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Utilization of seafood byproducts: biological activities and biotechnological applications

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Abstract

The global demands for seafood products are steadily increasing and consequently numerous amounts of solid and liquid byproducts are generated that usually discarded leading to serious problems including loss of nutrients and environmental pollution that consequently negatively affect the human health. These byproducts are considered as an undiscovered treasure having the potentiality for the production of various probiotics as well as several biomaterials possessing multiple functional and biological activities. Nitrogenous compounds, lipids, polysaccharides and minerals are the main constitutive components that can be recovered or converted to value added products with potential nutritional, biomedical and pharmaceutical applications. Biological conversions via microbial fermentation and/or enzymatic treatment are eco-friendly economic processes that are widely applied leading to the production of bioactive protein hydrolysates, chitin based products and various industrial enzymes. In addition, algae based bioconversion is an efficient method for the valorization of seafood industry effluents via the production of various bio-refineries.

Keywords: Seafood, solid byproducts, effluents, value added products

1. Introduction

The overgrowth in the human population enforces a global interest for the use of seas, oceans and marine resources for sharing a blueprint for the prosperity of people as well as sustainable development [1]. Seafood industry including either finfish or shellfish, has become one of the main sectors in food industry in which the global output of capture fisheries had been increased from 20 million ton in 1950 to 81.5 million ton in 2014 [2] reaching its highest recorded value (96.4 million ton live weight) in 2018 [1]. Additionally, the aquaculture sector provides 16% of the edible animal protein and has been estimated as a crucial component for providing food security for 9.8 billion people all over the world by 2050 [3].

In seafood industry, 80% of the total harvest has been processed into dried, smoked, frozen, marinated and other products in which several pre-processing operations including removal of heads, shells, scales, skin, gut and fins in addition to washing, filleting and others have been performed. These processes produce numerous amounts of solid and liquid byproducts that usually discarded causing environmental pollution and negatively affect the human health. In addition to incineration of these solid byproducts causing air pollution, huge amounts of by-catch are dumped in the oceans or nearby land. Microbial anaerobic fermentation of the dumped organic matters leads to the release of CO_2, CH_4, NH_3, amines and H_2S that significantly contributes in the climate changes. Also these solid byproducts negatively affect the aquatic life via alteration of the color and odor of the surrounding environment. Discharge of untreated effluents in the soil directly affect the inhabited microorganisms as it increases the moisture, salinity, carbon content and electric conductivity. Moreover, high levels of nitrogen, phosphorus, fat, oil and grease may lead to drinking water shortage, eutophication, biotic depletion, algal blooms, acidification of water, destruction of habitats, outbreaks of various diseases and corals siltation. Therefore, dealing with this huge amount of the produced wastes is a great challenge [4].

Solid byproducts including skin, viscera, bones, heads and other corporal structures reach about 65% of the total weight while liquid byproducts are the effluents produced during washing, cooking and thawing processes [5]. These byproducts are

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considered as an undiscovered treasure having the potentiality for the production of various biomaterials possessing several functional and biological activities. The valorization of these byproducts and their utilization in other industries is one of the main avenues that can close the loop in seafood production [6-10].

The problem of discarding the seafood byproducts is an emerging issue that indirectly increases the pressure on fisheries enforcing the search of an eco-friendly applicable solution to solve this problem via the adaptation of a circular economy based on business models [1]. Table (1) illustrated the negative and the positive issues that inherent the problem of seafood byproducts.

Table (1): The negative and the positive issue that inherent the problem of seafood byproducts (modified from Caruso *et al*., [6]).

Negative issue	Positive issue
Environmental impact	The utilization of these byproducts contributes in their safe disposal.
Loss of nutrients	These nutrients can be exploited in nutritional, pharmaceutical, industrial sectors (i.e., biorefinery).
Operational cost of its exploitation	Biotechnological studies can enhance the operational quality as well as its efficiency.

Solid byproducts

Fish composition is largely varied depending on several variables including the species, state of nutrition, health, age and season of collection [11]. The average percentage of the discarded seafood parts is illustrated in table (2).

Table (2): Average weight percentage of the discarded seafood parts.

Type	Discarded part	Average weight percentage (%)	Reference
Finfish	Head	21	Caruso *et al*., [6]
	Bones	14	
	Fins	10	
	Gut	7	
	Liver	5	
	Skin	3	
	Ovaries	4	
Shellfish	Shell and head	35-45	Suryawanshi *et al*., [12]

Source for probiotics

Probiotics are defined according to the Food and Agriculture Organization of the United Nations and World Health Organization [13] as "live microorganisms which when administered in adequate amounts confer a health benefit on the host" via the direct or the indirect influence on the composition of the intestinal microbiota. Fish gastrointestinal tract, gills and skin microbiota represent a rich source of probiotic bacteria [14] in which their isolation and their synthesized bioactive compounds attract the research interest. Different activities including antimicrobial [15-16] and antitumor [17] have been reported for various biomolecules produced by probiotics isolated from fish organs. Additionally, Floris *et al*., [16] estimated gilthead seabream intestinal microflora as biosurfactant producers with antimicrobial activity. Microbial surfactants produced by marine microorganisms have attracted a great interest in the 21st century as they possess multiple therapeutic functions including antifouling, anti-adhesive, antimicrobial, antithrombotic and antitumor [18]. The strains that have been isolated from fish organs are summarized in table (3).

Fishmeal production

Seafood byproducts are rich in nutritionally valuable ingredients with average values illustrated in table (4). In the last two decades, the utilization of fishery by-catch or processing byproducts as a fishmeal (prepared by drying followed by grinding) participating in the production of feed for aquaculture, poultry, ruminants and pets had been examined and well established [19-20].

Table (3): The microbial strains isolated from fish organs.

Gram positive strain			
Lactobacillus fructivorans	*Lactobacillus pentosus*	*Lactobacillus delbrueckii*	*Enterococcus faecium*
Bacillus sp.	*Paenibacillus* sp.	*Micrococcus* sp.	*Macrococcus* sp.
Leuconostoc sp.	*Brochothrix* sp	*Carnobacterium* sp.	*Arthrobacter arilaitensis*
Anoxybacillus sp.	*Staphylococcus* sp.	*Actinobacteria*	
Gram negative strain			
Citrobacter freundii	*Plesiomonas shigelloides*	*Enterobacter* sp.	*Shewanella xiamenensis*
Hafnia alvei	*Vibrio* sp.	*Aeromonas* sp.	*Psychrobacter* sp
Agrobacterium sp.	*Photobacterium* sp.	*Acinetobacter* sp.	*Azospirillum orizae*
Erwinia persicina	*Sphingomonas* sp.	*Pseudomonas* sp.	*Cyanobacteria*
Yeast			
Candida sp.	*Saccaromyces cerevisiae*	*Debaryomyces hansenii*	*Leucosporidium* sp.
Kodamea ohmeri	*Pichia* sp.	*Rhodotorula* sp.	

Table (4): Average composition of seafood processing discards [4].

Nutrient	Average percentage (%)
Crude protein	57.9 ± 5.3
Fat	19.1 ± 6.1
Crude fiber	1.2 ± 1.2
Ash	21.8 ± 3.5
Sodium	0.6 ± 0.1
Potassium	0.7 ± 0.1
Phosphorous	2.0 ± 0.6
Calcium	5.8 ± 1.3

Source for their constitutive compounds

In the last few years, the extraction of seafood derived compounds and their applications in various fields of life including food, agricultural and medical sectors have attracted growing interests [4]. There are various compounds that can be extracted from either finfish or shellfish byproducts and can be classified under four main groups including nitrogenous compounds, lipids, polysaccharides and minerals.

Nitrogenous compounds

Diverse proteins, peptides and amino acids are the main constitutive components of the nitrogenous fraction possessing valuable nutritional and functional properties including emulsifying, foaming and texture improving agents in addition to possessing various biological activities including antioxidant and antimicrobial activities [20]. In general, fish proteins are easy digestible with high nutritional value. They are composed of well-balanced composition of essential amino acids as valine, lysine and phenylalanine [22].

- ***Proteins***

The increasing demands for protein either for meeting the human or animal requirements enforces the research interest for its recovery from novel sources [23]. Seafood solid byproducts consist of about 60% proteins with high nutritional value (containing essential amino acids) that can be recovered retaining its native properties or converted to amino acid and polypeptides [4]. Isoelectric solubilization precipitation is a mild technique in which dilute acid (pH 2.5-3.5) or dilute alkali (pH 10.8-11.5) are used in the homogenization and solubilization of seafood byproducts followed by precipitation and filtration of the dissolved proteins. It has been efficiently used in the recovery of sarcoplasmic and myofilbrillar proteins from different byproducts of various species of finfish and shellfish with up to 95% recovery yield (Table 5) [20].

Table (5): Seafood byproducts and protein recovery yield.

Source	Extraction method	Yield (%)	Reference
Tilapia frame	Alkaline	68	Chomnawang Yongsawatdigul, [24]
Bighead carp	Acidic	74.8	Chang *et al*., [25]
Common carp	Acidic	76.3	Tian *et al*., [26]
	Alkaline	87.6	
Mackerel	sequential acid/ alkaline	95–100	Álvarez *et al*., [27]
Pangas processing waste	Acidic	59	Surasani *et al*., [28]
	Alkaline	69	
Catfish heads	Alkaline	36–55	Tan *et al*., [29]
Catfish frames	Alkaline	53	
Green crab	Alkaline	83	Khiari *et al*., [30]

Apart from myofibrillar protein, marine collagen represents a biocompatible alternative to the mammalian one. In general, collagen compromises 30% of the total protein exists in most organisms and it compromises 70% of the skin dry weight. Seafood byproducts are a collagen-rich source possessing various nutraceutical and functional properties [31-32]. Melgosa *et al*., [33] reported the preparation of collagen-rich protein extract from cod frames possessing anti-inflammatory activity. In addition, fish scales collagen is a natural biomaterial find application in various fields including drug delivery [34], wound healing [35], corneal tissue engineering [36] and oral mucosa regeneration [37].

Gelatin is a more soluble protein that structurally constructed connective tissues. Dara *et al*., [38] reported that the gelatin extracted from big eye tuna skin was suitable in nutraceutical and biomedical applications as it possessed good gelling properties. Valcarcel *et al*., [39] indicated seabream skin byproducts as suitable raw materials for the production of gelatin.

- ***Enzymes***

Enzymes are highly specific protein molecules that catalyze various biochemical reactions providing eco-benign, easy controllable and efficient processes. Viscera of fish are rich in enzymes including proteases (pepsin, trypsin, trypsin-like enzymes, collagenase, peptidase and elastase), chitinase, lipase and others. The isolated enzymes mainly exhibit high thermal activity and stability with high stability at wide pH range that make them suitable candidates in various food, detergent and pharmaceutical industries

[40-42]. The isolated enzymes and their potential applications are illustrated in table (6).

Table (6): Isolated enzymes and their potential applications [20].

Enzyme	Source	Application
Proteases	Fish intestines and shrimp heads	Recovery of seafood byproducts constituents and production of fish protein hydrolysate
Lipases	Fish discards	Production of omega-3-enriched triglycerides
Chitinases	Shellfish	Production of chitin hydrolysis products
Lysozyme	Arctic scallop shell, crab shell	Bacteriostatic agent
Catalase, glutathione peroxidase	Marine mussel	Antioxidants
5′-nucleotidase, Nucleoside phosphorylase	Fishery byproducts	Construction of biosensors to measure amines, nucleotides, and others

Lipids and co-products

- ***Oil production***

Fishery byproducts contain a varied amount of lipids (up to 30%) that present in the form of fish oil. The oil extracted from fish byproducts is a good quality one that can be exploited in pharmaceutical and food industries. It contains two main polyunsaturated fatty acids, eicosapentaenoic acid and docosahexaenoic acid that are classified as omega-3 fatty acids [43]. Bio-oils gained a global interest for either their lonely use or in blend with petroleum fuel. The use of biomasses in the production of bio-fuels has attracted the research focus from the prospective of their valorization and environmental protection. Fish oil produced from seafood byproducts can be considered as a convenient source for fuel production [44-45].

- ***Carotenoids***

They are red orange pigments present in crustaceans as well as salmon and trout. They are either hydrocarbon in nature as β-carotene and xanthophylls or oxygenated derivatives as astaxanthin and canthaxanthin. Crustacean shells are an important source of natural astaxanthin that has been reported as potent antioxidant [46]. In general, antioxidants are compounds that can be used to overcome the deleterious effects of free radicals in the biological systems [47]. Solvent extraction is the commonly applied method for the extraction of astaxanthin from crustaceans. Recently, the searching for a new eco-friendly sustainable technique as well as adjuvant treatments for the extraction process has attracted the research focus for example; microbial fermentation [48], ultrasound-assistance [49], enzymatic treatment [50] and microwave pre-treatment [51].

Polysaccharides

Crustacean shell is the primary source of chitin, linear polysaccharide of N-acetyl-D-glucosamine units linked by β-1,4-glycosidic bonds [52], prepared via several manipulation steps including deproteinization, demineralization and discoloration with a recovery yield of about 25% [53]. Chitin has attracted a growing interest due to its various food, agricultural and pharmaceutical applications in addition to its applicability in the production of valuable products including chitosan (de-acetylated derivative), N-acetyl glucosamine, chitooligosaccharide and various biologically active chitinolytic enzymes [54]. Chemical extraction is the commercial process that still applied for the preparation of chitin [55] but the development of green extraction processes gained more attention [56-57] preferring the use of enzymes and acid producing bacteria since the biological process produce product of better quality under mild and economic conditions [58-59] (Figure 1).

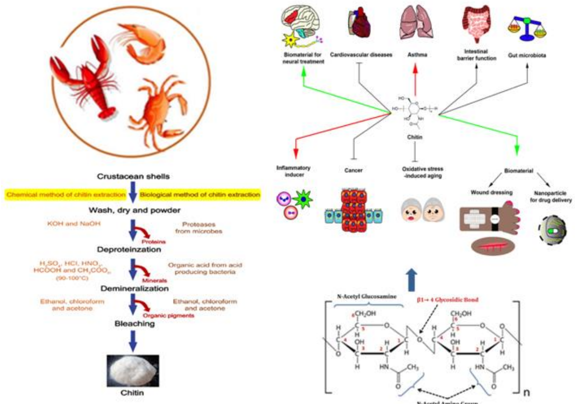

Figure (1): Recovery of chitin and its application.

Glycosaminoglycans are linear polysaccharides composed of disaccharide repeating units of amino sugars covalently linked to uronic acid. In the last two decade, the researchers investigate their potential applications in which they have been reported to possess various structural and functional properties including antitumor, anticoagulant and anti-inflamatory activities in addition to their applicability in tissue engineering [60-61]. Among them, hyalouronic acid and chondroitin sulphate are the main groups that have been extracted from seafood byproducts [62]. Murado *et al*., [63] reported the extraction of hyalouronic acid from fish eyeball and Vazquez *et al*., [64] reported the extraction of chondroitin sulphate from the cartilage of blackmouth catfish.

Minerals

Bone composed of about 70% minerals so bone-rich byproducts are a significant source of minerals. Tang *et al*., [65] reported the production of fermentable solution rich in calcium salts by the fermentation of grass fish bones using *Leuconostoc mesenteroides* suggesting its applicability as calcium supplement.

Hydroxyapatite is an inorganic material widely distributed in hard tissues for supporting their structure [66]. It has been reported to be applied in some biomedical field including bone tissue engineering, periodontal repair and dyes biosorbant [9]. Fish scales are efficient byproducts used for its preparation [67-68].

Conversion of the constitutive components

Protein hydrolysates, chitin based products and enzymes are the major value added products that resulted from the conversion of the components of seafood byproducts. The use of microorganisms or enzymes is the main employed conversion process.

Major conversion techniques

- ***Microbe-mediated conversion***

The use of microorganisms in the conversion processes is named as fermentation in which several products have been produced. In the fermentation process, the cultural and the nutritional conditions are crucial variables that influence the growth of the microorganisms as well as their released metabolic products. In the last two decade, statistical models have been widely employed in fermentation technology to adjust its condition for optimizing the productivity of the desired product [69]. Response surface methodology that described by Box and Wilson, [70] as well as artificial neural networks are the most popular mathematically based techniques that has been applied in the optimization processes [71]. The use of microorganisms in the fermentation of seafood byproducts is estimated as an efficient technique for their bioremediation that resulted in the production of valuable products including enzymes, antioxidant compounds, protein hydrolysate and others [72]. Enzymes, liquid fertilizers, glutamic acids, pigments and biologically active oligosaccharides are the main valuable products produced by the microbial conversion of seafood byproducts (Table 7).

- ***Enzyme- mediated conversion***

In general, hydrolases are the most famous group of enzymes used in biotechnological applications. Specifically, proteases are widely applied in the conversion of seafood byproducts [31]. In addition, glycoside hydrolases and lipases give rise to various biologically active hydrolysates by the conversion of seafood constitutive ingredients [83-84]. Proteins, pigment, chitin, chitooligosaccharides and deodorized oil are the main products produced by the enzymatic conversion of some seafood byproducts (Table 8).

Major conversion products

- ***Protein hydrolysate and bioactive peptides***

The protein content in seafood byproduct is an efficient source for the production of peptide-rich hydrolysates possessing various functional properties including emulsifying, foaming, rheological, textural and physical properties in addition to various biological activities including antimicrobial, antioxidant, anticancer, antidiabetic, anticoagulant and antihypertensive in addition to hepato and cardio protective agents [91].

- ***Chitin based products***

Chitosan is the de-acetylated derivative of chitin with the presence of less than 20% N-acetyl-D-glucosamine units. It is a non-toxic biopolymer extensively applied in various fields including biomedical, pharmaceutical, agricultural, food and feed industries in addition to possess various biological activities including anti-inflammatory, immune-modulatory [92], antitumor [93] and antimicrobial [94].

N-acetyl glucosamine (chitin mono-constituent sugar) is a clinical drug for the treatment of rheumatoid arthritis. In addition, it possesses antimicrobial, antioxidant and anticancer activities with potential food, agricultural, medical and pharmaceutical applications [95]. Currently, the conversion of crustacean byproducts to N-acetyl glucosamine attracts a growing interest as it can be exploited in the production of bioethanol [10].

Chitooligosachharides are water soluble homo- or hetero-oligomers of D-glucosamine and N-acetyl-D-glucosamine with an average molecular weight less than 3900Da [96]. They have been estimated to possess various biological activities including prebiotic, antioxidant [82, 97], antitumor [98], neuroprotective [99-100], antifungal [101-102], antibacterial [103], immuno-modulatory [92], hepatoprotective [104] and hypolipidemic effect [105].

- ***Enzymes***

Nowadays, green chemistry is attracting a great interest. Industrial enzymes have been considered as a green route for protecting the environment and popular health but the cost is a significant barrier that restricted its application. The reduction of the cost via the use of seafood byproducts as a substrate for the production of enzymes instead of using the refined one is attracting the research focus [54].

Proteases are the most popular class of enzymes that widely applied in various biotechnological processes including amino acid analysis, detergent, cosmetics, food and feed production [106]. Proteases in general are a complex group of enzymes that specifically catalyze the hydrolysis of proteins converting them to peptide chains and/or amino acids [107]. Ramkumar *et al*., [77] reported the use of fish gut waste as an efficient substrate for the microbial production of protease using *Bacillus licheniformis.*

Shrimp byproducts have also been reported as an efficient substrate for inducing the microbial production of various chitinolytic [54] and chitosanolytic [81] enzymes as well as chitin deacetylase [108]. Chitinases and chitosanases are chitin and chitosan specific hydrolytic enzymes that lead to the production of their monomer constituents as well as chitooligosaccharides while chitin deacetylases are the enzymes responsible for the deacetylation of chitin for chitosan production [109].

Liquid byproduct

The operations carried out during the processing of seafood result in the production of wastewater or effluents reach in soluble organic matters, salts and colloidal substances with high content of Chemical Oxygen Demand generated mainly from biodegradable lipids and proteins [110]. A variation in the volume of wastewater results from different processing operations was estimated and the average volumes are illustrated in table (9).

Table (9): The average volume of wastewater results from different seafood processing operations.

Operating process	Volume of wastewater (m^3/ton raw material)	Reference
Precooking of fish to be canned	0.07-0.27	Arvanitoyannis and Kassaveti, [111]
Unloading fish for canning	2-5	
Sterilization of cans	3-7	
Handling and storage of fish	10-12	
Scaling of white fish	10-15	
Oily fish skinning	0.2-0.9	
Marine finfish	14.0	
Frozen fish thawing	5.0	
Shrimp freezing	7.0	
Blue crab, mechanized plant	29-44	
Processing of tuna	3.0	Fluence, [112]
Canning of sardine	15.0	Venugopal and Sasidharan, [113]
White fish filleting	5–11	
Oily fish filleting	5–8	
Skinning of knobbed fish	17.0	
Filleting of un-gutted oily fish	1–2	

Algae based bioconversion

Microalgae is one of the resources that attracted the research focus for its economic biomass production as it can incorporate in the production of biofuels, animal feed, pharmaceutical and health products [114]. Gao et al., [115] indicated the feasibility of the production of algal biomass (*Chlorella* sp.) using seafood processing wastewater.

Source of biologically active compounds

Seafood liquid byproducts (cooking juice and stickwater) can be used as a source for the production of various bio-molecules including nitrogenous compounds, carotenoids, lipids and flavors that can be exploited in several biotechnological processes.

- ***Cooking juice***

Cooking juice or cooking wastewater is the effluent resulted from fish cooking operations performed mainly during canning processes. Tuna or small pelagic fish (sardine and anchovy) are the main traditional raw material. Hsu *et al*., [116] reported that the yield of cooking juice (with about 4% of water-soluble protein) produced every day was in the range of 15 to 27 ton for each fish canning plant. Tang *et al*., [117] reported the production of 1.5 ton of cooking wastewater for each ton of processed anchovy containing 5g/L of crude protein in addition to essential amino acids. Additionally, P´erez-Santín *et al*., [118] reported that the industrial shrimp cooking juice contains 13.5% protein.

- ***Stickwater***

Stickwater is the effluent resulted during the preparation of fishmeal. It represents 60% of the fish weight and composed of 5-9% protein content [119].

Nitrogenous compounds

Seafood effluents contain a considerable amount of soluble proteins that can be recovered and concentrated or used for the production of protein hydrolysates containing biologically active peptides.

Production of bioactive peptides

- ***Enzymatic hydrolysis***

The hydrolysis of protein-reach seafood byproducts leads to the production of peptides varied in their size as well as their composition and consequently their bioactivity [120]. The selection of the hydrolysis conditions is the crucial step in the application of enzymes in which the enzyme-substrate ratio, hydrolysis period and the temperature of the reaction have been reported as the main influencing variables [121]. The application of proteolytic enzymes in the hydrolysis of seafood liquid byproducts has been previously studied manifesting its applicability as a valuable source for the production of bioactive peptides. P´erez-Santín *et al*., [118] reported the use of proteolytic alcalase in the hydrolysis of shrimp cooking juice and production of bioactive peptides. Hung *et al*., [122] reported the production of biologically active protein hydrolysate from the hydrolysis of cooking juice of the industrial manufacturing of tuna by applying protease followed by ultrafilteration. The combination of enzymatic hydrolysis and ultrafilteration had also been reported for the production of protein hydrolysate results from the hydrolysis of shrimp cooking water [123]. Mahdabi and Shekarabi, [124] reported the production of protein hydrolysate by the enzymatic hydrolysis of stickwater resulted from the preparation of kilka fishmeal using alcalase.

- ***Membrane technology***

The use of semi-permeable membranes in the separation of valuable molecules from seafood liquid byproducts is one of the efficient techniques that have been applied in the preparation of biologically active peptides. It possesses several advantages as it minimizes the denaturation of protein and it can be utilized for obtaining specific molecular weight peptides [125].

Functional and biological activities

The recovered protein as well as the produced peptides can be widely applied depending on the base of their structural features including molecular weight, amino acid composition, sequence and hydrophobicity.

- ***Emulsifying and foaming agent***

The protein recovered from herring industry wastewater with a molecular weight of 50 KDa can be used as a natural emulsifying agent [126]. In addition, Gringer *et al*., [127] indicated that the foaming as well as the emulsifying property of the proteins recovered by ultra-filtration of herring industry wastewater was not affected.

- ***Antioxidant activity***

Antioxidant peptides have been previously prepared from tuna cooking juice [116], shrimp cooking juice [118], herring industry wastewater [126] and from kilka stickwater [124]. Hsu *et al*., [116] attributed the antioxidant activity of the produced peptides to the presence of proton donating amino acids, histidine and proline. Additionally, Tremblay *et al*., [128] indicated that the cooking effluent of snow crab was composed of 59% protein that possessed antioxidant activity.

- ***Antihypertensive activity***

The peptides prepared by the enzymatic hydrolysis of the protein recovered by ultrafilteration from cuttlefish processing wastewater had been reported to possess antihypertensive activity [129].

- ***Antiproliferative activity***

Mutations in general encourage carcinogenesis and proliferation of cells. Antiproliferative activity of peptides prepared from tuna cooking juice had been estimated against breast cancer cell line (MCF-7) without any cytotoxic activity against mammary epithelial cells [122]. The molecular weight of the produced peptide was greater than 2.5 KDa and composed mainly of hydrophobic amino acids. Huang *et al*., [130] indicated that hydrophobic peptides could penetrate into the hydrophobic core of the cell membrane participating in antiproliferative activity. In addition, Hung *et al*., [122] attributed the antiproliferative activity of the produced peptide to the induction of the expression of caspase 3 that activated cancer cell apoptosis.

Carotenoids

Shrimp cooking fluids can be used to isolate the carotenoid, astaxanthin that can exist freely or with esterified derivative possessing antioxidant activity [118].

Lipids

Fish processing effluents contain considerable amount of lipids that can be isolated and exploited in various applications. Bechtel, [131] reported that pollock, cod and salmon stickwater contain variable amount of lipids and Garcia-Sifuentes *et al*., [132] concentrated sardine stickwater in which the fat content reached 18%. Additionally, Alkaya and Demirer, [133] reported that gutting process water recycling system contains valuable fish oil/grease by-product and Monteiro *et al*., [134] reported the application of High hydrostatic pressure for the extraction of polyunsaturated fatty acid from fish canning effluents.

Flavor compounds

Flavor compounds are mainly used either to add aroma or taste. Aromatic compounds are usually volatile in nature with molecular weight less than 400Da as aldehydes and ketones while taste-adding compounds are mostly water soluble consisting of organic acids, amino acids and sugars [128]. Crustacean effluents including shrimp and crab are attractive proposition for the production of natural flavoring products [135, 128].

Bio-refinery approaches

Seafood byproducts are a treasure rich with various valuable products that can be a promising renewable biomass for bio-refineries. The International Energy Agency defined bio-refinery as the "sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, and materials) and bio-energy [136]. Several bio-refinery approaches have been designed for the utilization of seafood byproducts as illustrated in table (10).

Table (10): Bio-refinery approaches for seafood byproducts.

Bio-refinery	Products	Refrences
Cultivation of alga	Astaxanthin, single cell protein (SCP)	Khoo *et al*., [137]
	Various products	Mitra and Mishra, [138]
Lactic fermentation	Astaxanthin, hydrolyzed protein and chitin	Routray *et al*., [78]
Anaerobic fermentation with cow dung	Methane, Liquid mineral fertilizer	Kratky and Zamazal, [139]
Coupled alcalase hydrolysis and bacterial fermentation	Gelatin, oils, FPH, bioactive peptides, and fish peptones	Vázquez *et al*., [58]
Sequential extraction by ISP followed by enzyme	Collagen, myofibrillar proteins	Abdollahi *et al*., [140]
Sequential treatment of crustacean shells	Chitin, proteins, lipids, carotenoids and CaCO3	Hülsey, [141]

Conclusion

In a world of stagnating oceanic resources and increasing of environmental problems, it is imperative that seafood processing needs to be eco-friendly and economic. Management of the produced byproducts can significantly help seafood industry realize objectives of food security and environmental protection. In this article, seafood byproducts have been estimated as a potential resource for the production of various biomaterials that find applications in food, agricultural and biomedical fields. These byproducts either solid discards including skin, viscera, bones, heads and other corporal structures or liquid effluents produced during washing, cooking and thawing processes are source for diverse proteins, peptides, amino acids, oils, pigments, polysaccharides and minerals that possess various nutritional, functional and biological activities. In addition, Fish gastrointestinal tract, gills and skin microbiota represent a rich source of probiotic bacteria capable for the production of various bioactive compounds. For more economic approaches, integrated refinery-type processes for the extraction of multiple products are widely applied.

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