Potential Applications of Biopolymers in Fisheries Industry

Meenakshi Singh, Krupa Unadkat, Sahil Kapoor, Manoj Kumar Enamala, Punita Parikh, and K. Chandrasekhar

Abstract The exponential rise in fish-derived biopolymers in the form of nets, gears, food packaging material, lures and traps has revolutionized the fishing industry in the recent years. The promising usage and emerging market potential of biodegradable films has resulted in the circular economy. This chapter summarizes re-use of fish by-products such as chitin, chitosan, collagen, glycosaminoglycans, and hyaluronic acids in multiple applications. The raw fish-derived biomaterial from skin, scales, fins, and eyeballs has good flexibility, tensile strength, and viscosity; thus, commercially viable as a protective matrix. The fabricated fishery waste is recycled in an ecofriendly way to meet the growing market demand. Additionally, the prominent market players that utilizes fish-derived biopolymer to prepare daily essentials like toiletries, paper bags, food packaging material, bottles, textiles are enlisted. Further, various biopolymer typologies of fishery industry are described in detail based on the source of origin, physical appearance and their significant role in pharmaceutical, cosmeceutical, nutraceutical, nanotechnological, and food applications. However, due to some technological barriers in packaging material like film permeability, porosity, oxidation of lipids, discoloration etc. the bioproducts are still at lab-scale; that need to be addressed to reach industrial-scale. Moreover, the chapter discuss about the sustainable strategies to design fish binders, gill nets, fishing lines, traps

---

M. Singh
Department of Ecology and Biodiversity, Terracon Ecotech Pvt. Ltd., Mumbai, Maharashtra, India

K. Unadkat · P. Parikh
Department of Botany, M.S. University of Baroda, Vadodara, Gujarat 390002, India

S. Kapoor
Department of Botany, Ganesh Goswami Dutta Sanatam Dharma College, Chandigarh 160032, India
e-mail: sahil.kapoor@ggdsd.ac.in

M. K. Enamala
Bioserve Biotechnologies (India) Pvt. Ltd., Unit: 4-7, 1st Floor, Industrial Estate, Moula Ali, Hyderabad, Telangana 500040, India

K. Chandrasekhar (✉)
School of Civil and Environmental Engineering, Yonsei University, Seoul 03722, Republic of Korea
e-mail: chanduibt@gmail.com

A. K. Nadda et al. (eds.), *Biopolymers*, Springer Series on Polymer and Composite Materials, https://doi.org/10.1007/978-3-030-98392-5_10

etc. that should be transparent, fragile, dissolvable to avoid ghost fishing and capable to boost the ecological restoration of aquatic bodies. Finally, it covers the commercial aspect of the seafood industry, where the fishery biopolymer is used as an edible functional food, as a biodegradable preservative with enhanced shelf-life and as a bioadsorbent to remove toxic compounds. Over the last few years, the nanotechnological advancement of biopolymers and their blends have been exploited to treat wastewaters for reuse in seafood processing industry. Therefore, the hybrid polymers are considered environmentally safe and far superior to synthetic polymers if redesigned at molecular and nanoscale level to minimize the bioburden on aquatic life.

Keywords Fish-derived biopolymers · Biodegradable fishing gears · Functional foods · Biofilm packaging · Wastewater treatment

1 Introduction

Biopolymers are chemically derived from a wide array of animal, vegetal and microbial sources. These polymeric biomolecules include lipids, polysaccharides, polynucleotides, and polypeptides, consisting of monomeric units linked by covalent bonds to form larger molecules. The non-toxic biopolymer has been derived from diverse biological sources including plants, bacteria, seafood waste, chicken feathers and other organic matter from the fishing industry [1–4]. To be animal-specific, the fishing industry is the major contributor to the bio-burden of the aquatic environment, which can be reduced by using fish-derived biopolymer like chitin, chitosan, collagen, glycosaminoglycans, and hyaluronic acids [5]. The circular reinforcement of this fish-derived polymer is an alternative to polyethylene, because it generates low biodegradable waste, similar to plastic in functionality and appearance, and requires less energy consumption to manufacture packaging material. For instance, MarinaTex is a novel, odorless, translucent, and flexible biopolymer with good shelf-life is made from the fish waste, and red algae [6]. Similarly, the seafood waste with crustacean shells is used to prepare recyclable bio-sheets [7].

Fish is considered to be one of the nutritious diets in human food because it is an excellent source of high-quality protein, omega-3-fatty acids, various minerals like phosphorous, magnesium, selenium, iodine etc. [8]. The fish-derived biopolymers are used in the activities of petroleum drilling, deep sea exploration photography, seafood packaging, and other ecological products that can restore the osmotic adaptation in aquatic life and aids in microbial genera to adapt to the harsh environment. The most extensively studied fish-derived biopolymer is chitin and its deacylated derivative chitosan. Chitin is considered the most abundant polysaccharide available in nature. Another biopolymer is collagen, which is extracted from the scales and bones of fishes [9]. It has good tensile strength and majorly applicable in pharmaceutical, biomedical, and food applications. Moreover, when dried solid fish waste is biologically processed with the bacterium, *Bacillus subtiltis* (KP172548), 1.62

gL^{-1} PHB (poly 3-hydroxybutyric acid) was produced [10]. Likewise, fermentation experiment of shrimp waste with the bacterium, *Salinivibrio* sp. M318 yielded 42% (w/w) PHB when fish oil was used as C-source and when the fish matrix was used as N-source, then the yield of PHB is 51.7% (w/w) [11].

1.1 Sources of Fish-Derived Biopolymers

The fish-derived biopolymers exist in several shapes, highly branched with low molecular weight and arranged intrinsically by delicate polysaccharides and proteins as a structural constituent of the skeletal system. Because of their complex polymeric structure bounded by glycosidic linkages, these polymers provide mechanical strength to the tissues and keep them intact [12]. The raw biopolymers belong to plant origin, microbial origin, agricultural wastes, fossil wastes etc. Also, they can be synthesized chemically from the monomer units such as amino acids, fatty acids, lipids, chitin, chitosan, proteins, DNA, RNA etc., that can be scaled readily at low cost, to commercialize processing of the biopolymers [13, 14]. Few of the biopolymers synthesized from microbes include chitosan (polyamides), polylactic acid (PLA), poly 3-hydroxybutyric acid (PHB), polyesters, polyphosphates, hyaluronic acid (HA) connected through linear polysaccharide chains bounded by hydrogen bonds [15]. They provide flexibility, tensile strength, and viscosity to the cells and act as a protective matrix.

The major biopolymer present/produced from fishes and its wastes include collagen (protein-based) such as hyaluronic acid (HA) and glycosaminoglycan (GAG), chitin, and its derivative chitosan (polysaccharide-based), and gelatin s found in various connective tissues of the body like scales, skin, bones, ligaments, tendons and cartilage [16–18] (Fig. 1). The collagen is responsible for drug and gene carriers. It is used as burn cover dressings as well in the wound healing process. Many researchers have diverted their studies to the extraction and characterization of collagens obtained from the various fishes like rabbitfish (*Chimaera monstruosa*), cuckoo ray (*Leucoraja naevus*), small spotted catshark (*Scyliorhinus canicula*), Atlantic grenadier (*Nezumia aequalis*), lantern shark (*Etmopterus* sp.), *Catla, Cirrhinus mrigala.* The collagen is extracted from the skin, bones, and fins of fish, which gets denatured at a low temperature (25–30 °C) as compared to mammalian collagen, which has a denaturation temperature difference of 9 °C i.e., (39–40 °C). The skin of the fish usually consists of type I collagen and is around 70% degree of purity depending upon the type of species, found in the various seasons and the fish has a capacity to retain the moisture and exhibits no irritation. Thus, fish collagen is an excellent source and can be used in dermal applications [19].

Chemically, chitin and chitosan are crystalline in nature and insoluble in common solvents, except the acidic solvent. They have strong inter/intra-molecular units of 2-acetamido-2-deoxy-β-D-glucose bounded by β (1–4) linkages. They are non-allergic in nature, therefore, suitable for controlled drug delivery systems, where they can

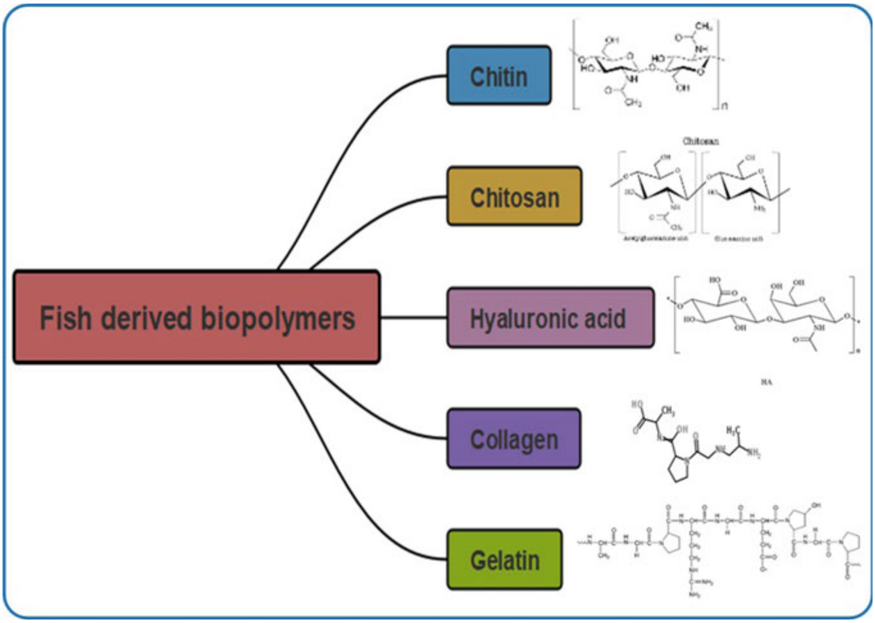

Fig. 1 Different types of Fish-derived biopolymers used in fishing industries

be used as protein-carrier (amino acids) and enzyme-carriers, and various types of packaging material [20].

1.2 Market Potential of Biopolymers in the Circular Economy

The fishing industry mainly depends on plastics for various activities such as fish luring, fishing nets, ropes, baskets, gloves etc. that further adds the cost of transportation from rural to urban areas. To reduce the financial burden, the proficient set-up of bioplastic plants near the fishing zone can lead to the sustainable development of the packaging industry and restore the environment.

The natural biopolymers obtained from marine sources have a minimum impact on food chain due to its high biocompatibility and rapid disintegration. Moreover, the natural biopolymers help in reducing the land and water pollution.

Also, in terms of employment, the biopolymers are advantageous to get profoundly skilled labour, and create ease of license for commercial fishing assignment with a monetary benefit. According to the global market report by Markets and Markets [21] it is estimated that the biopolymer market will grow to US $27.9 billion by 2025 at the CAGR of 21.7%. The global growth highlights the potential of bioplastic in accordance with environmental concerns. This is a great opportunity to minimize dependence on conventional plastic and enhance the production of biopolymer [22].

The fish-derived biopolymer can provide a restorative solution to marine life, and meet daily human needs of toiletries, paper bags, food packaging material, bottles, textiles and many more [23].

The fish-derived biopolymers are used to make compostable barrier coatings, using equal combination of cellulose pulp from plant sources. This type of sustainable coating can be used in multiple packaging of food and feed in daily lives. The fish residue valorization towards zero-waste sustainable industry can replace the global plastic dependence in the future if it is unanimously implemented under the climate action program [24]. The notable leading market players in utilizing fishery waste and manufacturing bioplastic are NatureWorks, Italy; Braskem, Brazil; BASF, Germany; Biome plastic, UK; Toray Industries, Japan; Plantic Technologies, Australia; Tianan Biologic Materials, China and many more [25]. The successful use of biopolymer in everyday life might bring monetary ramifications but from an ecological point of view, it can balance nature degradation [26]. However, there are certain drawbacks of biopolymers that need to be addressed for universal acceptance, such as, low thermal and tensile strength, high moisture-holding capacity, compatibility, slow production process as compared to synthetic counterparts. To alleviate these disadvantages, a blend of polymers is done to increase their applicability at a larger scale and change the design of the biopolymer for its feasibility in biological degradability.

2 Types of Biopolymer in Fishing Industries

The recent advancement in the biodegradable films in the fishing industry based on their mechanical, barrier and antioxidant properties has gained popularity amongst many industralists [27]. The significant attributes of biopolymers are stability, durability, feasibility and resiliency is further improved by incorporating graphene oxide, protein isolates, fatty acids, essential oils, and other cross-linkers. Natural biopolymers like starch, protein, cellulose, chitin, pectin, chitosan, lignin and collagen is obtained from animal and plant kingdom. Carbohydrate-based biopolymers are low toxic, renewable, biodegradable, and stable in nature; hence, frequently used commercially in pharmaceutical industries, cosmetic industries, fishing industries and so forth [22, 28]. The origin, physical appearance and role of biopolymer are listed in Table 1.

2.1 Chitin

Chitin is crystalline in nature; it is a microfibrillar polymer of glucose and extracted from the exoskeleton of insects, invertebrates, some fish cells, and wall of fungi. It is stable in alkaline solution and dissolves in acidic solutions only. A significant natural source of chitin is shrimp and crab, which are abundant in the seafood processing industry. The chitin biopolymer is mainly used in biomedical engineering to prepare

Table 1 Sources and applications of significant biopolymers

Name of polymer	Source of origin	Physical appearance	Role of biopolymers	References
Chitin	Crab, Shrimp and prawn	Translucent, pliable, resilient, and quite tough	Used in fishing and cosmetic industry	[29]
Chitosan	Shellfish and crustacean waste materials	Pale, white and flaky and its moisture content was 10.9%	Bioremediation of toxic phenolic product, promote osteogenesis, fat absorbent action, flocculating agent, purify drinking water, manufacturing, personal hygiene products, anti-bacterial, anti-acid, fat absorbent action	[30, 31]
Collagen	Exoskeleton of marine invertebrates	Hard, fibrous, insoluble, protein, and molecules form long, thin fibrils	Biodegradable matrices, solid support micro-carrier in the production of enzymes, Sutures, dental composites, sausage casings, skin regeneration templates, cosmetics	[32]
Gelatin	Fish, bones, pig skin	Translucent, water soluble, flavourless, moist and brittle when dry	Pharmaceutical and medical use, thickener, stabilizer, food wetting agent, emulsifier	[32]
Hyaluronic acid (HA)	Eyeballs of fishes (Tuna, Shark and Swordfish)	Transparent, viscous fluid or white powder, water soluble	Cosmeceuticals, anti-aging products, nutraceuticals, food ingredient, nanotechnological processes	[28–30, 33–35]

biomaterial that can repair and restore damaged tissue. Globally, the annual production rate of chitin from crustaceans and fish scale waste is estimated to be 10 billion tons. In coastal areas, the material form of chitin is a major source of beach pollution which is hard, inelastic and nitrogenous polysaccharides [36].

2.2 Chitosan

Chitosan is differing from chitin only by the acetyl content of the polymer. It is a modified natural biopolymer that is hard, non-toxic and cellulose-like fibre. A significant production material of chitosan is shrimp waste and other sources of chitosan are crustaceans, insects, fungi and some algae. Their excellent properties include biocompatibility, bioactivity, biodegradability, penetrability, anti-microbial activity, chelation, drug carrier for controlled release, film, and absorptive limit. It promotes bone tissue building, fat absorbent action decalcification of dental enamel, healing of ulcers and injuries and osteogenesis. It inhibits bacterial plaque formation [37]. ~~Commercially, chitosan offers a wide range of applications such as in cosmetic preparation, biomedical, paper industry, food industry, textile industry, pharmaceutical, biotechnology, and biochemistry~~. It is also used to prevent food spoilage from microbe contamination, preparation of biofilms for food packaging, purify the water, and delay blanching of fruit juices [38]. Commercially, chitosan offers a wide range of applications in diverse industries including biomedical, cosmetic, paper, food, textile and biotechnological industry.

2.3 Collagen

Mammalian cells are rich in collagen protein, which is usually synthesized by fibroblast that originates from pluripotential adventitial cells or reticulum. A collagen molecule is a triple helical structure with a length of 300 nm and a width of 1.5 nm, respectively. The molecular weight of collagen, based on amino acid sequence is 300000 Daltons [39]. Collagen is rod-shaped molecule and accounting for about 20–30% of total body proteins and primary structural materials [40]. The collagen matrix is used in the treatment of severe burns and collagen sponges used in dressing for acute injuries, nucleic acid and protein transporters to assist bone repairs. In addition, collagen hydrogel is used as genetic material delivery carriers in biomedical applications. For example, thermostable collagen nanoparticles utilized as an anti-cancerous agent such as camptothecin and hydrocortisone bearer for parenteral administration and other therapeutic compounds [27]. Collagen has wide range of applications because of their diverse physicochemical properties such as high biocompatibility, low anti-genecity, non-toxicity and high biodegradability [41].

2.4 Gelatin

Gelatin is water-soluble, a sterile biopolymer that does not contains preservative and have a three-year expiration date at room temperature. Structurally, it is a heterogeneous polypeptide, forming a complex mixture of α-chains, β-chains and γ-chains. Gelatin is synthetic colloids produced from the degradation of bovine collagen by incomplete hydrolysis of collagen removed from fish, pig skin and cow bones so forth. It is an important biopolymer that is colourless, translucent, flavourless food ingredients. It is extensively used in preservation of meat and fish-based products due to its good foaming, emulsifying and wetting properties [42]. Therefore, gelatin is widely used in food packaging industries owing to its exclusive functional and technical characteristics.

2.5 Hyaluronic Acid (HA)

HA is a water-soluble, translucent, high molecular weight biopolymer, which is only present in the eyeball and cartilage intracellular matrix of fishes. It is the only glycosaminoglycan member that is non-sulphated by alternating disaccharide units of N-acetyl-D-glucosamine and D-glucuronic linked by β-(1 → 3) and β-(1 → 4) glycosidic bonds [43, 44]. HA is highly used in the biomedical field due to its high biocompatibility in visco-surgery, controlled tissue permeation and hydration in arthritis treatment, and macromolecular carrier in cancer therapy, plastic surgeries and targeted drug-deliveries of intra-ocular surgeries. It has characteristic inflammation property that allows it to hold water molecules in limited space and provides lubricity to the tissues. Therefore, Hyaluronic acid have tremendous potential in regenerative medicine and cosmetology [45].

3 Commercial Applications in Fisheries

The fish gear should be reused for the sustainable use of biopolymers in the fishery industry (Fig. 2). The alternative approach to design fish binders, gill nets, fishing lines, traps etc. which should be transparent, flexible, dissolve in water after few days and possess superior permeability to prevent ghost fishing. The biopolymer fishing gears can halt the vicious circle of death of fishes and other aquatic animals by derelict nets, and boost ecological restoration of waterbodies and aquatic life [46].

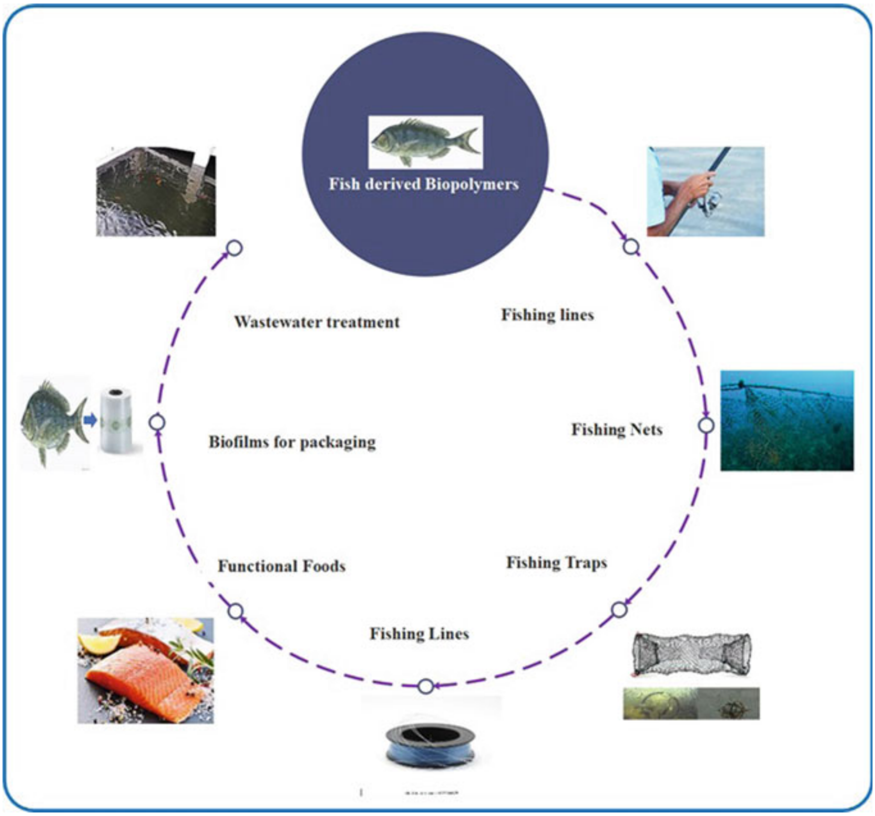

Fig. 2 Applications of fish-derived biopolymers in fisheries

3.1 Fishing Lines

Most of the fishing lines or ropes are made from synthetic polymers as they are single-stranded, strong, thin, and available in different colors to distinguish from other fishing lines. The synthetic polymer causes more harm to the fishes as they do not degrade and form a lump of fine network at the fishing place, further entangling and injuring the fishes and rest aquatic life. To overcome this situation, the biodegradable fishing lines were designed with natural materials such as polyglycolic acid resin (PGA) filament with high tensile and knot strength. These PGA filaments when mixed with *PLA, p*-dioxanone, and ε-caprolactone make it more heat resistant and firm. The monofilament of PGA also gave good results with blends of polybutylene succinate (PBS) and polybutylene adipate-co-terephthalate (PES) to yield optimal strength under seawater [47]. These fishing lines if left in the water bodies for more than a fortnight, they will maintain 25% of the original tenacity [48]. The successful brands of eco-friendly fishing lines, in the form of filament, fluorocarbon and braid (hybrid) are Toray, Eagle claw, Fieldmate showed a remarkable four-month biodegradation time.

3.2 Fishing Nets

Globally, the nylon nets are widely used as a fish gear. Despite its wide use, it is abandoned in the sea for a longer duration as it needs physical labor. According to the technical report available online, on average 13,941 gillnets are lost each year. Because of this, there are a negative effect on the benthic environment, navigational problems, marine litter, and plastic pollution.

To reduce this problem, the Norwegian Directorate of Fisheries has initiated a gear disposal and recycling program named Abandoned, Lost or Discarded Fishing Gears (ALDFG) and retrieved 20,450 lost gillnets and other fish gears [49]. Traditionally, the biodegradable fish nets were designed using a blend of 82% polybutylene succinate (PBS) and 18% polybutylene adipate-co-terephthalate (PBAT), which were tested for their catching efficiency for a longer time duration of 6–42 months [46]. As compared to conventional gear made of Nylon polyamide, polyester, polyethylene, and polypropylene; the biodegradable fishing nets started biodegradation into natural materials by the action of microorganisms and lose their ghost fishing capacity after few months of underwater exposure. However, the fishing performance and stiffness of biodegradable nets is lower with respect to nylon nets. Therefore, projects like Innovative Fishing Gear for Oceans (INDIGO), funded by the European Union is undergoing to design 100% biodegradable fishing net with a controlled lifespan [50].

3.3 Fishing Gear and Traps

As per the FAO [51] technical report, it is estimated to discard approximately 6.40,000 tonnes of all fishing gear in the oceans annually in bad weather conditions. The fishing traps are made to catch fish during low tides. It is usually made of steel boundary vessels, with sufficient enclosed space to house targeted fishes for their smooth entry and barricaded exit. Polyhydroxyalkanoate (PHA) is also used as trap apparatus and degrades naturally if continuously submerged for many months [52]. Currently, the biodegradable fishing trap derived from cellulosic derivatives such as polysaccharides, chitin or chitosan are widely used in fishing industry as it readily dissolves in the water in few days and prevent unwanted fish mortality [52].

3.4 Fishing Lure

The artificial fishing lures are well fabricated by fine plastics of PVC or silicone rubber. Such lures do not get digested in the fish body and thus become aquatic pollutants. They also affect the growth and development of fish by hindering its gastrointestinal tract and can eventually led to the death of the fish. The biodegradable, semitransparent, and the soft lure is made by molding like worms using jelly chitosan, water-soluble gum, cereals starch, soy protein, etc. Further, the addition of marine fats and oils, to the bait attracts the fish and makes the process less time-consuming. The PVOH polymers as hydrogel matrix of soluble capsules, which are prepared by mixing carrageenan and gum, is biodegradable, transparent, and used mostly in recreational fishing activities [53]. The biological lures can control the bait release in an effective way, as an aquatic feed in farmed fisheries.

4 Industrial Applications of Biopolymers

The fish-derived biopolymers can be valorised to produce various useful materials.

4.1 Functional Foods

Several edible marine invertebrates, including cuttlefish and sea cucumber, are promising potential ingredients as functional foods [54]. Many researchers have reported that chitin and chitosan (biopolymer) derived from these edible marine invertebrates exert a broad spectrum of bioactivities, namely antioxidant, antimicrobial, anticoagulatory, anticancer, hypocholesterolemic and wound healing properties [55, 56]. These bioactivities of chitin and its derivative have been mainly attributed to its physical and chemical properties, including molecular weight, functional groups and deacetylation degree [57].

Chitin is used as a health supplement in the form of capsules due to its exceptional lipid metabolism capacity [58]. Kuprina et al. [59] have developed a functional food from a mixture of pollock and salmon belly minced fish meat with the biologically active chitin mineral food supplement "Hizitel". Azuma and Ifuku [60] suggested that chitin nanofibers (CNFs) and surface-deacetylated chitin nanofibers (SDACNFs) are promising functional food for patients with inflammatory bowel disease or obesity. The authors observed that CNFs substantially ameliorate the clinical symptoms of IBD. SDACNFs reduced the levels of leptin in serum and repressed the rise in body weight.

Chitosan increases the nutritional benefits of the food products, including boosting immune response and glucose-lowering effect while maintaining the organoleptic properties of the product [61–63]. Chitosan is a promising source of dietary fibre in organisms that lacks a specific chitinase enzyme in their gastrointestinal tract [64]. Lie et al. [65] reported that the feed supplementation with high molecular weight chitosan decreased fatty deposit in liver, spleen, and muscle of broiler chickens. Qinna et al. [66] suggested a new functional food containing chitosan (1%) and pectin (5%) as an alternative to meat. Anandan et al. [67] found that dietary supplementation with chitosan had a protective effect on lipid oxidation in induced myocardial infarction in rats.

Microcrystalline cellulose (MCC) biopolymer is broadly considered as a functional ingredient in several food products, including dairy, bakery, and confectionary [68]. The colloidal MCC contains 98 g/100 g of insoluble dietary fibre [69]. The experimental animals fed with MCC fortified diet showed a reduced level of cholesterol [70]. MCC fortified food also plays a substantial role in the management of obesity and diabetes mellitus via hypolipidemic and hypoglycemic effect, respectively [71]. Cellulosic nanomaterials (CNMs) biopolymer is extensively utilized in nutraceutical and food industry because to its exceptional physico-chemical properties, namely high mechanical strength, lightweight, and biocompatibility [72]. Bacterial cellulose (BC) biopolymer is widely used as a resource of dietary fibre, and it is approved as a “generally recognized as safe” food by the U.S.FDA [73].

4.2 Biodegradable Preservative and Packaging

Seafood is a rich source of functional health-promoting compounds, including vitamins (vitamins D, B and A) and polyunsaturated fatty acid [74]. However, seafood products are highly perishable, and it is most prone to degradation by microbiological, enzymatic, and chemical reactions. Currently, chitin and chitosan biopolymer are used as an alternate biodegradable natural preservative for retaining seafood quality and increasing the shelf-life of seafood-based products [74]. Generally, chitin and chitosan increase the shelf life of marine-based products by improving oxidative stability, reducing lipid oxidation, and inhibiting the growth of microorganisms.

Chitin biopolymer is used as an edible coating in food safety as it principally maintains the sensory characteristics of food material. Moreover, chitin is also used as a support matrix for enzyme immobilization that imparts remarkable operational stability in the food processing industry [74]. Morganti [75] has developed chitin-based biodegradable food packaging material by using chitin nanofibrils. The combination of polylactic acid and nanocellulose biopolymer is also used as a novel promising sustainable eco-friendly food packaging material [76].

Chitosan is widely used as a packaging material component, additive and coating agent for seafood-based products because of its distinctive functional and physico-chemical properties [77, 78]. Several researchers have demonstrated that chitosan-based coatings help in maintaining the physico-chemical properties of fish and other seafood-based products[78]. Sathivel et al. [79] documented that an edible coating of 1 or 2% chitosan biopolymer suspended the degree of lipid oxidation in *Oncorhynchus gorbuscha* during frozen storage. Kumar et al. [80] demonstrated that the chitosan can be used as an encapsulation biomaterial for several sensitive products, including fish oil due to its noticeable emulsification capacity. Benjakul et al. [81] concluded that chitosan can enhance the gelling properties of marine-based products, including fish surmini products. Kok et al. [82] observed that chitosan (1%) constrained the growth of microorganisms in fish ball throughout 21 days of storage. Ye et al. [83] showed that chitosan-coated plastic films inhibited the growth of *Listeria monocytogenes* on salmon for at least 6 weeks. Mohan et al. [84] revealed that the edible chitosan coating (1 and 2%) improved the textural properties, water holding capacity, drip loss, and inhibited the bacterial growth in *Sardinella logiceps* during cold storage conditions.

Numerous researchers have repeated that chitosan-based coatings could impede the production of trimethylamine—nitrogen in marine food by inhibiting the growth of microorganisms [85, 86]. Chitosan has been used as an edible coating or film in marine-based products owing to its tremendous film-forming ability. Moreover, it is used as an antimicrobial and antioxidant agent in seafood-based products [87]. Chitosan-based coating is used as a preservative in seafood products due to its remarkable ability to reduce the increase in pH value [88]. Several studies have reported that chitosan-based coatings can increase the quality, sensory attributes (taste, odour, colour, appearance, texture, flavour and elasticity) and shelf life of seafood products [88]. Therefore, chitosan-based biopolymer possesses promising prospects in food preservatives and food packaging industries.

4.3 Wastewater Treatment

Wastewater contains heavy metals, dissolved and particulate matter, solids, micropollutants, nutrients, and microorganisms in a complex matrix [89]. The water is generally contaminated through various industrial processes, agricultural and domestic activities (swimming, boating, and fishing etc.) [90–92]. The contaminated wastewater is highly toxic and can adversely affect the organisms [93–95]. Therefore, it is of paramount importance to develop effective strategies for treating wastewater [96–98]. Additionally, in the current scenario, wastewater treatment is highly critical due to dwindling water supplies, tougher discharge regulations, and rising wastewater disposal costs [99]. The primary aim of wastewater treatment is to remove as many dissolved solids as possible before discharging the residual water (effluent) into the environment. Conventional wastewater treatment encompasses pre-, primary-, and secondary-treatment [100]. However, the conventional methods lack accuracy, cost-effective discharge standards and desired level of purification [101]. Over the last few decades, natural biopolymers including chitosan, chitin and cellulose have garnered tremendous interest in wastewater treatments due to their high efficiency, low-cost, high mechanical stability, abundance, renewability, biodegradability, and high porosity [102, 103]. The different biopolymers used for wastewater treatment are summarized in Table 2.

Table 2 List of different biopolymers used for the treatment of wastewater

S. no.	Biopolymer-based material	Wastewater treatment	References
1	MWCNTs/SnO_2 decorated cellulose nanofiber	Removal of Cu (II) from wastewater	[115]
2	Natural cellulose fiber	Sorbent for lead in wastewater	[116]
3	Reactive polyhedral oligomeric silsesquioxane nano-cellulose hybrids	Adsorption removal of Cu^{2+} and Ni^{2+} from wastewater	[117]
4	Cellulose-Based Solid Acid	Absorption of heavy meatal ions from printing wastewater	[118]
5	Cellulose-based membrane	Adsorption of liquid waste dyes and chromium	[119]
6	Chitin/polyethylenimine biosorbent (CH-PEI)	Removal of uranyl-carbonate compounds from water	[120]
7	Chitin-glucan nanopaper	Adsorption of heavy metal ions	[121]
8	Chitin/chitosan nano-hydroxyapatite composite	Removal of copper (II)	[121]
9	Chitosan microspheres	Selective heavy metal removal	[122]
10	Chitosan bed columns	Removal of arsenic	[123]
11	Chitosan and duckweed combination	Removal of boron	[124]
12	Chitosan-clay nanocomposites	Removal of Cu (II) from aqueous solution	[125]
13	Magnetic nanoparticles of chitosan modified with polyhexamethylene biguanide	Removal of hexavalent chromium from aqueous solution	[126]
14	Novel chitosan based thin sheet nanofiltration membrane	Rejection of heavy metal chromium	[127]

Chitosan biopolymer has widely used an adsorbent for removing several pollutants from wastewater, including heavy metals and dyes, because of its high degree of deacetylation that promotes higher interaction of free amine groups with the pollutants. It is also considered to be an efficient bio-sorbent towards several other contaminants because of its hydroxyl group enriched structure [104]. Chitosan is also an ideal alternative substitute to conventional synthetic materials for the treatment of effluents in agricultural wastewater, such as residual pesticides, herbicides, and fertilizers. Pambi and Musonge [105] suggested that chitosan is a suitable low-cost biodegradable material for treating wastewater from sugar industry by performing a dual role of coagulant and flocculant through its relatively high molecular weight and charge density. Crini et al. [106] reported a novel direct bioflocculation method for treating wastewater from paper and pulp industry by using low-cost chitosan. Ahmad et al. [107] effectively remove the solids from palm oil effluent using flake and powdered chitosan. Altaher [108] successfully remove the turbidity from seawater by dissolving chitosan in hydrochloric acid. Dima et al. [109] reported that reticulate chitosan micro/nanoparticles can efficiently remove the toxic Cr (VI) from seafood processing waste.

Gopi et al. [110] have successfully developed cellulose nanofibers (CNFs) basedbio-aerogels for specificadsorption of methylene blue and rhodamine 6G from wastewater. Albukhari et al. [111] purified nitrophenol and dye-contaminated water using silver nanoparticles@cellulose acetate paper prepared by impregnation method. Zhou et al. [112] used magnetic cellulose powder for purifying dye-polluted water–ethanol combination. Garcia et al. [113] immobilized laccase on chitosan and alginate-based matrix for effective removal of 17α-ethinylestradiol from water. Chitosan-silica nanoparticles have been successfully developed for catalytic degradation of 1,1-dimethylhydrazine from wastewater [114]. Overall, natural biopolymers have demonstrated prodigious potential in wastewater treatment.

5 Conclusion and Future Perspective

The multiple applications of fish-derived biopolymers have widened the scope of the circular economy of the fishing industry. Over the last few years, the nanotechnological advancement of biopolymers has been exploited to purify wastewaters. This treatment is environment friendly as it avoids chemical substances, thus safe for flora and fauna of the aquatic system. The treated wastewater is free from toxic micropollutants, dyes and pesticides and reusable for seafood processing. More specifically, seafood is highly perishable, and the biofilm packaging enhance the shelf-life of the food product without compromising the organoleptic characteristics. The edible coating is thermostable, pH stable, resistant to bacterial growth and a good emulsifier to be considered for food processing and packaging material.

Another promising industrial application is to prepare functional foods by blending fish waste with biopolymers. This can be used as a dietary supplement as it is rich in protein, omega-3-fatty acids, dietary fibres and minerals and GRAS in bakery, confectionary, and nutraceuticals. Because of the biocompatibility, elasticity, translucent and odourless characteristics of chitin, chitosan, collagen, gelatin, and hyaluronic acid are potential candidates for biomaterial. This soluble biopolymer is suitable for fishing gears as it will reduce ghost fishing incidents and reduce the physical activity of collecting submerged fishing nets/lines. The latest technologies involve hybrid polymers that need less time and energy to produce with superior flexibility and strength to lessen the dependence on plastics. As mostly fishing gears and plastic-based and many companies are working together on more sustainable ways to produce completely biodegradable products. However, many challenges like increasing the catching capacity of fishes, using biopolymeric fishing nets; low tensile strength of fishing lines; high water holding capacity of fishing lures which leads to microbial degradation etc. are needed to be addressed.

Therefore, the future study needs in-depth analysis on the structural and functional aspects of biopolymer to be reinforced in the fishing industry as an alternative to polyethylene. Despite all the challenges, the biopolymer prototypes need to be exclusively developed for efficient drug-delivery systems in medical and pharmacological products. In addition, the promotion of biopolymers in the fishing industry community will further reduce the global bioburden.

Acknowledgements The authors would like to express their gratitude to Head, Department of Botany, The M.S. University of Baroda for administrative and technical support.

References

1. Santos VP, Marques NSS, Maia PCSV et al (2020) Seafood waste as attractive source of chitin and chitosan production and their applications. Int J Mol Sci 21:1–17
2. Ramakrishnan N, Sharma S, Gupta A et al (2018) Keratin based bioplastic film from chicken feathers and its characterization. Int J Biol Macromol 111:352–358. https://doi.org/10.1016/j.ijbiomac.2018.01.037
3. Sharma S, Gupta A, Chik SMST et al (2017) Characterization of keratin microparticles from feather biomass with potent antioxidant and anticancer activities. Int J Biol Macromol 104:189–196. https://doi.org/10.1016/j.ijbiomac.2017.06.015
4. Sharma S, Gupta A, Kumar A et al (2018) An efficient conversion of waste feather keratin into ecofriendly bioplastic film. Clean Technol Environ Policy 20(10):2157–2167. https://doi.org/10.1007/s10098-018-1498-2
5. Wankhade V (2020) Chapter 6-Animal-derived biopolymers in food and biomedical technology. In: Biopolymer-based formulations. Elsevier Inc.
6. MarinaTex, a biodegradable material that resembles plastic but doesn't have its drawbacks. [Internet]. [Cited 2021 Apr 30]. https://www.livingcircular.veolia.com/en/inspirations/marinatex-bioplastic-sea
7. The Shellworks recycles lobster shells to make bioplastic [Internet]. [Cited 2021 Apr 30]. https://www.livingcircular.veolia.com/en/inspirations/biodegradable-bags-made-recycled-lobster-shells
8. Kalaivani R, Bakiyalakshmi S (2019) Neutraceutical preparation from Agaricus bisporus by value addition. Mushroom Res 28
9. Kaya M, Seyyar O, Baran T et al (2014) Bat guano as new and attractive chitin and chitosan source. Front Zool 11:59
10. Mohapatra S, Maity S, Dash HR et al (2017) Bacillus and biopolymer: prospects and challenges. Biochem Biophys Reports. 12:206–213
11. Van-Thuoc D, Quillaguamán J, Mamo G et al (2008) Utilization of agricultural residues for poly(3-hydroxybutyrate) production by Halomonas boliviensis LC1. J Appl Microbiol 104:420–428
12. Brigham C (2018) Biopolymers: biodegradable alternatives to traditional plastics. In: Green chemistry. Elsevier Inc.
13. Ojha S, Singh D, Sett A et al (2018) Nanotechnology in crop protection. In: Nanomaterials in plants, algae, and microorganisms, pp 345–391
14. Enamala MK, Pasumarthy DS, Gandrapu PK et al (2019) Production of a variety of industrially significant products by biological sources through fermentation. In: Arora PK (ed) Microbial technology for the welfare of society. Springer Singapore, Singapore. pp 201–221. https://doi.org/10.1007/978-981-13-8844-6_9

15. Kumaran S et al (2020) Trends in aquaculture feed development with chitosan nano particles–a review. Biosci Biotechnol Res Commun 13:73–78
16. Jujjavarapu SE, Chandrasekhar K, Naik S et al (2020) Sources of natural polymers from plants with green nanoparticles. In: Green polymeric nanocomposites, 1st ed. CRC Press, pp 81–102. [Cited 2021 May 1]. https://www.taylorfrancis.com/, https://www.taylorfrancis.com/chapters/edit/10.1201/9781351045155-4/sources-natural-polymers-plants-green-nanoparticles-satya-eswari-jujjavarapu-chandrasekhar-sweta-naik-aditya-toppo-veena-thakur
17. Naik S, Chandrasekhar K, Jujjavarapu SE (2020) Synthesis of green polymeric nanocomposites using electrospinning. In: Green polymeric nanocomposites. CRC Press, pp 23–46. [Cited 2021 May 1]. https://www.taylorfrancis.com/https://www.taylorfrancis.com/chapters/edit/https://doi.org/10.1201/9781351045155-2/synthesis-green-polymeric-nanocomposites-using-electrospinning-sweta-naik-chandrasekhar-satya-eswari-jujjavarapu
18. Chandrasekhar K, Eswari Jujjavarapu S, Kumar P et al (2020) Sources of natural polymers from microorganisms with green nanoparticles. In: Green polymeric nanocomposites. CRC Press, pp 103–132. [Cited 2021 May 1]. https://www.taylorfrancis.com/https://www.taylorfrancis.com/chapters/edit/https://doi.org/10.1201/9781351045155-5/sources-natural-polymers-microorganisms-green-nanoparticles-chandrasekhar-satya-eswari-jujjavarapu-prasun-kumar-gopalakrishnan-kumar-potla-durthi-chandrasai-enamala-manoj-kumar-murthy-chavali
19. Jafari H, Lista A, Siekapen MM et al (2020) Fish collagen: extraction, characterization, and applications for biomaterials engineering. Polymers (Basel) 1–37
20. Chakravarty J, Yang CL, Palmer J et al (2018) Chitin extraction from lobster shell waste using microbial culture-based methods. Appl Food Biotechnol. 5:141–154
21. Bioplastics & Biopolymers Market Global Forecast to 2025 | MarketsandMarkets [Internet]. [Cited 2021 Apr 30]. https://www.marketsandmarkets.com/Market-Reports/biopolymers-bioplastics-market-88795240.html
22. Aggarwal J, Sharma S, Kamyab H et al (2020) The realm of biopolymers and their usage: an overview. J Environ Treat Tech 8(3):1005–1016
23. Nisticò R (2017) Aquatic-derived biomaterials for a sustainable future: a European opportunity. Resources 6:1–15
24. Caldeira M, Barreto C, Pestana P et al (2018) CODEN (USA): JSERBR fish residue valorisation by the production of value- added compounds towards a sustainable zero waste industry: a critical review. J Sci Eng Res 5(4):418–447. www.jsaer.com
25. Nawaz A, Li E, Irshad S et al (2020) Valorization of fisheries by-products: challenges and technical concerns to food industry. Trends Food Sci Technol 99:34–43
26. Ahuja H, Dhapola PS, Rahul et al (2020) Ionic liquid (1-hexyl-3-methylimidazolium iodide)-incorporated biopolymer electrolyte for efficient supercapacitor. High Perform Polym 32:220–225. https://doi.org/10.1177/0954008319897763
27. Aggarwal J, Sharma S, Kamyab H et al (2020) The realm of biopolymers and their usage: an overview. J Environ Treat Tech. 8:1005–1016
28. Alashwal BY, Saad Bala M, Gupta A et al (2020) Improved properties of keratin-based bioplastic film blended with microcrystalline cellulose: a comparative analysis. J King Saud Univ Sci 32(1):853–857. https://doi.org/10.1016/j.jksus.2019.03.006
29. Babu RP, O'Connor K, Seeram R (2013) Current progress on bio-based polymers and their future trends. Prog Biomater 2:8. http://www.progressbiomaterials.com/content/2/1/8
30. Yadav P (2015) Biomedical biopolymers, their origin and evolution in biomedical sciences: a systematic review. J Clin DIAGNOSTIC Res 9:21–25. http://jcdr.net/article_fulltext.asp?issn=0973-709x&year=2015&volume=9&issue=9&page=ZE21&issn=0973-709x&id=6565
31. Kawalkar A (2015) A comprehensive review on osteoporosis. J Trauma 10:3–12
32. Mariod AA, Adam HF (2013) Review: gelatin, source, extraction and industrial applications. Acta Sci Pol Technol Aliment 12:135–147
33. Vazquez JA, Montemayor MI, Fraguas J et al (2010) Hyaluronic acid production by Streptococcus zooepidemicus in marine by-products media from mussel processing wastewaters

and tuna peptone viscera. Microb Cell Fact 9:46. http://microbialcellfactories.biomedcentral.com/articles/https://doi.org/10.1186/1475-2859-9-46

34. Vázquez JA, Montemayor MI, Fraguas J et al (2009) High production of hyaluronic and lactic acids by Streptococcus zooepidemicus in fed-batch culture using commercial and marine peptones from fishing by-products. Biochem Eng J 44:125–130
35. Murado MA, Montemayor MI, Cabo ML et al (2012) Optimization of extraction and purification process of hyaluronic acid from fish eyeball. Food Bioprod Process 90:491–498. https://doi.org/10.1016/j.fbp.2011.11.002
36. Elieh-Ali-Komi D, Hamblin MR (2016) Chitin and chitosan: production and application of versatile biomedical nanomaterials. Int J Adv Res. [Cited 2021 Apr 30] 4:411–427. http://www.ncbi.nlm.nih.gov/pubmed/27819009
37. Raafat D, Sahl H-G (2009) Chitosan and its antimicrobial potential–a critical literature survey. Microb Biotechnol 2:186–201. http://www.ncbi.nlm.nih.gov/pubmed/21261913
38. Shahidi F, Arachchi JKV, Jeon YJ (1999) Food applications of chitin and chitosans. Trends Food Sci Technol 10:37–51
39. Owonubi SJ, Agwuncha SC, Fasiku VO et al (2017) Biomedical applications of polyolefins. In: Polyolefin fibres. Elsevier, pp 517–538. https://linkinghub.elsevier.com/retrieve/pii/B9780081011324000175
40. Harkness RD (1961) Biological functions of collagen. Biol Rev. [Cited 2021 Apr 30] 36:399–455. https://doi.org/10.1111/j.1469-185X.1961.tb01596.x
41. Maeda M, Tani S, Sano A et al (1999) Microstructure and release characteristics of the minipellet, a collagen-based drug delivery system for controlled release of protein drugs. J Control Release 62:313–324. http://www.ncbi.nlm.nih.gov/pubmed/10528069
42. Ramos M, Valdés A, Beltrán A et al (2016) Gelatin-based films and coatings for food packaging applications. Coatings 6:41. https://www.mdpi.com/2079-6412/6/4/41
43. Boeriu CG, Springer J, Kooy FK et al (2013) Production methods for hyaluronan. Int J Carbohydr Chem 2013:1–14
44. Gallo N, Nasser H, Salvatore L et al (2019) Hyaluronic acid for advanced therapies: promises and challenges. Eur Polym J 117:134–147. http://www.sciencedirect.com/science/article/pii/S0014305719306895
45. Sumogod A, Nacional L, Nillos MG et al (2020) Isolation of hyaluronic acid from yellowfin tuna thunnus albacares (Bonnaterre, 1788) eyeball. Asian Fish Sci 33:1–9
46. Kim S, Kim P, Lim J et al (2016) Use of biodegradable driftnets to prevent ghost fishing: physical properties and fishing performance for yellow croaker. Anim Conserv 19:309–319
47. Tokiwa Y, Calabia BP, Ugwu CU et al (2009) Biodegradability of plastics. Int J Mol Sci 10:3722–3742
48. Kim SG, Lee WIL, Yuseok M (2014) The estimation of derelict fishing gear in the coastal waters of South Korea: trap and gill-net fisheries. Mar Policy 46:119–122
49. Deshpande PC, Philis G, Brattebø H et al (2020) Using material flow analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway. Resour Conserv Recycl X 5:100024. https://doi.org/10.1016/j.rcrx.2019.100024
50. Biodegradable fishing nets-My Green Pod | Sustainable Products & News. [Cited 2021 Apr 30]. https://www.mygreenpod.com/articles/biodegradable-fishing-nets/
51. Fao. Abandoned, lost and discarded gillnets and trammel nets
52. Anderson JA, Alford AB (2014) Ghost fishing activity in derelict blue crab traps in Louisiana. Mar Pollut Bull 79:261–267. https://doi.org/10.1016/j.marpolbul.2013.12.002
53. Niaounakis M (2015) Agriculture/Forestry/Fishery. Biopolym Appl Trends
54. Ganesan AR, Saravana Guru M, Balasubramanian B et al (2020) Biopolymer from edible marine invertebrates: a potential functional food. J King Saud Univ Sci 32:1772–1777. https://www.sciencedirect.com/science/article/pii/S1018364720300173
55. Islam S, Bhuiyan MAR, Islam MN (2017) Chitin and chitosan: structure, properties and applications in biomedical engineering. J Polym Environ 25:854–866. https://doi.org/10.1007/s10924-016-0865-5.

56. Ravi Kumar MNV (2000) A review of chitin and chitosan applications. React Funct Polym 46:1–27. https://www.sciencedirect.com/science/article/pii/S1381514800000389
57. Aranaz I, Mengíbar M, Harris R et al (2009) Functional characterization of chitin and chitosan. Curr Chem Biol 3:203–230
58. Kumar R, Xavier KAM, Lekshmi M et al (2018) Fortification of extruded snacks with chitosan: effects on techno functional and sensory quality. Carbohydr Polym 194:267–273. https://www.sciencedirect.com/science/article/pii/S0144861718304363
59. Kuprina EE, Kiprushkina EI, Shestopalova IA et al (2018) Research of the influence of chitin-containing food additives on the rheological properties and biological value of minced fish. Prog Chem Appl Chitin its Deriv. 23:114–119
60. Azuma K, Ifuku S (2016) Nanofibers based on chitin: a new functional food. Pure Appl Chem 88:605–619. https://doi.org/10.1515/pac-2016-0504
61. Xie C, Guo X, Long C et al (2015) Supplementation of the sow diet with chitosan oligosaccharide during late gestation and lactation affects hepatic gluconeogenesis of suckling piglets. Anim Reprod Sci 159:109–117. https://www.sciencedirect.com/science/article/pii/S0378432015001359
62. Rahimnejad S, Yuan X, Wang L et al (2018) Chitooligosaccharide supplementation in low-fish meal diets for Pacific white shrimp (Litopenaeus vannamei): effects on growth, innate immunity, gut histology, and immune-related genes expression. Fish Shellfish Immunol 80:405–415. https://www.sciencedirect.com/science/article/pii/S1050464818303668
63. Crini G, Lichtfouse E (2019) Sustainable agriculture reviews 36: chitin and chitosan: applications in food, agriculture, pharmacy, medicine and wastewater treatment. Springer
64. Borderías AJ, Sánchez-Alonso I, Pérez-Mateos M (2005) New applications of fibres in foods: addition to fishery products. Trends Food Sci Technol 16:458–465. https://www.sciencedirect.com/science/article/pii/S0924224405000750
65. Li QP, Gooneratne SR, Wang RL et al (2016) Effect of different molecular weight of chitosans on performance and lipid metabolism in chicken. Anim Feed Sci Technol 211:174–180. https://www.sciencedirect.com/science/article/pii/S0377840115300699
66. Qinna NA, Akayleh FT, Al Remawi MM et al (2013) Evaluation of a functional food preparation based on chitosan as a meal replacement diet. J Funct Foods 5:1125–1134. https://www.sciencedirect.com/science/article/pii/S1756464613000789
67. Anandan R, Ganesan B, Obulesu T et al (2012) Dietary chitosan supplementation attenuates isoprenaline-induced oxidative stress in rat myocardium. Int J Biol Macromol 51:783–787. https://www.sciencedirect.com/science/article/pii/S0141813012002899
68. Nsor-Atindana J, Chen M, Goff HD et al (2017) Functionality and nutritional aspects of microcrystalline cellulose in food. Carbohydr Polym 172:159–174. https://www.sciencedirect.com/science/article/pii/S0144861717304058
69. Ghanbarzadeh B, Almasi H, Entezami AA (2010) Physical properties of edible modified starch/carboxymethyl cellulose films. Innov Food Sci Emerg Technol 11:697–702. https://www.sciencedirect.com/science/article/pii/S1466856410000640
70. Adel AM, El-shinnawy NA (2012) Hypolipidemic applications of microcrystalline cellulose composite synthesized from different agricultural residues. Int J Biol Macromol 51:1091–1102. https://www.sciencedirect.com/science/article/pii/S014181301200308X
71. Bartley GE, Yokoyama W, Young SA et al (2010) Hypocholesterolemic effects of hydroxypropyl methylcellulose are mediated by altered gene expression in hepatic bile and cholesterol pathways of male hamsters. J Nutr 140:1255–1260. https://doi.org/10.3945/jn.109.118349
72. Khan A, Wen Y, Huq T et al (2018) Cellulosic nanomaterials in food and nutraceutical applications: a review. J Agric Food Chem 66:8–19. https://doi.org/10.1021/acs.jafc.7b04204
73. Shi Z, Zhang Y, Phillips GO et al (2014) Utilization of bacterial cellulose in food. Food Hydrocoll 35:539–545. https://www.sciencedirect.com/science/article/pii/S0268005X13002142
74. Inanli AG, Tümerkan ETA, Abed N El et al (2020) The impact of chitosan on seafood quality and human health: a review. Trends Food Sci Technol 97:404–416. https://www.sciencedirect.com/science/article/pii/S0924224419303000

75. Morganti P (2013) Commentary innovation, nanotechnology and industrial sustainability by the use of natural underutilized byproducts 0–4
76. Gan I, Chow WS (2018) Antimicrobial poly(lactic acid)/cellulose bionanocomposite for food packaging application: a review. Food Packag Shelf Life 17:150–161. https://www.sciencedirect.com/science/article/pii/S2214289418300474
77. Kong M, Chen XG, Xing K et al (2010) Antimicrobial properties of chitosan and mode of action: a state of the art review. Int J Food Microbiol 144:51–63. https://www.sciencedirect.com/science/article/pii/S0168160510005167
78. Alishahi A, Aïder M (2012) Applications of chitosan in the seafood industry and aquaculture: a review. Food Bioprocess Technol 5:817–830. https://doi.org/10.1007/s11947-011-0664-x
79. Sathivel S (2005) Chitosan and protein coatings affect yield, moisture loss, and lipid oxidation of pink salmon (Oncorhynchus gorbuscha) fillets during frozen storage. J Food Sci 70:e455–e459. https://doi.org/10.1111/j.1365-2621.2005.tb11514.x
80. R.G. Kumar L, Chatterjee NS, Tejpal CS et al (2017) Evaluation of chitosan as a wall material for microencapsulation of squalene by spray drying: characterization and oxidative stability studies. Int J Biol Macromol 104:1986–1995. https://www.sciencedirect.com/science/article/pii/S0141813016326988
81. Benjakul S, Visessanguan W, Tanaka M et al (2001) Effect of chitin and chitosan on gelling properties of surimi from barred garfish (Hemiramphus far). J Sci Food Agric 81:102–108. https://doi.org/10.1002/1097-0010(20010101)81:1%3C102::AID-JSFA792%3E3.0.CO
82. Kok tn, park jaew (2007) Extending the shelf life of set fish ball. J Food Qual 30:1–27. https://doi.org/10.1111/j.1745-4557.2007.00103.x
83. Ye M, Neetoo H, Chen H (2008) Effectiveness of chitosan-coated plastic films incorporating antimicrobials in inhibition of Listeria monocytogenes on cold-smoked salmon. Int J Food Microbiol 127:235–240. https://www.sciencedirect.com/science/article/pii/S0168160508003942
84. Mohan CO, Ravishankar CN, Lalitha KV et al (2012) Effect of chitosan edible coating on the quality of double filleted Indian oil sardine (Sardinella longiceps) during chilled storage. Food Hydrocoll 26:167–174. https://www.sciencedirect.com/science/article/pii/S0268005X11001603
85. Li T, Hu W, Li J et al (2012) Coating effects of tea polyphenol and rosemary extract combined with chitosan on the storage quality of large yellow croaker (Pseudosciaena crocea). Food Control 25:101–106. https://www.sciencedirect.com/science/article/pii/S0956713511004336
86. Yu D, Li P, Xu Y et al (2017) Physicochemical, microbiological, and sensory attributes of chitosan-coated grass carp (Ctenopharyngodon idellus) fillets stored at 4 °C. Int J Food Prop 20:390–401. https://doi.org/10.1080/10942912.2016.1163267
87. Bonilla F, Chouljenko A, Reyes V et al (2018) Impact of chitosan application technique on refrigerated catfish fillet quality. LWT 90:277–282. https://www.sciencedirect.com/science/article/pii/S0023643817308897
88. Qiu X, Chen S, Liu G et al (2014) Quality enhancement in the Japanese sea bass (Lateolabrax japonicas) fillets stored at 4 °C by chitosan coating incorporated with citric acid or licorice extract. Food Chem 162:156–160. https://www.sciencedirect.com/science/article/pii/S0308814614005834
89. Warwick C, Guerreiro A, Soares A (2013) Sensing and analysis of soluble phosphates in environmental samples: a review. Biosens Bioelectron 41:1–11. https://www.sciencedirect.com/science/article/pii/S0956566312004526
90. Chandrasekhar K, Kumar G, Venkata Mohan S et al (2020) Microbial Electro-Remediation (MER) of hazardous waste in aid of sustainable energy generation and resource recovery. Environ Technol Innov 100997. [Cited 2020 Oct 2] https://linkinghub.elsevier.com/retrieve/pii/S2352186420308026
91. Park J, Chandrasekhar K, Jeon B et al (2021) State-of-the-art technologies for continuous high-rate biohydrogen production. Bioresour Technol 320:124304. [Cited 2020 Oct 30] https://linkinghub.elsevier.com/retrieve/pii/S0960852420315789

92. Venkata Mohan S, Chiranjeevi P, Chandrasekhar K et al (2019) Acidogenic biohydrogen production from wastewater. In: Pandey A, Mohan SV, Chang J-S et al (eds) Biohydrogen. Elsevier, pp 279–320. http://www.sciencedirect.com/science/article/pii/B9780444642035000113
93. Bhatnagar A, Sillanpää M (2009) Applications of chitin- and chitosan-derivatives for the detoxification of water and wastewater—a short review. Adv Colloid Interface Sci 152:26–38. https://www.sciencedirect.com/science/article/pii/S0001868609000888
94. Chandrasekhar K, Velvizhi G, Mohan SV (2021) Bio-electrocatalytic remediation of hydrocarbons contaminated soil with integrated natural attenuation and chemical oxidant. Chemosphere 130649. [Cited 2021 May 1] https://linkinghub.elsevier.com/retrieve/pii/S0045653521011206
95. Gambino E, Chandrasekhar K, Nastro RA (2021) SMFC as a tool for the removal of hydrocarbons and metals in the marine environment: a concise research update. Environ Sci Pollut Res 1–16. [Cited 2021 Apr 28] https://doi.org/10.1007/s11356-021-13593-3
96. Chandrasekhar K, Naresh Kumar A, Kumar G et al (2021) Electro-fermentation for biofuels and biochemicals production: current status and future directions. Bioresour Technol 323:124598
97. Chandrasekhar K, Cayetano RDA, Mehrez I et al (2020) Evaluation of the biochemical methane potential of different sorts of Algerian date biomass. Environ Technol Innov 20:101180. https://linkinghub.elsevier.com/retrieve/pii/S2352186420314802
98. Flagiello F, Gambino E, Nastro RA et al (2020) Harvesting energy using compost as a source of carbon and electrogenic bacteria. Bioelectrochem Syst
99. Crini G, Lichtfouse E, Wilson LD et al (2019) Conventional and non-conventional adsorbents for wastewater treatment. Environ Chem Lett 17:195–213. https://doi.org/10.1007/s10311-018-0786-8
100. Zeng EY (2018) Microplastic contamination in aquatic environments: an emerging matter of environmental urgency. Elsevier
101. Hamed I, Özogul F, Regenstein JM (2016) Industrial applications of crustacean by-products (chitin, chitosan, and chitooligosaccharides): a review. Trends Food Sci Technol 48:40–50. https://www.sciencedirect.com/science/article/pii/S0924224415002721
102. Dandil S, Akin Sahbaz D, Acikgoz C (2019) Adsorption of Cu(II) ions onto crosslinked chitosan/Waste Active Sludge Char (WASC) beads: kinetic, equilibrium, and thermodynamic study. Int J Biol Macromol 136:668–675. https://www.sciencedirect.com/science/article/pii/S0141813018371289
103. González JA, Bafico JG, Villanueva ME et al (2018) Continuous flow adsorption of ciprofloxacin by using a nanostructured chitin/graphene oxide hybrid material. Carbohydr Polym 188:213–220. https://www.sciencedirect.com/science/article/pii/S0144861718301590
104. Sharififard H, Zokaee Ashtiani F, Soleimani M (2013) Adsorption of palladium and platinum from aqueous solutions by chitosan and activated carbon coated with chitosan. Asia-Pacific J Chem Eng 8:384–395. https://doi.org/10.1002/apj.1671
105. Pambi R-L, Musonge P (2015) The efficiency of chitosan as a coagulant in the treatment of the effluents from the Sugar Industry. J Polym Mater. [Cited 2021 Apr 30] https://openscholar.dut.ac.za/handle/10321/2380
106. Crini G, Badot P-M (2009) Guibal ric. Chitine et chitosane : du biopolymre l’application. Presses Universitaires de Franche-Comt, Paris
107. Ahmad AL, Sumathi S, Hameed BH (2005) Adsorption of residue oil from palm oil mill effluent using powder and flake chitosan: equilibrium and kinetic studies. Water Res 39:2483–2494. https://www.sciencedirect.com/science/article/pii/S0043135405001296
108. Altaher H (2012) The use of chitosan as a coagulant in the pre-treatment of turbid sea water. J Hazard Mater 233–234:97–102. https://www.sciencedirect.com/science/article/pii/S0304389412007042
109. Dima JB, Sequeiros C, Zaritzky NE (2015) Hexavalent chromium removal in contaminated water using reticulated chitosan micro/nanoparticles from seafood processing

wastes. Chemosphere 141:100–111. https://www.sciencedirect.com/science/article/pii/S0045653515006499

110. Gopi S, Balakrishnan P, Divya C et al (2017) Facile synthesis of chitin nanocrystals decorated on 3D cellulose aerogels as a new multi-functional material for waste water treatment with enhanced anti-bacterial and anti-oxidant properties. New J Chem 41:12746–12755. https://doi.org/10.1039/C7NJ02392H
111. Albukhari SM, Ismail M, Akhtar K et al (2019) Catalytic reduction of nitrophenols and dyes using silver nanoparticles @ cellulose polymer paper for the resolution of waste water treatment challenges. Colloids Surfaces A Physicochem Eng Asp 577:548–561. https://www.sciencedirect.com/science/article/pii/S0927775719304789
112. Zhou S, Xia L, Fu Z et al (2021) Purification of dye-contaminated ethanol-water mixture using magnetic cellulose powders derived from agricultural waste biomass. Carbohydr Polym 258:117690. https://www.sciencedirect.com/science/article/pii/S0144861721000771
113. Garcia LF, Lacerda MFAR, Thomaz DV et al (2019) Optimization of laccase–alginate–chitosan-based matrix toward 17 α-ethinylestradiol removal. Prep Biochem Biotechnol 49:375–383. https://doi.org/10.1080/10826068.2019.1573195
114. Wang J, Zhou Y, Shao Y et al (2019) Chitosan–silica nanoparticles catalyst (M@CS–SiO2) for the degradation of 1,1-dimethylhydrazine. Res Chem Intermed 45:1721–1735. https://doi.org/10.1007/s11164-018-3697-1
115. Mwafy EA, Mostafa AM (2020) Tailored MWCNTs/SnO2 decorated cellulose nanofiber adsorbent for the removal of Cu (II) from waste water. Radiat Phys Chem 177:109172. https://www.sciencedirect.com/science/article/pii/S0969806X20308938
116. Ilangovan M, Guna V, Olivera S et al (2017) Highly porous carbon from a natural cellulose fiber as high efficiency sorbent for lead in waste water. Bioresour Technol 245:296–299. https://www.sciencedirect.com/science/article/pii/S0960852417314554
117. Xie K, Jing L, Zhao W et al (2011) Adsorption removal of Cu2+ and Ni2+ from waste water using nano-cellulose hybrids containing reactive polyhedral oligomeric silsesquioxanes. J Appl Polym Sci 122:2864–2868. https://doi.org/10.1002/app.34411
118. Li F, Wang B, Pang Z et al (2018) Application of cellulose-based solid acid in absorption of heavy metal ions from printing waste water BT In: Zhao P, Ouyang Y, Xu M et al (eds) Applied sciences in graphic communication and packaging. Springer Singapore, Singapore, pp 893–900
119. Putri CA, Yulianti I, Desianna I et al (2018) Water hyacinth cellulose-based membrane for adsorption of liquid waste dyes and chromium. J Phys Conf Ser 1008
120. Lin Z, Chen L, Ye Z et al (2021) Film-like chitin/polyethylenimine biosorbent for highly efficient removal of uranyl-carbonate compounds from water. J Environ Chem Eng 9:105340. https://www.sciencedirect.com/science/article/pii/S2213343721003171
121. Yousefi N, Jones M, Bismarck A et al (2021) Fungal chitin-glucan nanopapers with heavy metal adsorption properties for ultrafiltration of organic solvents and water. Carbohydr Polym 253:117273. https://www.sciencedirect.com/science/article/pii/S0144861720314466
122. Wang B, Bai Z, Jiang H et al (2019) Selective heavy metal removal and water purification by microfluidically-generated chitosan microspheres: characteristics, modeling and application. J Hazard Mater 364:192–205. https://www.sciencedirect.com/science/article/pii/S0304389418309312
123. Pérez Mora BE, Bellú SE, Mangiameli MF et al (2019) Optimization of continuous arsenic biosorption present in natural contaminated groundwater. J Chem Technol Biotechnol 94:547–555. https://doi.org/10.1002/jctb.5801
124. Türker OC, Baran T (2018) A combination method based on chitosan adsorption and duckweed (Lemna gibba L.) phytoremediation for boron (B) removal from drinking water. Int J Phytoremed 20:175–183. https://doi.org/10.1080/15226514.2017.1350137
125. Azzam EMS, Eshaq G, Rabie AM et al (2016) Preparation and characterization of chitosan-clay nanocomposites for the removal of Cu(II) from aqueous solution. Int J Biol Macromol 89:507–517. https://www.sciencedirect.com/science/article/pii/S0141813016304093

126. Aslani H, Ebrahimi Kosari T, Naseri S et al (2018) Hexavalent chromium removal from aqueous solution using functionalized chitosan as a novel nano-adsorbent: modeling and optimization, kinetic, isotherm, and thermodynamic studies, and toxicity testing. Environ Sci Pollut Res 25:20154–20168. https://doi.org/10.1007/s11356-018-2023-1
127. Sangeetha K, Angelin Vinodhini P, Sudha PN et al (2019) Novel chitosan based thin sheet nanofiltration membrane for rejection of heavy metal chromium. Int J Biol Macromol 132:939–953. https://www.sciencedirect.com/science/article/pii/S0141813019309766