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Review

Seafood Waste-Based Materials for Sustainable Food Packing: From Waste to Wealth

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Abstract: Sustainable development is a global goal that entails an interdisciplinary approach for tackling ongoing and future challenges regarding the environment, climate change, economic limitations, and resource efficiency. Against this background, valorizing available and high-potential waste to manufacture value-added products that facilitate recycling resources and energy meets the significant objectives of a circular economy. Renewable and biodegradable biopolymers from seafood waste are recognized as promising alternatives for developing sustainable food packaging materials, boosting resource efficiency, and diminishing environmental concerns. Based on the concepts of waste to wealth and circular economies, the present review summarizes the recent advances regarding the production and utilization of seafood waste, as well as current problems in food packaging and the market demand for natural biopolymer-based food packaging. The principal objective of this review is to analyze the utilization of seafood waste and by-products to manufacture biodegradable bio-based materials for food packaging materials that are environmentally and economically sustainable. The applications of edible films produced from fish gelatin and chitosan extracted from seafood waste for food packaging are also highlighted. The present study will provide researchers, food technologists, and academia with more robust knowledge to facilitate future food packaging research and the creation of a cyclical economy.

Keywords: seafood waste; resource efficiency; food packaging; cyclical economy; sustainability

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1. Introduction

Over the past century, the dramatic growth of the global population and consumer demands has resulted in massive energy and resource consumption, severely impacting ecosystems and biodiversity [1]. At the same time, the inadequate disposal of industrial production waste and by-products has also harmed the environment and human health [2]. Therefore, a sustainable food resource production system via effective recycling for reducing waste will contribute to environmental and ecological protection [3]. As resources become increasingly precious, the circular bio-economy has flourished in politics, academia, and many industries [4,5]. As shown in Figure 1, bio-economy principles include reusing, remanufacturing, sharing, and recycling materials, cascading uses, resource efficiency, and nutrient cycling [6]. Moreover, the reuse of bio-waste and by-products is crucial in bio-economies for converting low-value waste into new materials and products [4,6]. In this regard, Chen and his co-workers conducted many research studies, such as converting waste $LiFePO_4$ batteries into sea urchin-like materials [7], developing cementitious materials from industrial solid waste [8], converting electronic wastes into high-efficiency energy conversion catalysts [9,10], and transforming waste adsorbents into efficient electrocatalysts [11], etc. These "waste-to-wealth" introduce tremendous environmental and economic significance, as these strategies can significantly reduce the environmental impact of solid/liquid waste and slash the cost of manufacturing functional materials (e.g., adsorbents and catalysts) [12,13]. Additionally, the European Commission has integrated aspects of the bio-economy into the Circular Economy Action Plan, where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimized. This is an essential contribution toward the EU's efforts to develop a sustainable, low-carbon, resource-efficient, and competitive economy [14].

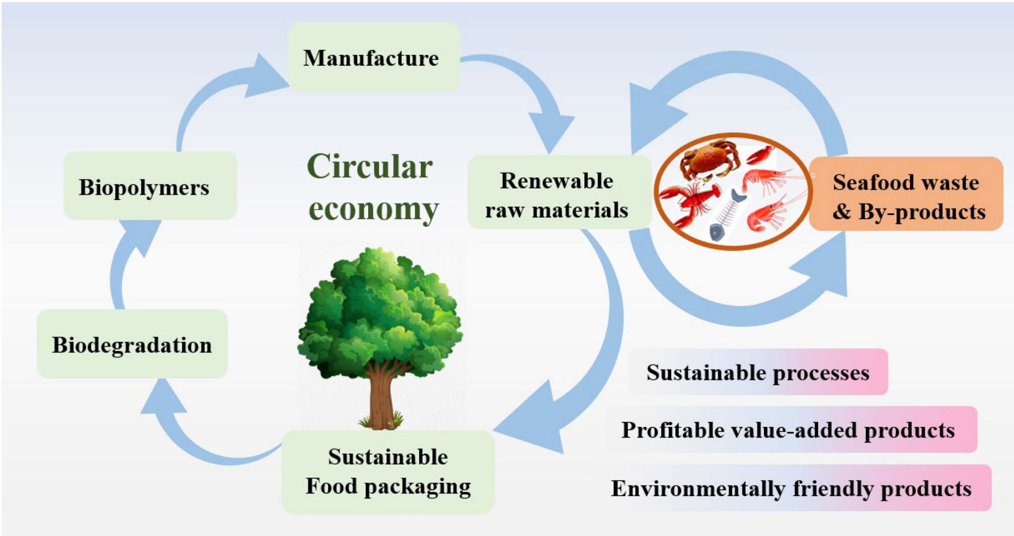

Figure 1. Valorization of seafood waste and by-products towards circular economy.

Seafood consumption is globally increasing, resulting in large amounts of waste, waste accumulation, and environmental pollution. As shown in Figure 2 (scientific data based on Web of Science, accessed on 25 October 2022), it is notable that nearly 75% of the articles investigated were published within this decade, of which over 45% were published in the last 5 years, indicating that seafood waste has attracted the attention of researchers in recent years. According to the Food and Agriculture Organization of the United Nations (FAO), it was reported that global seafood production (fishes, mollusks, crustaceans, and other aquatic animals) reached nearly 175 million tons in 2017, of which 25% ended up as wasted [15]. In particular, crustaceans comprise about 40% meat, and the remaining 60% is inedible, accumulating large amounts of crustacean waste [16]. In 2020, the global production level of crustaceans reached 16.83 million tons, generating 7–9 million tons of lobster, crab, and shrimp waste [17]. Therefore, effective management solutions are needed to administer this seafood waste and to prevent them from wasting and polluting the environment. In actuality, a variety of nutrients can be extracted from seafood waste, which is an abundant source of nutrition for the human diet. For example, fish processing by-products and wastes, including skins, heads, guts, bones, scales, and fins, are sources of several potentially valuable molecules, such as proteins and peptides, oils and lipids, vitamins, minerals, pigments, and enzymes [1,18]. In addition, crustacean waste contains chitin and chitosan, a biocompatible and biodegradable polymer covered with proteins and minerals that are invaluable for producing high-value products with economic attractiveness and environmental feasibility [16,19]. The full utilization of seafood waste to produce bioactive compounds and functional ingredients for application in the food industry would be a critical method for sustainable resource utilization and the principal objective of a circular economy.

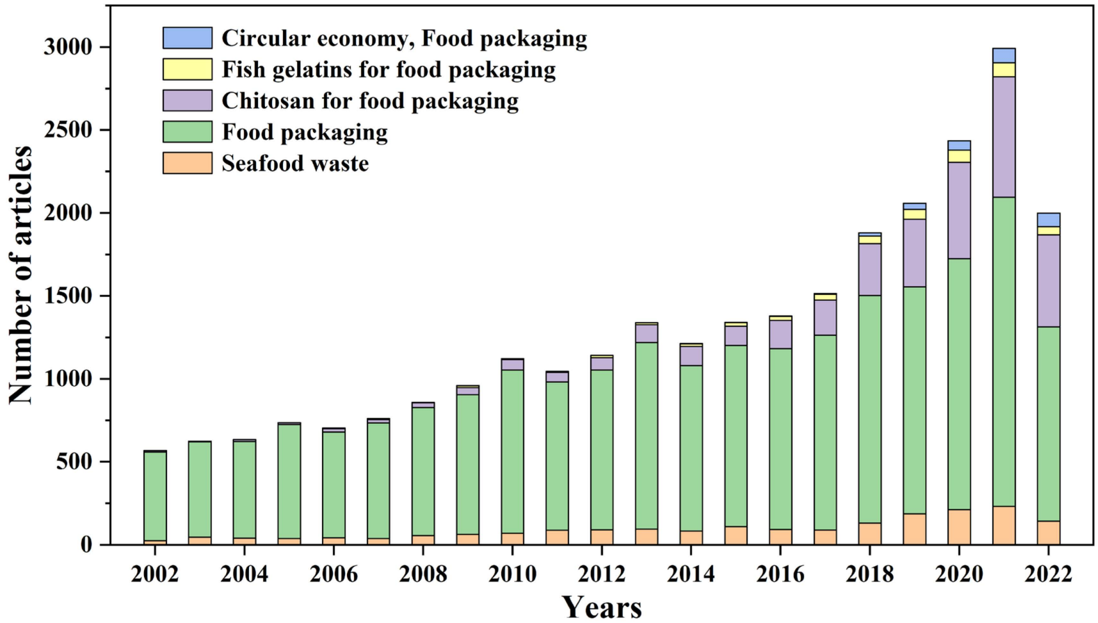

Figure 2. Distribution of published papers over the last two decades. The keywords: "Seafood waste", "Food packaging", "Chitosan for Food packaging", "Fish gelatins for Food packaging", and "Circular economy, Food packaging" were searched for on the Web of Science analytics. The same articles may appear in more than one section.

Food processing and packaging are crucial processes of the food industry. As shown in Figure 2, food packaging has always been a significant concern in research. Food packaging extends the freshness and shelf life of food. In turn, this also minimizes food wastage caused by spoilage during storage or transportation. Nevertheless, the end-of-life scenario of plastics derived from fossil fuels frequently has adverse effects on the natural environment, including the generation of microplastic pollution and elevated greenhouse gas emissions [20,21]. The replacement of plastic with renewable and biodegradable food packaging materials would undoubtedly further reduce the global plastic waste problem [22,23]. Recently, it has been demonstrated that the extracted fish gelatin and chitosan from seafood waste with antioxidant and antimicrobial properties could be considered suitable alternatives to plastic products for food packaging to reduce food spoilage, post-processing operations, and to extend shelf life [4,21]. Specifically, the European Commission has funded the N-CHITOPACK project specifically aimed at producing antimicrobial and biodegradable bioplastics for food packaging using chitin nanofibers. Recently, the project produced three different materials for various applications: coffee capsules, food bags, and packaging films. The results of the N-CHITOPACK project will reduce waste in the seafood and packaging industries and improve economic and environmental impacts [24]. Considering the trend of producing wealth from waste, processing of seafood waste for biodegradable bio-based food packaging materials opens up a new market for the comprehensive utilization of seafood waste.

This review presents a comprehensive analysis of seafood production, waste, and utilization in recent years. Simultaneously, the demand for new biodegradable food packaging materials in the food industry is summarized. Moreover, the applications of edible films produced from fish gelatin and chitosan extracted from seafood waste for food packaging are also highlighted. Apart from these technical and scientific issues related to food packaging, environmental and socio-economic impacts will be addressed with the aim of developing more sustainable packaging systems. The present review will provide a promising direction for future research on food-derived bioactive compounds in packaging from the perspective of circular bio-economies and sustainable development in order to achieve the waste-to-wealth transformation.

2. Seafood Waste and Utilization

2.1. Global Seafood Production in 2020

Seafood comprises shellfish and finfish from estuarine, ocean, freshwater, and semi-saltwater ecological systems, representing a high percentage of globally produced food [25]. Fishes are a valuable source of proteins (~17% of protein intake), vitamins, micronutrients, and essential fatty acids (omega3), which are crucial to human health [19]. In accordance with FAO, in 2020, the total global production of fisheries and aquaculture reached a historical record of 214 million tons, including 178 million tons of aquatic animals (90 million tons from capture fisheries and 87 million tons from aquaculture) and 36 million tons of algae (Figure 3a), which exhibit a moderate growth compared with the previous record of 2018 (213 million tons+) [17]. The restricted increase is primarily due to the impacts of the COVID-19 pandemic in 2020 and the continued reduction in China's catches (10% less in 2020 than the prior three-year average) [17].

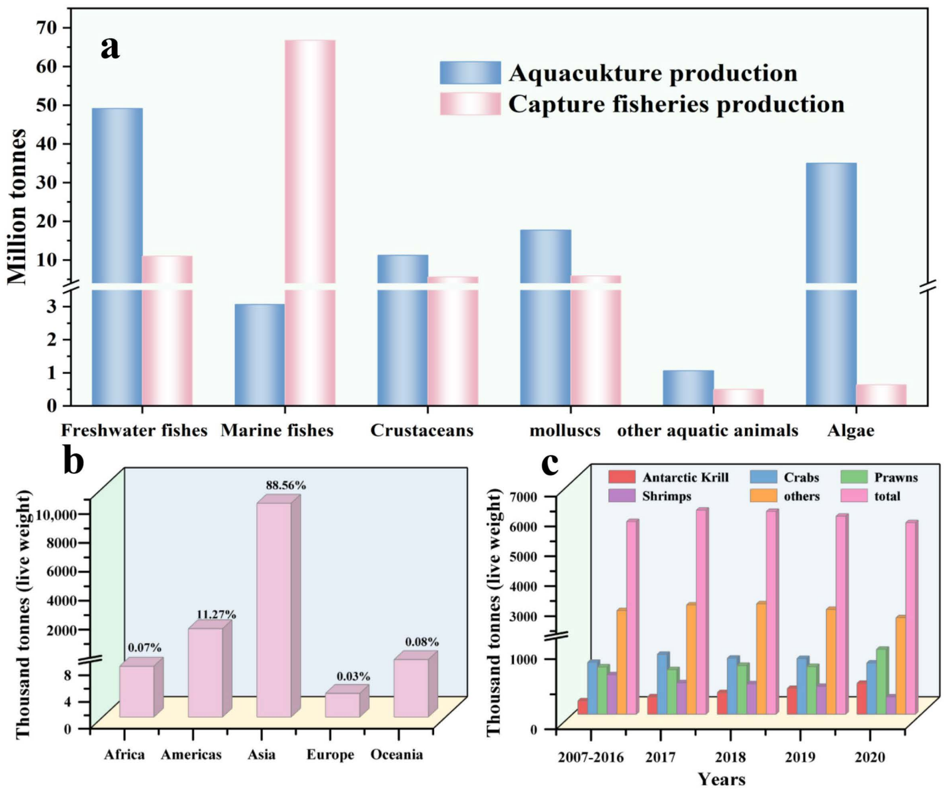

Figure 3. The world production of capture fisheries and aquaculture in 2020. (**a**) The production of world capture fisheries and aquaculture for different seafood products in 2020. (**b**) The total aquaculture production of crustaceans in five continents in 2020. (**c**) Major types of crustaceans globally produced by capture over the last two decades. The data were obtained from the Fishery Statistical Collections, Food and Agriculture Organization of the United Nations with permission (https://www.fao.org/fishery/statistics/global-production (accessed on 25 October 2022)).

Significantly, the global production level of crustaceans reached 16.86 million tons in 2020, of which capture fisheries contributed 5.63 million and aquaculture 11.23 million tons. Crustaceans were nearly universally sourced from coastal aquaculture, and Asia was the biggest producer (88.56%), followed by the Americas (11.27%), Oceania (0.08%), Africa (0.07%), and Europe (0.03%) (Figure 3b) [17]. In addition, the total number of globally captured marine crustaceans over the past 20 years varied little, and their species are shown in Figure 3c [17]. In conclusion, although the COVID-19 pandemic spread globally in 2020, seafood production kept increasing, indicating the high global demand for seafood.

2.2. Seafood Waste

The expansion of fisheries and aquaculture production and processing caused an increase of by-products and waste, negatively impacting the environment and the economy [26]. In the aquaculture and fisheries industries, it was evaluated that up to 35% of global aquaculture and fishery production is discarded or wasted annually. As shown in Figure 4, it is estimated that annual discards (averaged over 2000 to 2018) were around 8.5 million tons, which was about 10% of the total catch [27]. Besides, due to low-value discards, storage problems, and spoilage, 30% of the fish captured are not utilized. The rest of the harvested fish proceed through processing facilities, with 30–50% being available as consumable products and the remaining portion (70–50%) being thrown away as by-products or residuals [8]. In addition, processing crustaceans produces a high level of gross underutilized by-products. These wastes comprise shells and heads, accounting for approximately 35–40% of the total wet weight [4,28].

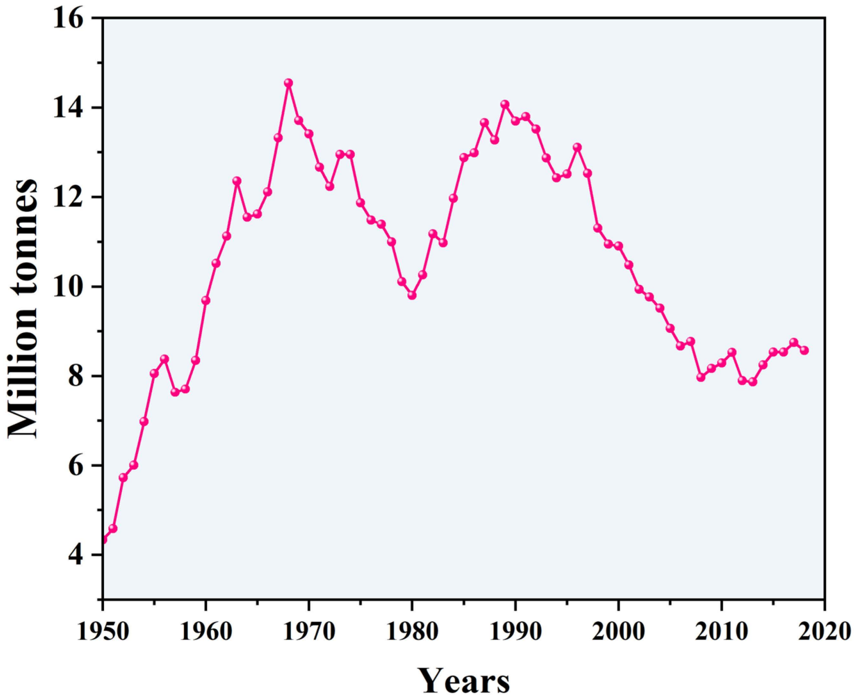

Figure 4. Number of fishes discarded in recent decades. Discards are animals thrown back (alive or dead) into the sea after being caught during fishing activities. (data from [27]).

2.3. Seafood Waste and By-Product Utilization

Managing the sustainable utilization of seafood waste and by-product resources is exceptionally vital in order to provide resource sustainability and to prevent environmental problems. In recent years, a vast amount of research has been conducted to exploit components/compounds from industrial seafood by-products in various fields, including functional foods, biomedicine, aquaculture feed, and agriculture [18]. By-products and wastes of fish processing, involving skins, heads, guts, bones, scales, and fins, are sources of several potentially valuable molecules. For example, fish gelatin could be extracted from fish skin and further processed into edible films and coatings for food applications [29]. Fish guts are essential sources of specific enzymes such as pepsin, pancreatin, pancreatic rennet and collagenase, and lipase [25,26]. Minced fish meat could be hydrolyzed to yield bioactive peptides [30]. Due to the high calcium content, fish bones can be processed into fish bone powder for calcium supplementation as a new additive in food processing [31]. A fish's head is enriched with lecithin and polyunsaturated fatty acids, which could enhance memory, improve sleep, and reduce cardiovascular diseases. Fish oil from the fish's head can be extracted to produce fish oil products for the development of healthcare products [32]. In addition, fish processing waste and by-products could be manufactured and transformed into fish sauce, fish paste, and feed, which effectively improves the utilization efficiency of by-products and minimizes the waste of resources [18,26].

Crustacean and bivalve by-products and waste are other seafood wastes that have raised concerns. In fact, crustacean and shellfish waste is presently the primary biomass source for chitin production [33]. As an odorless/tasteless nitrogenous polysaccharide, chitin is a high molecular weight natural bio-polymer that is second only to cellulose [34]. Chitosan is obtained by the deacetylation of chitin to different degrees. Chitosan and its derivatives exhibit superior biodegradability, non-toxicity, and biocompatibility, which have been widely used in food, cosmetics, and pharmaceuticals [16,35]. In summary, the full utilization of seafood waste and the by-product is essential for circular bio-economy and sustainable development, and is also the priority of Sustainable Development Goal (SDG) indicator 12.3, which targets the halving of waste by 2030 [36].

3. Demand for Sustainable Biopolymer Based-Food Packaging Materials

The world's population is forecasted to reach 9.6 billion people by 2050, which means that food demand will increase by over 50%. The future will require better land utilization for agriculture and, most importantly, the optimal conservation of raw materials and finished food products. The latter mainly involves adopting appropriate packaging that protects food and ensures a longer shelf life while meeting societal expectations, including protecting the environment and health [15]. In recent years, plastic materials, primarily obtained from petrochemicals, dominated food packaging and are indispensable in many areas, from meat and dairy products to fruits and vegetables and from fresh to frozen products [15,37]. However, plastics are traditionally produced from unsustainable petrochemicals and are not biodegradable, resulting in a global waste problem [38]. In addition, the entry of microplastic particles in food into human tissues is caused by plastic food packaging, which may cause adverse health effects. Therefore, the design and development of biopolymer-based food packaging materials represent a current imperative for the food industry [15,39]. Sustainable biopolymer molecules derived from seafood wastes with good film-forming properties are being used to develop food packaging materials that exert excellent food preservative effects.

Notably, a number of seafood wastes are desirable sources of sustainable biopolymers. For example, fish gelatin is regarded as a substitute for gelatin from cattle and pigs, which has recently been considered as a promising biological material with great potential for both pharmaceutical and biomedical applications [40]. Moreover, crustacean waste usually has a high chitin content, a polysaccharide that exhibits specific excellent properties, including biocompatibility, biodegradability, and antibacterial and antioxidant activities. The industrial bottlenecks of using waste-derived chitin-nanofibrils, for producing food packaging have been evaluated in a European Union project. The project claimed that substituting non-renewable materials in food packaging with chitin-based films could reduce carbon dioxide emissions by 12 million tons per year [24]. Therefore, the production of food packaging materials from seafood by-products and waste to achieve the waste-to-wealth transformation represents a profitable strategy for environmentally friendly and economically effective utilization.

4. Seafood Waste-Based Materials for Food Packing

The edible film is a thin layer of material that could alter the molecular exchange between food and the environment as well as different compartments of the same food to maintain the freshness of the food during transportation, storage, and display. Fish gelatin and chitosan present excellent film-forming abilities, and they have been suggested as alternatives for petroleum-based polymers and for applications in ever-growing food packaging industries.

4.1. Fish Gelatins as Antioxidant Antimicrobial Films for Food Packaging

Gelatins are tasteless food-grade materials with excellent biocompatibility, biodegradability, and antibacterial and antioxidant properties, rendering them the effective materials for preserving fresh food. Due to religious restrictions and a variety of sociocultural factors, fish gelatin received a substantial amount of attention as an alternative to mammalian gelatins [29]. Fish gelatin, obtained via collagen denaturation, is a readily available raw material for industrial applications such as manufacturing films for food packaging [41]. Residues from fish filleting account for up to 75% of harvested biomass, with skin and bones containing high collagen content and accounting for approximately 30% of such residues [42]. Gelatin's composition is comparable to that of the collagen from which it is derived, with proline (Pro) and hydroxyproline (Hyp) predominating [29].

Although fish gelatin offers excellent film-forming properties, the mechanical and barrier properties still require improvement. Additionally, fish gelatin is highly water-soluble, viscous, and subject to natural weather conditions and air moisture; thus, it still has significant limitations when applied in food packaging. In order to overcome the restriction of pure fish gelatin films in terms of water solubility, the mechanical and barrier properties, and biological properties, most of the current research studies focused on incorporating antioxidants, antimicrobial agents, and bio-polymers in fish gelatin film formulations to obtain modified composite films. Table 1 lists some common antioxidants, antimicrobial agents, and biological polymers incorporated into fish gelatin to prepare a composite film for food packaging. The modified composite film with favorable physicochemical and biological properties further effectively inhibits lipid oxidation and microbial growth, thereby preventing food spoilage.

Table 1. Natural antioxidants, antimicrobials, and biological polymer added to fish gelatin to develop composite films in recent decades.

Type	Compounds Name	Reference
Antioxidants	Ferulic acid, Caffeic acid and Tyrosol	[43]
	Hydroxytyrosol (HT) 3,4-dihydroxyphenylglycol (DHPG)	[44,45]
	Black rice bran anthocyanins	[46]
	Fructose and Ascorbic acid	[47]
	Betalains from vegetable amaranth	[48]
	Resveratrol	[49]
	Ferulic acid, Caffeic acid, Gallic acid, Catechin, and Rutin	[50]
	Gallic Acid	[51]
Antimicrobials	Seed juice by-product	[52]
	ε-poly-Llysine (ε-PLL)	[53]
	Leaf extract	[54]
	TiO_2-Ag	[55]
Biological polymer	Pectin	[44,45]
	Oxidized chitin nanocrystals	[46]
	Lecithin, Tween-20, and Tween-80	[56]
	Chitosan	[55]

Currently, there are many pieces of research on the production of edible films based on fish gelatin for food packaging. For example, Bermudez et al. prepared a pectin–fish gelatin edible film to conserve raw beef during refrigeration storage, which was able to inhibit lipid oxidation in beef during a 7 days storage period at 4 °C [44]. Furthermore, Salem et al., extracted gelatin from the skin of the dogfish (*Squalus acanthias*) to prepare a functional gelatin-based film that could be employed as an active packaging material to maintain the quality of the cheese [57]. Additionally, Jeya Shakila et al., fabricated four types of films, gelatin, gelatin—montmorillonite, gelatin—chitosan, and gelatin—montmorillonite—chitosan, from red snapper and grouper bone gelatin, and compared them with mammalian gelatin films with respect to their mechanical properties and barrier properties. The results showed that the composite fish gelatin films containing montmorillonite and chitosan possessed favorable mechanical and barrier properties, making them natural biodegradable films [58]. In summary, the modification of fish gelatin films could effectively strengthen its mechanical and biological properties (antioxidant, antimicrobial, etc.), thereby broadening its applications in the food packaging field.

4.2. Chitosan-Based films for Food Packaging

The crustacean carapace is the predominant source of chitin, which is the richest polysaccharide in nature, following cellulose [35]. Chitin is chemically a cellulose-like polysaccharide chemically, where the hydroxyl group at the C2 position is replaced by an acetamide group, which makes chitin an insoluble polymer and restricts its application [59]. However, the chitosan obtained after the deacetylation of chitin is soluble in acidic solutions, which enhances the processability and other functional characteristics, such as antibacterial properties associated with the presence of amine groups [34,60,61]. Chitosan's antimicrobial properties, non-toxicity, ability to bond with metal oxides, and biodegradability make it a desirable material for a variety of food packaging applications [19,28,61]. In recent years, numerous approaches have been reported for chitosan-based film fabrication, including direct casting, impregnation, coating, extrusion, and layer-by-layer assembly [23]. These fabrication technologies greatly promote the development of chitosan-based films in the food packaging industry. Furthermore, researchers integrated other functional materials into chitosan to fabricate composite films to extend the combinatorial advantages [62]. Table 2 summarized the main modified materials and preparation tools as well as the drying conditions in the preparation of chitosan composite films in the last three years.

Table 2. The main modified materials and preparation tools, as well as the drying conditions in the preparation of chitosan composite films in the last three years.

Chitosan Concentration	Modified Materials	Tools	Drying Conditions	Reference
1% (*w*/*v*)	Glycerol	Plastic Petri dishes	48 h at 25 °C	[63]
3% (*w*/*v*)	Basil essential oil	polypropylene sheet (24 × 18 cm^2)	5 h at RT	[64]
3–9% (*w*/*v*)	Nickel oxide nanoparticles	plates (8 cm)	45 °C for 3 days	[65]
2% (*w*/*v*)	Luteolin	Plexiglas plate (24 cm × 24 cm)	30 °C for 2 days, 50% (RH)	[66]
2% (*w*/*v*)	Cynara cardunculus leaves extracts	Petri dishes (90 mm diameter)	40 °C for 48 h.	[67]
2% (*w*/*v*)	cellulose	Petri dishes	35 °C for 48 h	[68]
0.5–1.5% (*w*/*v*)	Marine Yeast Debaryomyces hansenii	Petri dishes (60 × 15 mm^2)	40 h at 40 °C (22% RH)	[69]
2% (*w*/*v*)	Glucose, Fructose, Xylose, Arabinose	Petri dishes (13.5 cm diameter)	48 h at 25 °C	[70]
2% (*w*/*v*)	Oregano essential oil Black rice bran anthocyanin	Petri dishes (9 cm diameter)	25 °C for 3 days, 50% (RH)	[71]
1.5% (*w*/*v*)	Clove essential oil	-	48 h at 25 °C (50% RH)	[72]
1% (*w*/*v*)	Caffeic acid poly (ethylene glycol)	Plastic holder 40 mL per 10 × 10 cm^2	-	[73]
3% (*w*/*v*)	Glycol (PEG-600) 3-Aminopropyltriethoxysilane	glass plate	5–6 h at 60 °C	[74]
0.8 (*w*/*v*)	potato starch, anthocyanins	Glass plate (15 × 15 × 0.5 cm^3)	45 °C for 12 h	[75]
2 wt%	N-doped carbon dots	Petri dishes (9 cm diameter)	60 °C for 12 h	[76]
1% (*w*/*v*)	2-amino-4,5,6,7-tetrahydrobenzo[b]thiophene-3-carbonitrile	Petri dishes (47 mm diameter)	50 °C for 24 h	[77]

Table 2. *Cont.*

Chitosan Concentration	Modified Materials	Tools	Drying Conditions	Reference
0.32 g/cm^2	Red cabbage Clove bud oil	Petri dishes (8 cm diameter	-	[78]
0.5% (w/v)	Zein	Disks (9 mm diameter),	3 h, 24 h, and 5 days, 12 days	[79]
2 wt%	Gelatin	Flat Teflon film-coated glass plate	RT for 48 h.	[80]
0.5–1.5% (w/v)	Olibanum Gum		60 °C by a heater–stirrer for 3 h.	[81]
2%(w/v)	Zinc oxide nanoparticles gallic-acid	Petri-plates	50 °C for 12 h in an oven.	[82]
1.5% (w/v)	Cinnamon essential oil Ethyl-Nα-lauroyl-L-arginate hydrochloride Hydroxypropyl-β-cyclodextrin	Polyethylene Petri dishes	45 °C for 12 h	[83]

Note: RH: Relative Humidity, RT: Room Temperature.

The obtained films with excellent preservative effects have been applied to different food products such as meats, fruits, and vegetables, showing promising potential as an alternative to food packaging. For example, Zhang et al. prepared chitosan and chitosan-TiO_2 composite films with efficient antimicrobial activity against foodborne pathogenic microbes, which could preserve red grapes for 15 days with pure chitosan membranes and 22 days with chitosan-TiO_2 composite films before mildew occurred (Figure 5A) [84]. Furthermore, Lin et al. also used fish gelatin and chitosan as film-forming substrates and incorporated different concentrations of TiO_2-Ag to prepare composite films, which exhibited superior antibacterial properties [55]. In addition, Liu et al. investigated the effects of different drying temperatures (45~85 °C) on the microstructure, mechanical properties, and barrier properties of chitosan films. As shown in Figure 5B, the blank sample became increasingly darker, harder, and drier during 10 days of storage, which was mainly caused by the evaporation of water. Therefore, the water vapor barrier properties of packaging materials are critical in determining the preservation performance of meat. However, the excessively low water vapor permeability of films might in turn accelerate the spoilage of meat [85]. For example, the meat packaged with LDPE films exhibited a dull color, and its surface turned yellow or black, indicating that there may be bacteria and mold colony colonies production causing the frozen meat to deteriorate. Notably, meat wrapped in chitosan films largely maintained its color (white or bright red) and freshness (tight meat texture), and the preservation effect of chitosan films on frozen meat decreased with the increase in drying temperature. Thus, the chitosan films could preserve the quality and freshness of frozen meat for a more extended period than LDPE films and blank samples (Figure 5B) [85,86]. Additionally, the N-CHITOPACK project uses chitin derived from seafood waste to manufacture entirely new and perfectly biodegradable bio-based products made from chitosan and chitin fibers. Moreover, the project in collaboration with some SMEs already produced degradable food packaging materials based on chitin, and this emerging market of eco-innovation is expected to produce profits reaching 25–30% market share. In summary, it has been demonstrated that the prepared chitosan-based film is a promising food packaging material that could protect food from microbial infections and, thus, extend its shelf life. Further work is also desired to highlight the important characteristics of the active agent-enriched films, such as those that affect mechanical strengths and those that control release properties, including the microstructure, intermolecular interactions, and the environment in which the composite films are located.

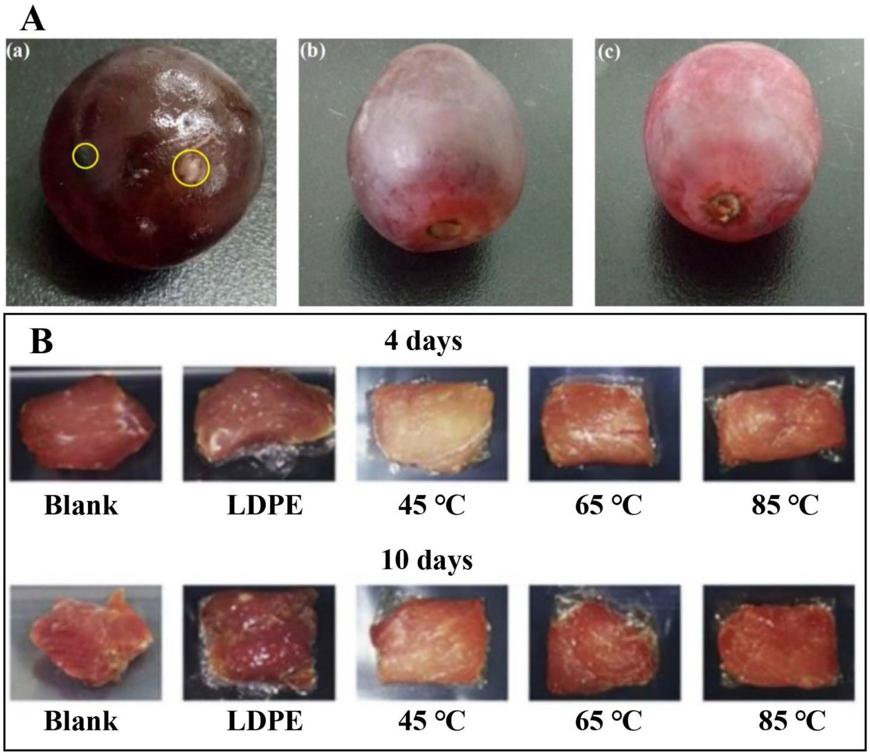

Figure 5. Chitosan-based films for food packaging. (**A**) Preservation of red grape packed in different materials at 37 °C for 6 days: (**a**) plastic wrap; (**b**) pure chitosan film; (**c**) chitosan-TiO_2 film, reprinted from [84] with permission. (**B**) The appearance of chilled meat packaged with chitosan films dried at different temperatures samples during 10 d storage at 4 °C. The chilled meat without packaging was tested as the blank sample, and the chilled meat packed by LDPE (low-density polyethylene) was tested as the control sample, reprinted from [85] with permission.

5. Conclusions and Future Prospect

The seafood industry generates a large number of by-products and waste during processing, causing environmental pollution, economic burden, and health hazards. However, these seafood by-products and wastes contain valuable protein and lipid components, as well as a variety of bioactive compounds with potential health benefits. These extensive application potentials could be applied to develop numerous novel products and biodegradable materials for nutritional/functional foods and pharmaceuticals/biomedicine applications. On the other hand, the non-degradability and potential human health hazards of current plastic food packaging materials have raised concerns. The design and development of biopolymer-based food packaging materials are the current priorities for the food industry. This review analyzes the global production of seafood and its waste in recent years, focusing on seafood waste such as chitosan and fish gelatin as renewable and biodegradable raw materials for food packaging, contributing to the sustainability of materials and the transformation from waste to wealth.

Although new biodegradable food packaging materials using chitosan and/or gelatin-based films and coatings are available, more constructive research is needed on the valorization of seafood waste. Future research directions may involve considering the following points: (i) The functional components derived from seafood by-products need to be further integrated into the entire food packaging cycle, including the following: low complexity synthetic routes, low cost component materials, robust application properties such as excellent moisture exchange properties and low oxygen permeability, and greater ductility, tensile strength, and flexibility. (ii) Further developments with respect to edible packaging films based on natural biopolymers should be explored via the selection of biodegradable biomaterials, which is conducted on the basis of establishing favorable quality safety measures and reducing consumer concerns about potential allergenicity. (iii) Knowledge on production technologies and the design of innovative packaging materials should be developed, including the preparation of packaging equipment to produce sustainable and profitable seafood packaging, thereby breaking the technological and generational gap between laboratory-scale production and mass production for more rational commercialization. (iv) Establish standardized management systems, policies and enforceable metrics for the effective recycling of seafood waste and the assessment of seafood waste-based degradable functional materials. In conclusion, utilizing seafood byproducts to produce food packaging materials is potentially environmentally sustainable and economically viable, as it saves energy and resources, reduces waste generation, and prevents littering. Importantly, the behavior of biodegradable packaging materials at different end-of-life scenarios should be tested to determine the best disposal route, which is an important indicator associated with the reduction in plastic waste. The development of new technologies is expected to introduce more value to the seafood industry in the future.

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