Prospects of Biodegradable Packaging in the Seafood Industry: A Review

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Abstract

Biodegradable packaging holds significant potential for the seafood industry as a sustainable and eco-friendly alternative to traditional packaging materials. With growing concerns about plastics and their environmental impact, there is a strong demand for innovative solutions. The use of biodegradable packaging aligns with consumer preferences for sustainable and eco-friendly products. The challenges include the scalability, cost-effectiveness, and the need for standardised labelling to differentiate genuine biodegradable packaging. This article discusses the potential of biodegradable packaging in the seafood industry as a promising, sustainable solution to reduce plastic waste, aligning with consumer preferences, and maintaining product quality.

Keywords: food packaging, biodegradability, barrier properties, bioplastics, cold chain

Introduction

Food packaging aims to prevent product deterioration by retaining the beneficial effects of processing which helps maintaining the quality and safety resulting in further extension of shelf life. The barrier properties of packaging materials have a significant influence on the shelf life, safety, and quality of packaged food products (Singh et al., 2017). The food industry is one of the largest consumers of disposable packaging and using biodegradable options is an important requirement for addressing the associated environmental concerns (Popa et al., 2011). The significance of pollution by discarded petroleum-based packaging materials is the reason that they tend to accumulate in nature owing to their excellent mechanical properties, as well as resistance to natural degradation (Parvin et al., 2010). According to long-term population and GDP predictions, the production of municipal plastic garbage worldwide could reach 300 mt annually by 2040 and 380 mt by 2060 (Lebreton and Andrady, 2019; Borrelle et al., 2020). The wide use of petroleum plastics in food packaging is also attributed to their easy availability, cost effectiveness and physical characteristics like tensile and tear strength, barrier properties against water vapour, oxygen, and aroma compounds as well as heat sealability (Álvarez-Chávez et al., 2012).

Polyethylene or co-polymer based plastics are the most common packaging materials that meet these criteria, which have been in use for food packaging for more than 50 years (Vallejos et al., 2022). In fisheries and aquaculture, insulated crates or boxes are frequently used to carry fresh fish products from the point of catch to the point of processing and distribution. For assuring adequate thermal insulation and safety, expanded polystyrene (EPS) is used in seafood as it is light in weight, which helps in lowering the load and expenses during transport (Ho et al., 2018). The global thermoformed plastics market was valued at USD15.51 billion in 2023 and is forecast to reach a value of USD20.66 billion by 2030 with an anticipated compound annual growth rate (CAGR) of 4.9 % (Grand View Research, 2024). EPS based materials have a chance of being easily littered due to their extremely low density and brittle nature. They are also non-biodegradable, and their photodegradable properties often render them into small pieces posing threat to marine and terrestrial life. Products such as EPS boxes without coating are difficult to sanitise after use as they are fragile and they also soften and melt at temperatures above 100 °C, limiting their reuse (FAO, 2021).

Throughout the years, there has been an increase in the production and utilisation of plastics such as polyethylene terephthalate (PET), styrofoam, polypropylene (PP), and polyolefin which are considered as food contact safe or food grade (Joseph et al., 2024). Food grade plastics even though safe as a food contact material have a major role in environmental pollution due to their wider usage. Studies estimate that 31 % of the plastic debris in marine environment originates from food and beverage packaging (Webb et al., 2013). Over 300 million metric tons (mt) of plastics are produced in the world annually and about 50 % of this volume is discarded within a year of their purchase. Most of them are also not recycled leading to clogging of drainage and river systems, and they may be ingested by stray animals, but predominantly are incinerated, all of which having a negative impact on human health and the environment.

According to estimates, 8 million tonnes of plastics leak into the ocean each year, which is the equivalent of dumping one garbage truck's worth of trash into the ocean every minute (Van Crevel, 2016). There are also issues such as chemical adulterants in plastic packaging remaining in the recycled material and further migrating to packaged food item (Raheem, 2013) and phthalate esters, widely used in plastics getting easily released to the environment, are transported long distances to seas with underground and discharge waters (Alp and Yerlikaya, 2020). All food commodities such as seafood needs proper handling and preservation to ensure commercial viability and consumer safety (FAO, 2022). The seafood industry on other hand has also been accused of being the most damaging industry for marine life due to its high exploitation of resources and production of plastic waste (Wilcox et al., 2016; FAO, 2020; Wootton et al., 2022). This review discusses the viability of biodegradable packaging options that could be adapted by the seafood industry for reducing its impact on the environment assuring a sustainable future.

Review Methodology

This review systematically examines the current advances in biodegradable packaging pertaining to the seafood industry by analysing peer-reviewed literature, industry reports, and regulatory guidelines. The selection of articles was guided by predefined criteria to ensure relevance, credibility, and comprehensiveness.

Literature search strategy

The literature review process involved a structured search of multiple scientific databases, including: Web of Science; Scopus; PubMed; Google Scholar; ScienceDirect; and SpringerLink. Additionally, authoritative sources such as reports from the Food and Agriculture Organization (FAO) and regulatory documents were consulted to include industry perspectives and legislative frameworks on biodegradable seafood packaging.

Criteria for article selection

The articles included in this review were selected based on the following inclusion criteria:

- Research articles, review papers, patents, and industry reports published in the last 15 years (2009–2024) were selected.
- Studies focusing on biodegradable and bio-based packaging materials applicable to chilled, frozen, and processed seafood products.
- Papers discussing the mechanical, barrier, antimicrobial, and environmental performance of biodegradable packaging alternatives.
- Studies on nanotechnology-based innovations and biopolymer composites in seafood packaging.
- Reports on regulatory frameworks and sustainability assessments related to biodegradable packaging materials in the seafood industry.

The following number of articles were categorised based on the above said criteria:

- Conventional materials for packaging of seafood - Bioplastic food packaging - 23
- Frozen and chilled seafood packaging - 47
- Vacuum packaging and MAP - 31
- Smart and active packaging - 21

Data extraction and synthesis

After identifying relevant studies, the following data were systematically extracted:

- Type of biodegradable material (e.g., polylactic acid, chitosan, alginate, carrageenan-based biopolymers).
- Packaging properties (mechanical strength, barrier properties, biodegradability).
- Application in seafood (fresh, frozen, vacuum-packed, MAP, dried seafood).
- Impact on shelf life, microbiological safety, and sensory quality.
- Comparative analysis with conventional plastics.

Packaging Requirements for Fish and Fish Products

Fish is extremely perishable and needs to be handled with caution. Chemically, fish and other seafood are composed of four major components such as moisture, protein, lipid, and minerals (Gokoglu and Yerlikaya, 2015). The respective proportions of all these constituents gives seafood its characteristic flavour, texture, colour, and nutritional value. If not handled properly, these components could be broken down into undesirable constituents due to oxidation of lipids, enzymes, and metabolic activities of microorganisms, leading to quality deterioration and potential shelf-life reduction (Nwaigwe, 2017). The main function of packaging is to protect the product and extend shelf life (Wikström et al., 2019). The fish-processing industry is actively looking for alternative methods for economically sustainable extension of shelf life, considering the rising energy costs associated with freezing and frozen storage (Tavares et al., 2021). Chilled and frozen, thermally processed (ready-to-eat) and dried are some of the popular forms of seafood products which require unique packaging and storage needs, necessitating the use of versatile packaging materials (Ravishankar et al., 2017).

Conventional Plastic Materials Used for Seafood Packaging

More than thirty distinct types of plastics are used for packaging seafood, the most common being polyolefins, polyvinyl and polyesters (Raheem, 2013). Generally, seafood is processed as frozen, with a core temperature of -20 °C and a storage temperature of -18 °C. Since most frozen goods become rigid and sharp when frozen, damage to the flexible films which compromises package integrity is common and therefore the packaging used must withstand low temperatures without breaking along with excellent glass transition temperature (Tg) and flexibility properties (Laorenza et al., 2022). Considering this, PP, polyethylene (PE), or nylon due to their high elongation at break, and barrier properties are used as flexible packaging, while rigid packaging is normally made from PET or PS due to low elongation at break for frozen fish products (Ravishankar et al., 2017). Table 1 presents a list of conventional plastic polymers used for packaging of seafood commodities.

Bioplastics for Food Packaging

According to (Dilshad et al., 2021) the term "bioplastics" are used for products that are manufactured exclusively or partially from renewable bio resources, such as biopolymers (starch, chitin, protein) and bio-polyesters (polyhydroxy-alkenoates, polylactic acid). These biopolymers undergo decomposition into carbon dioxide (CO_2), water (H_2O) and inorganic compounds under natural or stimulated conditions predominantly by enzymatic action of microorganisms (Kumar and Thakur, 2017). The surrounding environmental factors such as temperature, humidity, and oxygen (aerobic or anaerobic conditions) have high influence on biodegradation process of materials (Siracusa, 2019; Folino et al., 2020). The most prevalent category of biodegradable materials that is used in food packaging is cellulose-based paper and cartons. These alternatives to petroleum plastics could be broadly classified as biobased, biodegradable, and compostable, depending on their source and process of biodegradation, which is discussed below.

Bio-based

Bio-based plastics are the polymers that have their carbon partially or completely produced from renewable resources or are derived from a biomass material (Song et al., 2009; Adamcová et al., 2017; Koch and Mihalyi, 2018). Biomass is a material of biological origin, excluding materials embedded in geological formations or fossilised (Van den Oever et al., 2017). The bio-based materials can also be non-biodegradable as evident from biobased non-biodegradable polymers like bio-polyethylene (Bio-PE) (Van den Oever et al., 2017). Even though this terminology is comparatively recent, bio-based polymers have existed for a long time and have been considerably used in fibre and film applications like cellulose which is the most abundant biomass material on earth. Cellulose has been used as a natural fibre, such as cotton and jute, and as a regenerated fibre, such as rayon (Iwata, 2015).

Biodegradable

Biodegradable packaging materials refers to those that can be broken down into water and naturally occurring gases such as CO_2 and methane (CH_4) by microorganisms within a short time after disposal, typically a year or less (Song et al., 2009; Soroudi and Jakubowicz, 2013; Molenveld et al., 2015; Adhikari et al., 2016). The environmental factors like temperature, presence of microorganisms, oxygen, and water have a significant impact on rate of biodegradability of these polymers. Considering this, the rate of degradation of a biodegradable plastic product varies considerably depending on the environment to which it is exposed like type of soil, whether on or under the soil, in humid or dry climate, in surface water, in marine water, or in human made systems like home composting, industrial composting or anaerobic digestion (Van den Oever et al., 2017; Lackner et al., 2023).

Compostable

Compostable polymers are materials that break down at composting conditions like the industrial composting conditions that require elevated temperatures (55–60 °C) combined with high relative humidity and the presence of oxygen (Van den Oever et al., 2017). According to Kale et al. (2007), Briassoulis et al. (2010)

Table 1. Summary of synthetic polymers used for seafood packaging identified in the review from 2009–2024.

Abbreviation	Full form	Application	Reference
PE	Polyethylene	Multilayer packaging materials/ and suitable for microwave heating packages	Laorenza et al. (2022)
PP	Polypropylene	Multilayer packaging materials/ and suitable for oven heatable packaging materials	Laorenza et al. (2022)
PET or PETE	Polyethylene terephthalate	PET-based trays in retail or convenience store fresh produce displays	Gokoglu (2020)
PA	Polyamide (nylon)	Nylon has excellent barrier properties and is mostly used as vacuum packaging and multi-layer packaging materials	Majumdar et al. (2015)
PVC	Polyvinylchloride	Bottom base plate for skin packaging of seafood	Hauzoukim and Mohanty (2020)
EPS	Expanded polystyrene	Insulated styrofoam boxes for storage/ (EPS) trays	Gokoglu (2020)

and the European Bioplastics Association (2015), plastic packaging can only be called compostable if it is demonstrated that:

- The packaging material and its relevant organic components (>1 wt. %) are naturally biodegradable.
- Disintegration of the packaging material takes place in a composting process for organic waste within a certain time frame.
- The packaging material has no negative effect on the composting process.
- The quality of the compost is not negatively influenced by the packaging material.

Compostable polymers are being developed as environmentally friendly alternatives, especially if they can be recycled organically and derived from renewable resources (Emadian et al., 2017). In order for a polymer to be considered compostable, it must convert 90 % of its carbon content to carbon dioxide in accordance with the American Society for Testing and Materials (ASTM) international standards (Ahsan et al., 2023). Their rate of decomposition is compared to that of other known compostable materials, like cellulose, which is typically used as a control (Song et al., 2009; Folino et al., 2020.). Figure 1 discusses the major categories of biodegradable packaging available for seafood industry.

Biodegradable Packaging Options for Chilled and Frozen Seafood

Chilled seafood

The packaging materials traditionally used in fresh fish transport were bamboo or wicker baskets with polyethylene or sheet metal coatings (Bindu, 2018). Previously plywood boxes were also used but as they do not offer much resistance to the inflow of heat accelerating melting of ice, became less popular. They were also difficult to clean, resulting in their gradual replacement by synthetic polymers (Noseda et al., 2014). Polystyrene (PS) and its expanded form (EPS) are widely used for iced storage of freshly caught seafood (Laorenza et al., 2022). Many polysaccharides, including chitosan and alginate, have been considered for their potential use as materials for developing packaging for chilled seafood (Cazón et al., 2017). Chitosan shows both antimicrobial and antioxidant properties, which suggests it can retard bacterial growth and lipid oxidation, correspondingly helping to improving the quality of seafood products. It has been observed that chitosan-based films can effectively control *Listeria monocytogenes* growth on the surfaces of cold-smoked salmon (Jiang et al., 2011). By incorporating additional antimicrobial agents, such as sodium lactate or sodium diacetate, to the chitosan-based films, the shelf life can be further prolonged (Bazargani-Gilani, 2018; Kulawik et al., 2020; Tan et al., 2021). By delaying microbial development, lipid oxidation, and moisture loss, active edible films/coatings can be formed to enhance the quality and increase the shelf life of chilled seafood. In order to minimise the rate of melting ice, the material of the container used to carry fish should have insulating properties. It should also support a lower water evaporation, fat oxidation, microbiological and chemical degradation, dripping and odour penetration; the material should also possess sufficient mechanical strength and should be light in weight (Nwaigwe, 2017; Mohan et al., 2018).

Biodegradable polyvinyl alcohol (PVA) foam has been broadly applied in the pharmaceutical and biomedical fields due to its properties such as nontoxicity, hydrophilicity, and oxidation resistance (Nargesi Khoramabadi et al., 2020) which holds a potential be used to replace EPS. Starch, chitosan, and cellulose are some of the natural polymers that have been applied to create porous foams and sponges (Liu et al., 2014). The bio-foam made from cassava starch and blended with 30 % kraft fibre and 4 % chitosan exhibited some of the equivalent characteristics as polystyrene foam (Kaisangsri et al., 2012). Biodegradable foam using PVA, sugarcane bagasse

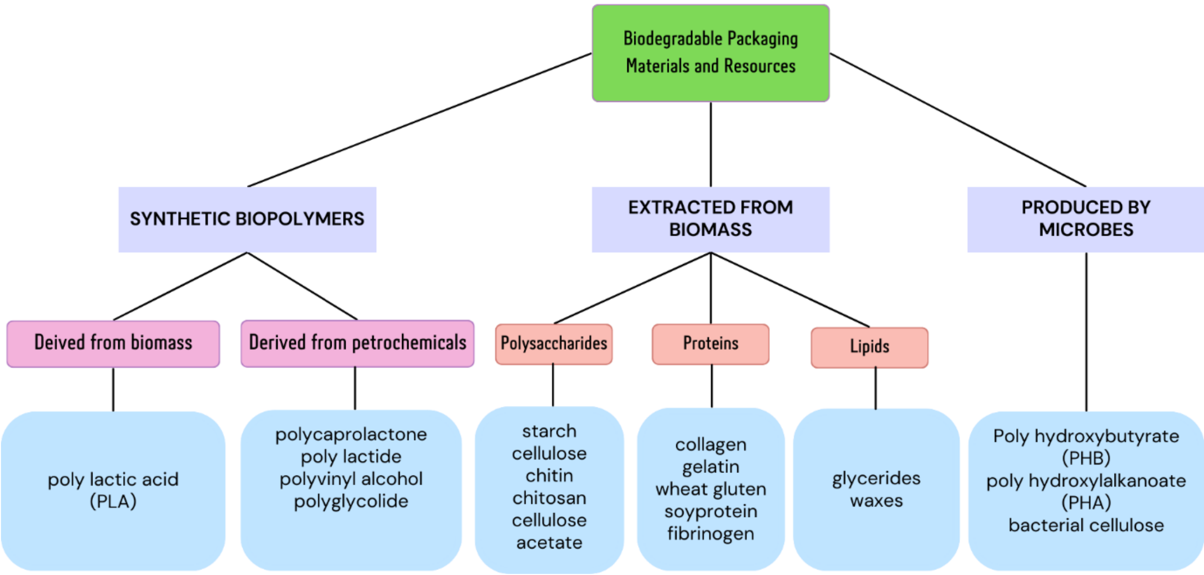

Fig. 1. Major categories of biodegradable packaging available for the seafood industry.

fibres, cassava starch, and chitosan developed through extrusion method has showed resistance to moisture loss up to 75 % relative humidity. The expansion index and mechanical resistance of these foams were both boosted by the addition of starch/PVA in significant amounts (Debiagi et al., 2011). There are other biopolymers used for packaging like polylactide (PLA) and PVA which has the potential to be used for commercial applications as a substitute for high-density polyethylene (HDPE), low-density polyethylene (LDPE), PS and PET (Naser et al., 2021).

Frozen seafood

Freezing is one of the most popular and widely used preservation methods for seafood (Guillotreau et al., 2017). The quality and shelf life of frozen seafood depends on different factors such as the fishing method, storage conditions onboard and offboard, including the entire logistics referred as the cold chain (Selamoglu, 2021). Cold chain is important as a lack of proper cold chain infrastructure could compromise with providing consumers with quality seafood (Ye et al., 2022). The sensory properties of the frozen seafood can be adversely affected due to dehydration and chemical variations which can take place under poor cold storage conditions (Miyawaki, 2018; Nakazawa et al., 2020). The frozen product must be packed in materials with appropriate barrier and mechanical properties to avoid or limit losses in product quantity and quality (Indergard et al., 2014).

Fishes are usually frozen and packaged in duplex board cartons lined with LDPE, which are then placed within a master carton consisting of 5 or 7 ply corrugated fibre board boxes (Ravishankar et al., 2017). Yamane et al. (2014) suggested that due to its good oxygen/water barrier properties, poly glycolic acid (PGA) or polyglycolide is an appealing biodegradable polymer with potential to be applied for frozen seafood packaging. The chemical structure of PGA is identical of polylactide (PLA) but without the adjacent methyl group, which enables the polymer chains to pack closely together and adopt an all-trans structure in its crystalline state. As a result of this, PGA has a high degree of crystallinity (45–55 %) and a low free volume, which contributes to its strong oxygen and water vapour barrier property which is also observed to be a hundred times greater than PET and the water barrier being on par with, or even superior to, polypropylene (PP)(Jem and Tan, 2020). PGA can also be incorporated as a supplementary layer to compensate the poor barrier nature of other biopolymer films used for frozen storage. Similarly, Zong et al. (2022) observed that a starch/polyvinyl alcohol (starch/PVA) film with cinnamaldehyde (CIN) could be beneficial for the packaging of giant yellow croaker (*Pseudosciaena crocea*) during frozen storage and the starch/PVA films were also able to prevent microstructure damage of fish, water loss, water migration, protein degradation, and lipid oxidation.

Another group of biopolymers which could be utilised in frozen seafood packaging are the bacterially produced poly hydroxy alkanoic acid (PHAs) (Li et al., 2016). In terms of food packaging, poly 3-hydroxybutyrate (PHB) and its copolymers such as poly 3-hydroxybutyrate-co-3-hydroxyvalerate (PHBV) or poly 3-hydroxybutyrate-co-4-hydroxybutyrate (PHBH), offers potential due to their good oxygen/water vapour barrier properties (with permeability lower than 50 cc) and thermal processability. The notable crystallinity of PHBV, which has been reported to be up to 60 %, is attributed to its high barrier characteristics with low hydroxyalerate concentrations (Srubar et al., 2012). However, intrinsic fragility, physical ageing at ambient temperature, and short processing windows limit their processing and use to a large extent (Anjum et al., 2016).

Poly(butylene succinate (PBS) is more flexible and has a greater elongation at break than PLA, which is advantageous for soft packaging (Duan et al., 2016). A study by Siracusa et al. (2015) demonstrated that PBS has a very high selectivity ratio of CO_2 and O_2, where the CO_2 shows a very high transmission rate which was ten times more than O_2. This is ideal for seafood packaging because the excessive CO_2 concentration within the inner surroundings of the packaging will provide protection against oxidation and enhance shelf-life. Rodriguez-Turienzo et al. (2011) applied a whey protein-based coatings on frozen Atlantic salmon replacing water glace after freezing which maintained the colour of frozen whole fish and fillet throughout the storage. Table 2 discusses the current technologies available for biodegradable packaging for chilled and frozen seafood.

Biodegradable Packaging Options for Vacuum Packed Seafood

Vacuum packaging is applied to a wide range of foods, to prevent loss of nutrients like vitamins, prevent lipid oxidation, reduce oxidative browning, and loss of pigments (Patil et al., 2020). Use of vacuum packaging for chilled and frozen seafood has the potential to double the shelf life and reduce risk of freezer burn when compared to normal packaging (Kumar and Ganguly, 2014; Ravishankar et al., 2017). Vacuum additionally helps to prevent the growth of aerobic microorganisms, particularly moulds, in processed products, with an extension in shelf life up to weeks, under refrigeration (Farmer, 2013; Berk, 2018). Gas barrier properties are the primary quality one search in the packaging materials used for vacuum packed food products (Patil et al., 2020). These essential properties could be imparted by biodegradable plastics with whey protein components with improved mechanical properties. Kodal Coşkun et al. (2014) experimented with soy protein edible film (SPEF) incorporated with oregano and thyme essential oils on both beef patties and fresh ground beef vacuum packed with polyamide-ionomer polyethylene pouches having an oxygen permeability of 45 cm^3/m^2/24 h/690 mm Hg, under refrigerated conditions. During the evaluation, the biofilm demonstrated excellent antimicrobial properties with lower peroxide value and free fatty acids (FFA), especially at later times of refrigerated storage, with no evident effect on TBA value.

Collagen is another important biopolymer with potential to be considered for biodegradable packing. Collagen is the primary structural protein of connective tissue, including bone, ligaments, tendons, and cartilage (Shit and Shah, 2014). Alparslan et al. (2014) suggested gelatine films incorporated with laurel essential oil (LEO) for salted, dried and smoked seafood, which are low in moisture. UV sterilised films (2 min) of gelatine enriched with LEO was used as wraps in rainbow trout fillets, vacuum packaged and stored at 4 °C. When considering chemical indices (pH, TVB-N, TBA, FFA, PV), gelatine films with 0.1 and 1 % LEO improved the quality of fish during storage. Fish fillets wrapped in gelatine film containing 1 % LEO showed the best quality based on the sensory, chemical, and microbiological analysis. Several biodegradable polymers can also be employed for vacuum packaging applications. Dong et al. (2015) developed a multi-layered biofilm by combining two films poly (propylene carbonate) (PPC) and poly (vinyl alcohol) (PVA) which showed high barrier and tensile properties. For enhancing the mechanical properties, three layers of PPC/PVA/PPC were used while casting the film. Compared to single layered films and controls, meat packaged with multi-layer film had a longer shelf life and overall higher quality during storage.

Biodegradable Packaging Options for Modified Atmosphere Packaged (MAP) Seafood

Modified atmosphere packaging (MAP) is a technique that uses an altered environment with different gas composition to preserve perishable goods (Nagarajarao, 2016; Kontominas et al., 2021). Because of the specific barrier property requirements, not many of the bio-based materials could be used for MAP unlike PLA which offers new sustainable substitution to the problem (Mistriotis et al., 2016). For providing MAP-friendly barrier properties to the biodegradable options, it is recommended to use multilayer biobased materials; the suitability of biobased polymers like PLA and cellulose-based multilayer materials for packaging of various highly perishable food products like meat and cheese in MAP has been evaluated and compared with conventional packaging materials, both on laboratory and industrial scales (Eissenberger et al., 2023). Studies conducted by Peelman et al. (2014) recommend application of multilaminate biodegradable films with enhanced moisture barrier properties for application in seafood MAP packaging under refrigerated conditions. Bionanomaterials like crystalline nano material (CNM) with excellent oxygen barrier properties in dried condition could be used for enhancing the barrier properties of the biodegradable films used for MAP (Wang et al., 2018a).

Biodegradable Packaging Options for Dried Seafood

Dried seafood is highly hygroscopic, and when exposed to air or oxygen, results in quality degradation. Palmyra leaf baskets, coconut leaf baskets, bamboo baskets, newspaper baskets, and gunny sacks are among the traditional packing materials used for packing or storing dried fish which do not provide protection from moisture, oxygen, or insect infestation (Bindu, 2021). Large quantities of dried seafood are also frequently packed in plywood boxes and waxed corrugated cartons which even though this saves the products from physical damage, are marginal in protecting against excessive humidity and pest threat (Srinivasa Gopal, 2015; Remya et al., 2018). By using thermal expansion, thermoplastic foams made out of cassava starch and cabernet sauvignon grape stalks were effectively tested by Engel et al. (2019) which proved to

Table 2. Summary of biodegradable packaging for chilled and frozen seafood identified in systematic review of the literature from 2009 to 2024.

Applied product	Bio-packaging composition	Observation	Reference
Pacific white shrimp (*Litopenaeus vannamei*)	Blend films of polybutylene adipate terephthalate) and poly lactic acid)(PBAT/PLA) compounded with carvacrol, citral and α-terpineol essential oils (EOs)	Inhibited lipid oxidation, microbial growth and textural changes in shrimp stored with Eos containing film	Laorenza and Harnkarnsujarit (2021)
Indian white prawn (*Fenneropenaeus indicus*)	Polylactic acid/chitosan film	Improved functional properties, retained microbial and biochemical quality indices	Fathima et al., (2018)
Grass carp (*Ctenopharyngodon idella*) fillets and rainbow trout fillets	Gelatine and oregano oil, gelatine film enriched with curcumin and b-cyclodextrin (natural preservatives)	Reduced the formation of volatile bases and oxidation products, inhibited microbial growth in fish fillet under chilled storage	Hosseini et al. (2016); Sun et al. (2019)
Flounder fillets (*Paralichthys orbignyanus*)	Agar, fish protein hydrolysate and clove essential oil films	Lowered pH value and total volatile bases, delayed the growth of H_2S-producing microorganisms in fillets	da Rocha et al. (2018)
Peeled shrimp	Zinc oxide nanorods/clove essential oil incorporated Type B gelatine composite films	Showed strong antimicrobial activity against both *Listeria monocytogenes* and *Salmonella typhimurium* in-vitro during refrigerated storage for 20 days	Ejaz et al. (2018)
Trout (*Oncorhynchus mykiss*) fillets	Alginate coating incorporated with apple pomace extract	Significantly reduced thiobarbituric acid (TBA) and total volatile basic nitrogen (TVB-N) values with significant antioxidant activity	Gharedaghi et al. (2020)
Red sea bream (*Pagrus major*)	Chitosan nanoparticles, collagen protein films reinforced with Anthocyanidin and Cinnamon-perilla essential oil	Extended shelf life	Zhao et al. (2022)
Salmon (*Salmo salar*)	Gallic acid clove oil incorporated in gelatine chitosan film	Improved gas and oxygen barrier properties, inhibition of microbial growth and rancid effects by coating, prolonged the shelf life of fillet for five days	Xiong et al. (2021)
Mackerel (*Scomber scombrus*)	Lyophilised algae (*Fucus spiralis*) powder incorporated gelatine films	Enhanced antimicrobial and antioxidant effects with increased algae content in the film	Trigo et al. (2022)
Fish burger rainbow trout (*Oncorhynchus mykiss*)	Bio-based seaweed (*Himanthalia elongata* and *Palmaria palmata*) edible films	Significantly controlled pH and water activity changes and reduced microbial growth over storage	Albertos et al. (2019)
Pacu (*Piaractus mesopotamicus*)	Glycerol, PBAT and cassava starch biodegradable film	360 days of frozen storage at −18 °C, results show good stability of the packaging material	Cossa et al. (2022)
Nile tilapia (*Oreochromis niloticus*)	Pomegranate peels extract (PPE) incorporated with gelatine (Gf) and k-carrageenan (Cr)	The coating enhanced overall quality and extended the shelf life of fish fillet on storage	Khojah (2020)

Table 2. Continued.

Applied product	Bio-packaging composition	Observation	Reference
Prawns (*Penaeus monodon*)	Cellulose nanoparticles (CNP) + fennel seed oil incorporated in polyvinyl alcohol (PVA) film	Helped to maintain quality of processed prawns up to 63 days under frozen storage	Shruthy et al. (2021)
Anchovy (*Stolephorus indicus*)	Polylactic acid (PLA) nanocellulose (NC) films	Enhanced shelf life	Thomas et al. (2021)
Ovate pompano (*Trachinotus ovatus* L.)	Chitosan and citric acid or liquorice extract	Inhibited primary and secondary lipid oxidation, lower peroxide value (PV) and thiobarbituric acid reactive substances (TBARS)	Qiu et al. (2016)

have low moisture permeability and indicated no microbial growth. Biodegradable films from cassava starch blended with PVA, and silica particles (SiO_2) showed improved physical properties such as water barrier and hydrophobicity making them suitable alternative to synthetic plastics for packing dried products (Arayaphan et al., 2020). Trinh et al. (2021) used thermoplastic starch (TPS) and PLA to develop biodegradable multilayer film with better gas and moisture barrier attributes by reactive extrusion, compression moulding, and dip coating processes. Maleic anhydride (MA) modification of TPS was employed to improve the interfacial adhesion between the TPS and PLA layers of the film. Melendez-Rodriguez et al. (2021) developed biodegradable multi-layered high gas barrier films using layers of polyhydroxyalkanoate (PHA) assembled using interlayer of CNC and a hot-tack layer made of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) fibres generated by electrospinning. Chang et al. (2021) investigated the fabrication process of multilayer thermoplastic starch/poly(butylene adipate-co-terephthalate) (TPS/PBAT) and malleated counterpart (MTPS/PBAT) film combinations with compositions ranging between 50 and 70 % by weight of TPS. While ductility only increased at high PBAT concentrations, all composite films generally shown enhanced thermal stability, tensile strength, and modulus. Table 3 presents the biodegradable packaging options available for dried, MAP and vacuum-packed seafood.

Table 3. Summary of biodegradable materials for dried, MAP, and vacuum packed seafoods.

Applied product	Bio-packaging composition	Observation	Reference
Dried anchovy	Chitosan with acetic acid (ACS) and propionic acid (PCS) with glycerol)	Chitosan films at ambient room temperature could prolong the shelf life better than plastic films. Possibly a successful method to maintain the microbiological quality of dried fish	Vimaladevi et al. (2015)
Sea bass	Chitosan-based edible film	The combination of chitosan-based edible film wrapped of sea bass fillets in vacuum packaging significantly reduced TVB-N and trimethylamine-nitrogen (TMA-N) values and prevented the multiplication of spoilage causing bacteria	Günlü and Koyun (2013)
Smoked salmon	*Gracilaria vermiculophylla* extract films containing zinc oxide nanoparticles	Smoked salmon that had been enclosed in GVE film that included 3 % ZnO-NPs exhibited minimal levels of lipid oxidation and antibacterial action against pathogenic microorganisms	Baek and Song (2018)
	Fish gelatine reinforced with chitosan nanoparticles (CSNPs)	The addition of CSNPs to fish gelatine (FG) films increased its elastic modulus, TS, and water vapour barrier, demonstrating that the nanoparticles increase the film's suitability for use as edible packaging	Hosseini et al. (2015)
Smoked salmon	Chicken feather protein (CFP), gelatine and clove oil	Composite film formed by CFP/gelatine incorporated with 1.5 % clove oil can be considered a potential active packaging material for smoked salmon preservation which have improved water barrier properties	Song et al. (2014)

Table 3. Continued.

Applied product	Bio-packaging composition	Observation	Reference
Smoked tuna	Chitosan nanoparticles	Fillets of smoked tuna that have 3 (% w/v) CS-NPs added to the fish coating can fulfil SNI (Indonesian National Standards) requirements	Rasulu et al. (2020)
Shrimps	cassava starch and chitosan	Based on the physical, chemical, and microbiological factors, the use of edible coatings made of chitosan and cassava starch, along with vacuum packaging, can improve the conservation of the coated shrimps	Benevides et al. (2020)

Biodegradable Options for Smart and Active Seafood Packaging

Innovative technologies are being developed with an emphasis on making packaging more interactive (Dobrucka and Cierpiszewski, 2014). One such innovative packaging method is smart packaging or intelligent packaging, which is being used to preserve a variety of food systems, including fish and shellfish (Mohan et al., 2018; Salgado et al., 2021). Based on variations in pH, temperature, light, time, and ammonia generation, bioactive molecules alter their colour to serve as an indication for detecting the deterioration of packed seafood products (Bhargava et al., 2020). Adenosine triphosphate breakdown, microbial plate counts, total volatile base nitrogen (TVBN), lipid oxidation (rancidity), and sensory qualities are typically used to monitoring seafood spoilage. With the use of recently developed methods that employ halochromic (pH-sensitive) bioactive molecules, provides better bio-based smart packaging options for the consumers (Ma et al., 2021). Figure 2 indicates the applications of active and intelligent packaging in seafood products. Active packaging secure products by facilitating interactions between the package or package components and food or internal gas atmosphere, delaying, or preventing microbiological, enzymatic, and oxidative degradation (Biji et al., 2015; Chong et al., 2015; Nagarajarao 2016). Table 4 indicates some of the biodegradable smart/active packaging alternatives for seafood products.

Conclusion

Considering the significance of food contact primary packaging in seafood and the industry being one of the largest consumers of synthetic plastics, the shift towards sustainable packaging options is very important. The negative impact of petroleum based plastic packaging discards on the environment due to their non-biodegradable and toxic nature is alarming. It requires consistent research and development to identify and standardise biodegradable options for each type of polymer packaging required for different

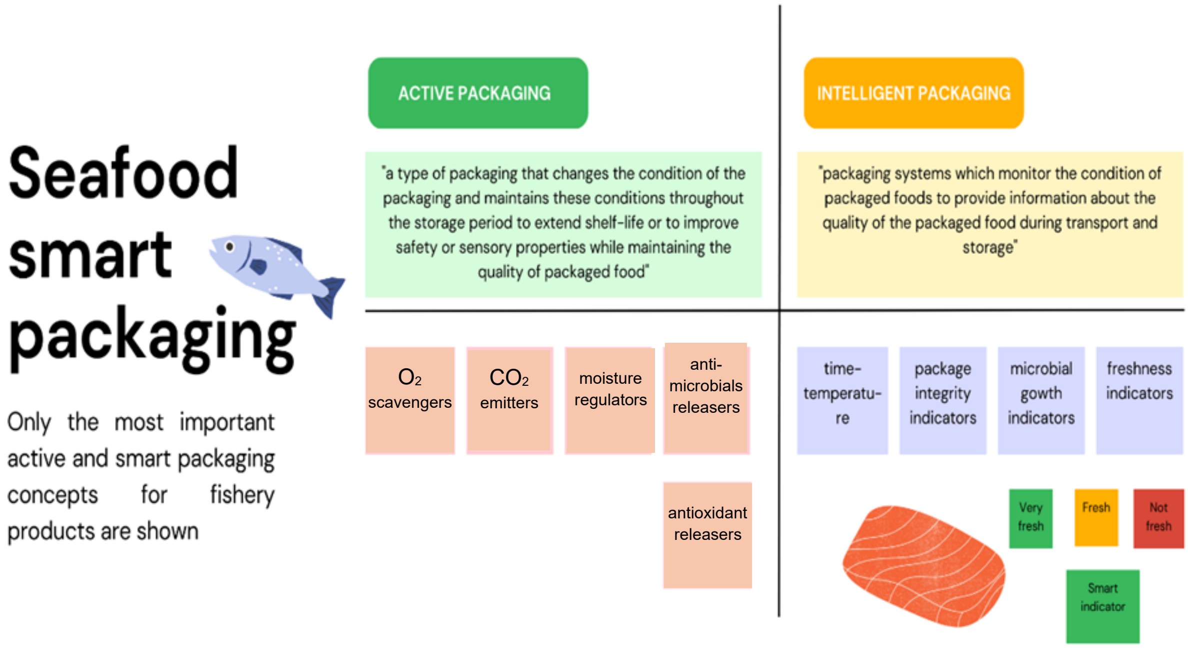

Fig. 2. Applications of active and intelligent packaging in seafood.

Table 4. Summary of recent innovation in biodegradable smart/active packaging materials applied in seafood and their effects.

Applied seafood product	Bio-packaging composition	Observation	References
Shrimp	Carboxymethyl cellulose/ cobalt-based metal-organic framework (Co-MOF) multifunctional films	Seafood freshness with UV-blocking, antibacterial and ammonia-responsive function	Tang et al. (2023)
Fish fillet	Chitosan + Methyl cellulose + *Phyllanthus reticulatus* anthocyanin	For smart packing at room temperature. The CMPR films showed a red shade at an acidic pH of 1 and a yellowish tint at a basic pH of 11	Gasti et al. (2021)
Rainbow trout fillet	Starch-cellulose and alizarin dye	Showed colour changes from yellow to purple (ASC) and dark red (AC) at pH 2–11. High sensitivity and colour response to ammonia. The colour changes in indicators at pH 7–9 was detectable by naked eye	Ezati et al. (2019)
Wuchang bream (*Megalobrama amblycephala)*	Colorimetric indicator films based on agar incorporating with *Arnebia euchroma* root extracts (AEREs)	The colorimetric labels with lower AEREs content would be more suitable for monitoring fish freshness. The designed colorimetric indicator films have a noticeable colour response, are non-toxic, and are spoilage resistant	Huang et al. (2019)
Shrimp (*Metapenaeus monoceros*)	*Echium amoenum* anthocyanins incorporated into bacterial cellulose film	Visually - distinguishable colour changes, i.e., fresh (violet), use soon (grey), and spoiled (yellow) in packed shrimp. The TVC and TVB-N values of the prawns were consistent with these colour changes. Novel pH-sensitive dye for intelligent packaging of protein-rich food	Mohammadalinejhad et al. (2020)
Tilapia (*Oreochromis*)	Polyaniline (PANI) based film	TVB-N (one of the freshness parameters of fish) was monitored for the spoiling indication in order to determine the relationship between the freshness of tilapia and the colour change of PANI film.	Wang et al. (2018 b)
Hake (*Merluccius gayi*)	β-Chitin film incorporated with elderberry extract	Due to an increase or reduction in volatile basic nitrogen (TVB-N), which is created during bacterial growth and the breakdown of protein compounds contained in the medium, the sensor films' colour changes signal the pH levels	Cabrera-Barjas et al. (2021)
Shrimp	pH-sensitive films based on starch/polyvinyl alcohol and food anthocyanin from purple sweet potato extracts	Total volatile basic nitrogen (TVB-N), mostly composed of trimethylamine (TMA), dimethylamine (DMA), and ammonia (NH_3), was produced during the rotting of prawns. As a result, shifting the initial light purple colour to blue spoilage during shrimp storage	Zhang et al. (2020)
Mackerel	Cellulose nanofiber /carboxymethyl cellulose added with shikonin	Discoloration of shikonin at weak acid and weak alkali to monitor fish freshness	Ezati et al. (2021)
Tilapia (*Oreochromis*)	Bacterial cellulose film incorporated with pelargonidin dye	Indicates changes in total volatile base nitrogen (TVB-N) amounts of fillets under storage	Liu et al. (2021)
Silver pomfret (*Pampus argenteus*) and shrimp	Chitosan and curcumin film incorporated with oxidised chitin nanocrystals as filler	Due to a pH alteration, the colour of the films changed, making it possible to detect when seafood is spoiled	Wu et al. (2019)

Table 4. Continued.

Applied seafood product	Bio-packaging composition	Observation	References
Giant gourami (*Osphronemus gouramy*)	Betacyanin incorporated glucomannan film	Smart packaging during storage of fish to monitor freshness. When TVB-N increase, the film's original purple colour had been replaced by a yellow	Ardiyansyah et al. (2018)
Shrimp	Poly(lactic acid)(PLA) and poly(propylene carbonate)(PPC) incorporated with curcumin	Demonstrating an evident colour change from yellow to light orange	Cvek et al. (2022)

varieties of seafood including the various processing and storage conditions required for different preservation techniques. The combination of various bio-components both in macro- and nano-level have been documented to efficiently compensate the versatile physical and barrier properties of the synthetic plastics. Continuing such innovations will result in enhanced and sustainable seafood packaging materials in the near future.

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