelf life by reducing dehydration and lipid oxidation. Sodium alginate ($C_6H_7NaO_7$), an eco-friendly byproduct of brown seaweeds, is extensively used in food packaging and pharmaceuticals (Majumder & Balange, 2023) [11].

Alginates are indigestible polysaccharides naturally found in various brown algae, such as *Laminaria hyperborean*, *Macrocystis pyrifera*, and *Ascophyllum nodosum* among others. Additionally, certain bacteria, like *Azotobacter vinelandii* and mucoid strains of *Pseudomonas aeruginosa*, also produce alginate-like exopolysaccharides. Details on alginate production from marine algae and *A. vinelandii* can be found in other sources. The U.S. Food and Drug Administration (FDA) categorizes food-grade sodium alginate as GRAS (generally recognized as safe) under Title 21 of the Code of Federal Regulations, where it is approved as an emulsifier, stabilizer, thickener, and gelling agent. The European Commission also recognizes alginic acid and its salts (E400-E404) as authorized food additives. Alginate is widely utilized in various sectors, including food, beverages, textiles, printing, and pharmaceuticals, for functions like thickening, stabilizing, and forming gels, films, and membranes. Sodium alginate is the most commonly employed type of alginate. Sodium alginate coatings on tilapia fish effectively reduced bacterial counts and spoilage indicators during six months of frozen storage. In a separate study, polysaccharide blends used in breeding prefried trout fillets improved shelf life and sensory qualities. Rainbow trout fillets coated with 3% sodium alginate and stored at 4 °C maintained quality for 20 days, while other polysaccharides like starch, pectin, and agar enhanced the mechanical properties of these films (Gürdal, & Çetinkaya, 2024) [5].

3) Carrageenan

Carrageenan is a water-soluble polysaccharide derived from red seaweeds, known for its film-forming capabilities due to its linear chain structure with partially sulfated galactans. It serves various functions in food and other industries, including as a stabilizer, oxygen barrier, and antimicrobial agent in products like pet food, infant food, and nutritional supplements. While carrageenan-based films offer valuable applications, they typically lack the transparency of starch-based films and are mainly used as surface coatings. Research on enhancing the structural and mechanical properties of carrageenan films, particularly with active components, is limited applications (Majumder & Balange, 2023) [11]. Carrageenans are water-soluble polymers derived from red seaweeds, categorized into kappa (κ), iota (ι), and lambda based on their structure. Kappa carrageenan is particularly popular for making strong, less hydrophilic packaging films. While refined κ -carrageenan is costly, semi-refined κ -carrageenan (SRC) offers a more affordable alternative for food packaging. Enhancing SRC films to create active packaging can significantly benefit both the films and the food products they contain (Farhan, & Hani, 2020) [4].

4) Agar

Agar is a polysaccharide derived from marine red algae, primarily from the *Gelidium* and *Gracilaria* species. It serves as a structural component in the cell walls of these seaweeds and consists of two main components: agarose, which forms a gel, and agarpectin, a non-gelling fraction that is typically removed during processing to enhance gel strength. Agarose has a linear structure of D-galactose and 3,6-anhydro-L-galactose linked by specific glycosidic bonds. The extraction process involves soaking dried algae in boiling water, filtering the liquid, and using freezing techniques to isolate the agar. Alkali treatment can improve gel strength but may negatively affect the properties of films made from agar. Research shows that native agar is cheaper and has better viscosity, elasticity, and water vapor barrier properties than alkali-modified agar. Agar films are transparent, heat-sealable, and biodegradable, making them suitable for coating food products and interacting with bioactive substances. However, they tend to be brittle, lacking elasticity, and exhibit poor thermal stability, high water sensitivity, and significant water vapor permeability. These limitations hinder their use compared to plastic-based packaging materials (Mostafavi, & Zaeim, 2020) [13].

7.1.1.2 Protein-based films and coatings

Proteins, as polymers of amino acids, are pivotal in developing edible films and coatings for food preservation (Hassan *et al.*, 2018) [7]. Derived from both plants and animals, these films enhance the shelf life of perishables like fruits, meat, and dairy (Dehghani *et al.*, 2018) [3]. The film formation involves denaturation of proteins, leading to intermolecular interactions that confer structural integrity. While they offer strong mechanical resistance and good oxygen barrier properties, protein films are less effective as moisture barriers, resulting in significant moisture loss compared to conventional materials. This underscores their potential and limitations in food packaging applications.

1) Whey protein

Whey protein-based films and coatings are gaining attention for their potential in seafood preservation due to their strong gas barrier properties. Whey protein coatings also play a crucial role in retaining aromatic compounds, which enhances the flavor of the food. These films exhibit strong mechanical strength and effective gas barrier properties, particularly at low humidity levels. They provide good protection against aroma compounds and oils, making them suitable for various food applications (Majumder & Balange, 2023) [11]. However, the hydrophilic nature of whey protein poses challenges, particularly regarding moisture barrier properties. This can lead to increased moisture loss in packaged products. To mitigate this issue, researchers are exploring the incorporation of different types of lipids into whey protein films (Hassan *et al.*, 2018) [7] to improve moisture resistance. Overall, whey protein films are a promising area of research in food preservation, combining nutritional benefits with effective barrier properties, despite some limitations related to moisture retention. Whey protein can create transparent, flexible, and tasteless edible films that effectively block oxygen, aromas, and oils, particularly in low humidity. Typically, whey protein isolate is used at concentrations between 5% and 10% for this purpose. Recent studies found that films made

from polymerized whey protein concentrate (WPC) help meat retain moisture during cooking without altering its texture. Additionally, adding antimicrobial agents to WPC films successfully inhibits harmful microorganisms like *Listeria monocytogenes*. This combination enhances food preservation and safety (Prabhu, 2006) [16].

2) Gelatin

Gelatin polymers have been utilized to create edible films and coatings since the 1960s, valued for their affordability and accessibility. These films offer good transparency, mechanical strength, and barrier properties, produced through extrusion or casting methods. Gelatin is derived from collagen, a protein found in bones, skin, and connective tissues, and is rich in glycine, proline, and hydroxyl-proline, which contribute to its unique characteristics. Its structure features hydrophilic single and double unfolded chains that revert to a collagen-like triple helix during gelation. Typical formulations include 20-30% gelatin, 10-30% plasticizers (like glycerin or sorbitol), and 40-70% water. Gelatin is widely used in the pharmaceutical industry and for encapsulating oil-based food products (Hassan *et al.*, 2018) [7]. In food applications, it enhances gelation, water retention, foaming, and emulsification, improving elasticity and viscosity. Beyond food, gelatin is also valuable in pharmaceutical and biomaterials packaging, as well as photography. Additionally, it offers health benefits, such as supporting joint and bone health and promoting hair and nail strength (Karayannakidis & Zotos, 2016) [9].

7.1.1.3 Lipid based film and coatings

Unlike hydrocolloids, lipids are not biopolymers and cannot form self-supporting film structures. Their primary use is in creating edible coatings (ECs). However, when combined with polysaccharides or proteins, lipids can enhance films by improving moisture barrier properties due to their low polarity. Common lipid materials include waxes and resins, such as beeswax and carnauba wax, which are often used to coat fruits like oranges and apples (Majumder & Balange, 2023) [11].

1) Waxes

Waxes are in high demand for packaging sweets, baked goods, and dairy products because of their hydrophobic nature, high gloss, and semi-transparent appearance. They are commonly used to treat, laminate, and coat food contact paper, especially in situations where moisture and grease resistance are crucial, such as in fast-food packaging.

Waxes can be either petroleum-based, like paraffin and montan wax, or natural, such as beeswax, soy wax, candelilla wax, carnauba wax, jojoba wax, and rice-bran wax. Their effective moisture barrier properties help protect dry foods from humidity and minimize moisture loss. Additionally, wax coatings can improve the respiratory function of foods that need cold storage, preventing sweating and extending shelf life (Tyagi *et al.*, 2021) [25].

2) Fatty acids

Saturated fatty acids (SFAs) are generally more effective at blocking moisture than their unsaturated counterparts. This is primarily due to their structural differences. Saturated fatty acids lack double bonds, which allows their acyl chains to pack closely together in a more orderly fashion. This tight

packing creates a more stable barrier against water vapor, reducing permeability. In contrast, unsaturated fatty acids (UFAs) contain one or more double bonds, resulting in kinks in their structure. These kinks prevent the acyl chains from aligning as tightly, leading to less efficient packing and increased water vapor permeability. Additionally, the branching that often occurs in unsaturated fatty acids contributes to this reduced packing efficiency. This difference in molecular arrangement has significant implications, especially in applications like skincare and food preservation, where moisture retention is crucial. Understanding these properties can help in formulating products that maximize moisture barrier functions, leveraging the unique Characteristics of saturated versus unsaturated fatty acids (Stuchell, & Krochta, 1995) ^[20].

3) Aceto-Glycerides

Acetic acid esters derived from monoglycerides are known as acetylated monoglycerides (AMGs). One of the notable properties of AMGs is their ability to solidify into a waxy consistency when cooled from a molten state. This unique characteristic allows them to be easily manipulated for various applications. Moreover, AMGs can be extended up to 800% of their original length, significantly surpassing the typical extension capacity of most lipids, which generally only reach about 102% of their original length (Majumder & Balange, 2023) ^[11].

This remarkable flexibility makes AMGs ideal for creating films and coatings, particularly in the food industry. When applied to meat products, these coatings serve an essential function by minimizing moisture loss during storage, thus preserving quality and extending shelf life. Additionally, AMGs can enhance the texture and mouthfeel of food products, making them more appealing to consumers. The ability to form stable films also opens avenues for incorporating bioactive compounds, potentially adding health benefits while maintaining product integrity. Overall, the versatility of acetylated monoglycerides positions them as valuable components in both food technology and other industries focused on moisture management and product preservation (Hassan *et al.*, 2018) ^[7].

8. Protective effects of edible coatings for the fishery products

Fishery products are highly perishable, and their post-mortem changes due to biochemical reactions and microbial activity lead to a swift decline in their quality. Numerous studies have demonstrated the effectiveness of edible coatings in extending the shelf life of fresh seafood, utilizing methods such as bacterial counts, physicochemical assessments, and sensory evaluations. These coatings not only inhibit microbial growth and reduce spoilage but also help retain moisture and improve overall freshness, making them a valuable tool in the preservation of fishery products. Furthermore, they can enhance consumer appeal through improved appearance and texture.

1) Microbial Quality

Total viable count (TVC) is a crucial measure for assessing the freshness of fishery products, with a permissible limit often set at 7.0 log₁₀ CFU/g. Various spoilage and pathogenic bacteria, such as *Pseudomonas* sp., H₂S-producing bacteria (like *Shewanella*), and *Aeromonas* sp., play significant roles in quality deterioration. Studies also

show that bio-based coatings can effectively reduce microbial spoilage. For example, chitosan coatings (2%) decreased TVC by 1.9 log₁₀ CFU/g in Indian oil sardines after 9 days (Mohan *et al.*, 2012) ^[14]. A combination of chitosan and gelatin significantly inhibited microbial growth in shrimp, achieving reductions of nearly 3.5 log₁₀ CFU/g for TVC (Yu *et al.*, 2019) ^[27]. Edible films and coatings containing the highest concentrations of active agents demonstrated the greatest antimicrobial effectiveness. Additionally, these antimicrobial films and coatings were more efficient at lower temperatures during testing across various storage conditions. Furthermore, under modified atmosphere packaging, their effectiveness surpassed that of packaging in air (Socaciu *et al.*, 2018) ^[21].

2) Physical properties

Deterioration of physical properties such as texture, water retention, and color can adversely affect the flavor and appearance of fishery products sold by weight. Fish fillets are particularly sensitive, often losing 30-60% of their texture within a few days. Enzymes contribute to this softening, but edible coatings can significantly slow this process by inhibiting enzyme activity. These coatings also enhance water retention, leading to a notable reduction in drip loss. Additionally, they help maintain color by reducing lipid oxidation, resulting in less discoloration. Overall, edible coatings improve the quality and shelf life of fishery products (Yu *et al.*, 2019) ^[27].

3) Lipid oxidation

Lipid oxidation causes discoloration, rancid flavors, and potentially harmful compounds, while also reacting with proteins and diminishing their functionality and nutritional value. Recent studies have shown that edible coatings can inhibit oxidation in fishery products. For example, fish gelatin-tea polyphenol coatings significantly reduced oxidative spoilage markers in golden pomfret fillets. Chitosan-licorice extract coatings effectively decreased TBARS and peroxide values in frozen ovate pompano fillets. Licorice extract-coated Japanese sea bass showed a 64% reduction in TBARS after 8 days. Overall, edible coatings act as oxygen barriers and provide antioxidant properties, helping to slow lipid oxidation in various fish species (Yu *et al.*, 2019) ^[27].

4) Nitrogenous compounds

The accumulation of nitrogenous compounds, such as TVB-N, trimethylamine (TMA), and biogenic amines, in fishery products results from the activity of spoilage bacteria and enzymes, adversely affecting flavor, sensory quality, and safety. TMA is a primary contributor to fishy odors, while biogenic amines like histamine, cadaverine, and putrescine can pose health risks to humans. Edible coatings have demonstrated significant effectiveness in reducing the levels of TVB-N and TMA across various fish species, including silver carp, rainbow trout, and salmon. For example, using alginate-rosemary extract coatings on abalone resulted in reductions of 66% for cadaverine and 77% for putrescine, with the total content of biogenic amines dropping to one-third of that in the control. Similarly, chitosan-gallic acid coatings significantly decreased levels of histamine and other biogenic amines in Pacific mackerel during refrigerated storage. These reductions are largely due to the coatings' ability to inhibit spoilage bacteria like *Shewanella*,

Aeromonas, and Enterobacteriaceae, which are responsible for producing these harmful compounds. Overall, edible coatings not only help maintain the quality of fishery products but also enhance their safety for consumers (Yu *et al.*, 2019) ^[27]. Most marine fish contain TMAO, while freshwater fish have it in smaller amounts. Certain naturally occurring bacteria on fish skin, in their guts, and in the surrounding water can convert TMAO to TMA. The level of trimethylamine nitrogen (TMA-N) produced serves as an indicator of spoilage bacteria activity in fish flesh (Socaciu *et al.*, 2018) ^[21].

5) Sensory quality

Sensory evaluation is commonly employed to assess the freshness of fishery products through preference scores. Standardized methods like the European Union (EU) and Quality Index Method (QIM) utilize trained panelists for consistent assessments across different species. The organoleptic deterioration of fishery products manifests as texture softening, discoloration, and unpleasant odors, primarily due to microbial spoilage, enzyme activity, and lipid oxidation. Edible coatings have proven effective in preserving the sensory quality of fish. For instance, chitosan-based coatings significantly reduced unpleasant compounds like TMA in refrigerated grass carp fillets. Similarly, alginate-calcium coatings enhanced the sensory scores of snakehead fillets during storage, while chitosan coatings with cinnamon oil helped maintain fish sensory characteristics. These improvements highlight the antioxidant, antimicrobial, and barrier properties of edible coatings (Yu *et al.*, 2019) ^[27].

9. Challenge and future perspective

Bio-edible coatings are a promising solution for extending the shelf life and maintaining the quality of fresh fishery products. Most research has focused on physicochemical changes and sensory evaluations, often neglecting the mechanisms behind the protective effects of these coatings. Future studies should explore aspects such as film-forming characteristics, microbial interactions, oxidation control, flavor retention, and enzyme inhibition to improve preservation methods (Yu *et al.*, 2019) ^[27]. Converting fish processing waste into edible films (EFs) and coatings also presents a sustainable option for the industry, addressing environmental pollution while providing nutritional benefits and generating revenue. Edible coatings help control moisture and gas migration, carry food additives, and enhance food properties, making them a viable alternative to synthetic packaging (Majumder & Balange, 2023) ^[11]. Research on biopolymer-based coatings, especially alginate, shows potential in preserving fresh produce and meats. Enhancements can be achieved by incorporating antimicrobial and antioxidative agents. Additionally, blending different biopolymers could improve coating properties. More research is needed on the diffusion of active substances in alginate gels and the effects of various calcium salts on food quality. While most alginate research is laboratory-based, industrial applications remain limited. Future efforts should focus on practical implementations and improving coating methods, such as recycling processes and equipment design, to expand the use of sodium alginate-based coatings.

10. Conclusion

In conclusion, the seafood industry faces significant challenges related to waste management, with over 50% of raw fish captured resulting in by-products that contribute to environmental pollution. Edible coatings offer a promising solution to enhance the shelf life and quality of fishery products while minimizing waste. These bio-based coatings effectively reduce microbial spoilage, lipid oxidation, and harmful nitrogenous compounds, improving food safety and sensory attributes. Moreover, utilizing fish processing waste to develop sustainable coatings can transform by-products into valuable resources, benefiting both the environment and the economy. Continued research is essential to optimize the performance of these coatings and explore their interactions with various matrix materials. As consumer demand for sustainable practices grows, the adoption of innovative packaging solutions will be crucial for the seafood industry's future. By integrating eco-friendly technologies, the industry can promote a more circular economy, reducing waste and enhancing food preservation. Ultimately, these advancements contribute to a more sustainable and responsible food system.

11. References

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