Seafood industry effluents: Environmental hazards, treatment and resource recovery

ARTICLE IN PRESS

Journal of Environmental Chemical Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Environmental Chemical Engineering

journal homepage: www.elsevier.com/locate/jece

Seafood industry effluents: Environmental hazards, treatment and resource recovery

Vazhiyil Venugopal *, Abhilash Sasidharan

Department of Fish Processing Technology, Kerala University of Fisheries & Ocean Studies, Panangad, Kochi, 682 506, Kerala, India

ARTICLE INFO

Editor: Teik Thye Lim

Keywords:
Seafood industry wastewater
Environmental hazards
Effluent treatments
Valorization
Resource recovery

ABSTRACT

Global demand for fresh water is rising at a rapid rate and is struggling to keep pace with water requirements of increasing population. Against this scenario, the seafood industry including aquaculture routinely uses voluminous amounts of fresh water and discharges large volumes of post-process wastewater as effluents. The presence of proteins, oil, carotenoids, minerals, and other compounds in the effluents make them high in biological oxygen demand and chemical oxygen demand, and hence, responsible for significant environmental hazards. Therefore, appropriate treatments of the effluents are essential before they are discharged or disposed off to mitigate the environmental problems. Besides, there are good potentials to recover various ingredients from the effluents for uses as food additives, nutraceuticals, nutritional supplements, flavoring agents, fertilizers, plant bio-stimulants, animal and aqua feed. Recent developments in microbial technology, particularly, algal biotechnology has potentials for cost-effective and eco-friendly treatments of the effluents together with the recovery of various biomolecules. Cultivation of microalgae in the effluents provide single cell proteins (SCP) that can have applications as animal feed including feed for the rising aquaculture industry. The SCP is also sources of proteins, oils, carotenoids and other compounds. The rich contents of oil in SCP can be resource for biofuel. In addition, the treated wastewaters can also be used as fertilizer. Recent developments in effluent treatments have potentials to improve water security, protect the environment, support food and nutraceutical industries, and enhance seafood sustainability, thereby contributing an interesting value chain for a circular bioeconomy.

1. Introduction

The demand for food, water and energy is projected to increase rapidly to keep pace with the rise in global population. Food sustainability and safety are very much dependent on availability of fresh water. The two salient problems of modern food production systems are enormous use of fresh water, and the industry-associated environmental hazards. It has been estimated that agriculture and livestock production currently account for about 60 % of global fresh water withdrawals, with a current estimated consumption of roughly 7 600 m^3water per year. Freshwater requirement for food and live stock production is projected to increase by 65 % within the next 30 years [1]. The processing of food results in release of voluminous amounts of wastewater, which are rich in various nutritionally valuable and other components. Callous discharge of wastewater without any treatment is responsible for serious environmental hazards. In addition, it has been estimated that about one-third of food produced globally, amounting to about 1.3 billion tons, is lost or wasted, which contain more than 50 % of biodegradable organic matter [2]. One of the measures for clean food production is proper treatment of wastes including effluents in order to address environmental pollution and also to avoid loss of food components. The recovery of resources from waste streams can reduce losses and improve the overall sustainability of food production from both economic and environmental points of view. This review is intended to point out the environmental problems associated with seafood processing wastewaters and also benefits of their valorization. Appropriate treatments result in environmental protection, conservation of water, recovery of valuable ingredients, and also production of biofuel. The article also points out upcoming methods based on microbial biotechnology for valorization of seafood industry effluents towards a circular bioeconomy.

1.1. The seafood industry

The seafood industry comprises of both capture fisheries and

* Corresponding author at: D-901Concord Manhattans, Electronic City Phase I, Neeladri Road, Bangalore, 560100, India.
E-mail addresses: vvenugopalmenon@gmail.com, vrnugopalmenon@hotmail.com (V. Venugopal), drabhilash@kufos.ac.in, abhiif@gmail.com (A. Sasidharan).

https://doi.org/10.1016/j.jece.2020.104758
Received 8 August 2020; Received in revised form 13 October 2020; Accepted 6 November 2020
Available online 14 November 2020

Please cite this article as: Vazhiyil Venugopal, Abhilash Sasidharan, *Journal of Environmental Chemical Engineering*, https://doi.org/10.1016/j.jece.2020.104758

aquaculture to provide the consumer finfish and shellfish of choice. Global seafood production in the year 2018 was 178.5 million tons (MT). The marine seafood includes finfish (pollock, tuna, herring, mackerel, whiting, and others), crustaceans such as shrimp, krill, crab, and lobster, bivalves including mussels, oysters, clams, and scallops, cephalopods such as squid and cuttlefish. Aquaculture, with a production of 82.1 MT in 2018, has grown at an annual rate of 5.8 % during the period 2001−2016. The major items of fresh water aquaculture include carp, tilapia and shellfish species, while mariculture of Atlantic salmon, sea bass, and sea bream is also common [3,4]. The industry processes about 78 % of total harvest into diverse products such as chilled, frozen, smoked, dried, fermented or marinated or other items. Chilled fish, finfish fillets and steaks, shrimp products and fish protein products such as squirmy (mechanically deboned, water washed, minced fish meat), are some of the popular consumer products, which are traded in diverse international markets [5]. Both capture fisheries and aquaculture have complementary roles in increasing seafood availability for nutrition and health gains [6].

All the seafood that is made available is not however, fully used. Discards, by-catch on board and wastage ashore contribute to enormous amounts of wastes. The processing discards, such as skins, heads, frames, viscera, fillet cut offs and others account up to 40 % of the raw material processed. The growing aquaculture operations contribute to additional quantities of offal. It has been estimated that about 8% of seafood production is wasted annually, with about 7.3 MT during the period 1992–2001 [7]. Fishery wastes, unlike municipal wastes, have more proteins and other nitrogenous materials, responsible for rapid putrefaction. Grossly seafood wastes, on dry weight basis, have average contents of about 60 % proteins, 19 % fat and 21 % ash [8]. With the rising seafood industry, proportions of fishery wastes including effluents have increased posing rising global environmental concerns. Traditionally, the practice of disposal of solid wastes encompasses dumping into land fill, its use in silage, fishmeal, and fertilizer or as component of aqua- and poultry feeds [9].

1.2. Water consumption by the seafood industry

Water is the imperative component of fisheries sector. Fresh, brackish and saline surface waters provide fish habitats and are used for capture fishery, for cage and pen aquaculture as well as for the collection of fish fry or juveniles for aquaculture [10]. Aquaculture requires large volumes of fresh water varying with the production systems, such as re-circulating, semi-closed, and open water systems, cage systems, intensive, or semi-intensive, and also on the location of the farm, and the species being raised. Water in the farms is also lost due to evaporation. Generally, water requirements for farmed production per ton of fish range from 1.5 m^3 for spiny lobster, 6 m^3 for generic fish, and up to 48, 782 m^3 for sea-bass farmed in cages. sides, the indirect uses of water cover water required for diverse processing operations including farmed items, aqua feed production, and also for sanitation and hygienization of plant and equipments [11]. Table 1 gives direct and indirect consumptions of water in the seafood industry. Be

Water is essential for various pre-processing steps such as cleaning,

Table 1
Direct and indirect consumption of water in the fisheries sector.

Water	Direct consumption	Indirect consumption.
Used	Biomass formation in wild and aquacultured seafood*	Pre-processing and processing operations, transportation, storage of processed seafood items*** Feed production
Lost	Evaporation occurring during aquaculture**	Process wastewater, water used for cleaning of plant, equipments, etc. mostly returned to the environment***

* Comparatively negligible.
** varies according to the location and area.
*** varies according to operation.

beheading, filleting, scaling, peeling, cooking, icing and also for cold chain systems to overcome the perishable nature of captured fishery products at various stages of handling. Water is also required for storage and transportation of raw and processed products. Processing consumes large volumes of fresh water approximately an amount of 10–40 m^3 per ton of raw material processed [12]. This amounts to approximately US $ 22 as per current industrial water tariffs in India. Surimi production, which involves repeated washing of fish meat mince, uses more water than other operations such as canning, curing or freezing [5]. The amount of water required to produce a ton of marinated herring or peeled shrimp has been calculated to be 7,000–8,000 and 50,000 L, respectively [9] [13]. The process water generated during boiling, filleting, marination and other processes are continuously pumped out as effluents. One of the largest herring-processing factories in Europe with an annual production of about 50,000 tons releases approximately 1500 m^3 wastewater daily [14]. Fig. 1 shows generation of effluents during seafood processing. The consumption of water in fish processing industry and discharge of high-strength post-processing wastewater are of great concern world-wide. Table 2 gives approximate volumes of wastewater generated by various seafood processing operations. In spite of large consumption of water, the cost-benefit aspects of water used by seafood industry including aquaculture have not received sufficient attention. It has been cautioned that the ‘seafood gap’ in the food-water nexus will become increasingly problematic as seafood consumption is growing globally and aquaculture is one of the fastest growing animal food sectors in the world [15]. This demands judicious approaches in the use of water.

1.3. Characteristics of seafood industry wastewater

The wastewater discharged by the seafood industry can be divided into two categories: high volume and low strength, and, low volume and high strength. The former includes discharges from aquaculture farms, water used for unloading, fluming, and wash down water, while the latter includes wastewater after different processing operations. The processing plant effluents can contain significant quantity of organic matter in the form of total suspended solids (TSS), fats, oils, and grease (FOG), excess nutrients (nitrogen and phosphorus), and proteins [12]. The proteins encompass myofibrillar proteins, collagen, gelatin, enzymes, soluble peptides and volatile amines, which remain in soluble, colloidal or particulate forms. The TSS in the effluent sediments over time, clog pumps, and other equipments during their handling. FOG consists of the most objectionable components of the effluents, the decomposition of which generates unpleasant odors. Fish processing effluents generally are saline, as sodium chloride is frequently added to remove slime, blood and other substances and to improve the cleaning efficiency as well as water removal. Besides, detergents and disinfectants used during cleaning may also be present [16]. The wastewater from the canning of tuna has BOD, TSS and FOG of 7–20 mg/L, 4–17 mg/L, and

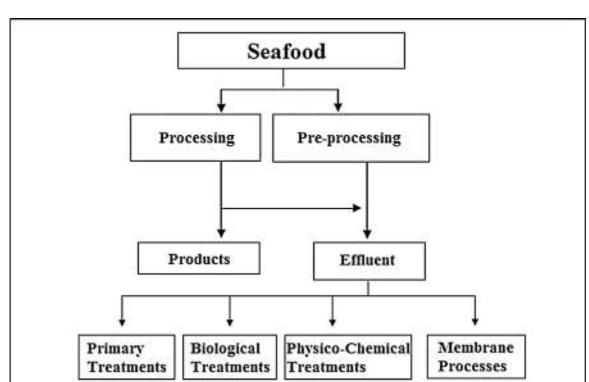

Fig. 1. Effluent generation during seafood processing.

Table 2
Approximate volumes of wastewater generated by seafood processing operations.

Process	Wastewater volume (m^3)
White fish filleting	5–11*
Oily fish filleting	5–8*
Grading	0.3–0.4
Handling and storage of fish	10–12
Scaling of white fish	10–15
Oily fish skinning	0.2–0.9
Marine finfish	14.0
Skinning of knobbed fish	17.0*
Unloading fish for canning	2.0–5.0
Precooking of fish to be canned	0.07–0.27
Canning of sardine	9 (15*)
Sterilization of cans	3.0–7.0
Frozen fish thawing	5.0
Filleting of un-gutted oily fish	1–2*
Processing of tuna	3.0**
Shrimp freezing	7.0
Blue crab, mechanized plant	29–44

The values are for one ton of raw material.
Source: References [9]; *[12]; and **[82].

2–13 mg/L, respectively [12]. Condensate and juices, the by-products of tuna canning industry, are rich in nitrogenous compounds, particularly, glutamic acid, and fat [17]. Other compounds include oil, pigments, and, minerals such as phosphate, sodium, calcium, chloride, sulfate and other salts. Effluents from cooking of snow crab contained significant amounts TSS [18]. The stickwater from processing of fish species including pollock, cod and salmon had approximately 6 % proteins, and 0.6–13.9 % ash with calcium and potassium at 0 to 0.1 %, and 1.7–2.8 %, respectively [19]. Marination of fresh and frozen herring in brine containing 6–10 % sodium chloride and 3–4 % acetic acid for 7 days resulted in the absorption of 33 % salt and 60 % acetic acid. The post-production brine had 6.4–7.3 % dry matter, 1.4–2.6 % protein and 0.5–2.7 % fat [20]. Leucine, glutamic acid and glutamine were the dominating amino acids in the proteins, while calcium and magnesium were the main minerals in herring industry processing waters, while long chain n-3 PUFA represented up to 45 % of total fatty acids [21]. It was observed that as much as 15 % of the herring protein coming into the industry leached out into cooking waters and was treated as waste. The effluents may also contain significant levels of microorganisms including pathogens, which may cause diseases to wild stocks or aquatic operators [13]. Sivaraman et al. [22] observed that effluents from fish processing industries may contain Enterobacteriaceae, *Staphylococcus aureus*, fecal Streptococci and other microorganisms in appreciable amounts. During summer, pathogenic microorganisms can be higher. Being rich in nutrients, improperly stored effluent supports rapid bacterial growth associated with obnoxious smell. Moreover, the possible presence of antibiotic resistant organisms may pose threat to public health safety

The effluent generated from processes such as canning and marination invariably contain 2–5 % (w/v) salt or sometimes, more [23]. Presence appreciable levels of salt can cause stress to microorganisms and can affect the treatment efficiency. The presence of nitrogen and phosphorus is among the most prevalent causes of water quality impairment, which make the effluents high in biochemical oxygen demand (BOD) and chemical oxygen demand (COD) values. These values are measures of substances that have an unfavorable influence on the oxygen balance [24]. BOD values are measured by the oxygen required for the oxidation of organic matter by the aerobic metabolism of the microbial flora. BOD is measured by diluting the wastewater with a nutrient (mineral salts) solution, saturated with air, storing the dilution in airtight bottles, and measuring the dissolved oxygen at periodic intervals. BOD is monitored for a five-day period and reported as BOD_5. Due to the inconvenience of BOD_5 determination, COD is also measured by chemical oxidation by permagnate or dichromate. The COD of an effluent is usually higher than the BOD_5 because the number of compounds that can be chemically oxidized is greater than those that can be degraded biologically. BOD and COD values are generally measured as mg/L effluent produced from processing of one kg of fish [24].

The juices released during cooking of fishery products contain typically 10–20 g COD/L [25]. Effluent from tuna processing had 1,570 mg/L suspended matter, a COD of 11 100 mg/L and a BOD of 6,600 mg/L [26]. The effluents from a Canadian seafood processing plant, which processes flat fish and salmon, had values (mg/L), 179–276 for BOD_5, 458–1717 for COD, 27.2–1201 for TSS; and, 1.5–12.9 for NH_3-N [27]. Cooking of jumbo squid (*Dosidicus gigas*) mantle muscle under simulating industrial procedures gave effluent having COD and BOD_5 varying from 27.4–118.5 and 11.3–26.7 g/L, respectively. The effluent consisted of 1 % total solids, 75 % of which represented crude protein. [28]. Table 3 gives BOD, COD, BOD to COD ratio, TSS and FOG values of some of seafood industry effluents. The success of effluent treatment is often related to BOD/COD ratio, lower the ratio, higher the biodegradability of organic nutrients. Raquel et al., [29] observed that effluents from a seafood canning unit, having a BOD_5/COD ratio of less than one exhibited a high biodegradability.

1.4. Seafood-associated environmental hazards

Food production has been recognized to cause between 20–30 % of total environmental hazards [30]. The seafood processing sector contributes serious organic pollution loads and high salinity to receiving waters The chemical parameters such as pH; BOD_5; the COD, ammoniacal nitrogen (NH_3-N), nitrate nitrogen (NO_3 -N), and phosphorus; and the physical parameters including odor, temperature, and color are considered important pollutant parameters of seafood effluents. The effluents may also contain portions of solid discards. The industry invariably dumps enormous amounts of solid wastes including by-catch in the sea or nearby land. Fish wastes degrade rapidly in warm temperatures. Anaerobic decomposition of organic matter leads to breakdown of proteins and other nitrogenous compounds, releasing carbon dioxide, methane, amines, diamines, ammonia (NH_3) and hydrogen sulphide (H_2S). These gases contribute to climate changes and rise in ambient temperatures. Organic matter in the water may alter the color and odor of water and provide nutrients to microbial growth. Obnoxious odor associated with fish spoilage and also the odor emanated from drying, smoking and other heat processes are often major causes of air pollution and induce stress, nausea or sickness to the general public [8].

The gases formed during putrefaction of the discards contaminate and alter the receiving water body environments and reduce the level of dissolved oxygen. In addition, the high levels of NH_3, chlorine, nitrogen and other gases, phosphorus based nutrients, and also detergents and disinfectants used for cleaning the processing facilities, may be toxic, posing threat to environmental safety and aquatic life [31]. For instance, the raw effluents from processing of salmon have shown acute toxicity [32]. Discharge of untreated seafood effluents to soil significantly enhances moisture, salinity, electrical conductivity, and inorganic carbon. The effluents also had an impact on prokaryotic organisms in the soil [33]. Life cycle assessment (LCA) is a tool traditionally used to elucidate the environmental and ecological impacts of products or processes. A LCA based study on the environmental impacts showed that fish processing contributed to 0.079 kg SO_2- eq (equivalent) acidification, 9.66 kg CO_2-eq. climate change, 0.02 kg PO_4-eq. eutrophication-generic, 0,17 kg 1.4 DCB-eq. human toxicity, and 0.0015 kg ethylene-eq. photochemical oxidation [34].

The environmental concerns associated with disposal of fish wastes into ocean waters include reduced oxygen levels in the seawaters at the ocean bottom; burial or smothering of living organisms; and introduction of disease or non-native and invasive species to the ecosystem of the sea floor [35]. During rainy season, seepage of water through the landfill dump causes additional problems. Nutrients, suspended solids, disinfectants and possible coliform bacteria from the seafood industry

Table 3
Characteristics of seafood processing effluents.

Seafood/ Operations	BOD	COD	Biodegradability Index (BOD/COD)	TSS	FOG	References
Canning of fish	52	116	0.45	5	6,160	[9].
Canning of tuna	15	–		4–17	2–13	[12]
Shrimp freezing	130	–		210	17	[12]
Shrimp canning	120	–		54	42	[12]
Salmon	45–51			20–25	5–7	[12]
Catfish	6–9	–		NA	4–6	[12]
White fish filleting	35	50	0.7	–	–	[12]
Fish canning	52	116	0.45			[12]
Oily fish filleting	50	85	0.69	–	–	[9]
Flatfish, salmon	179–276	458–1717	0.16 to 0.37	27 to 120	–	[27]
Squid cooking juice	11.3–26.7*	27.4–118.5	0.23 to 0.41	–	–	[28]
Tuna	700	1,600	0.44	–	–	[83]
Tuna	6600	11,000	0.60	1570	1450	[26]
Fish, general	–	–			1500	[70]
Aquaculture of Pangasius	740	1020	0.73	2050		[31]
Fish, general	–	–		2200		[23]
Fish processing	3,250	13,180	0.25	–	–	[62]
Salmon farming	–	60 to74**		82 to 102**	–	[41]
Fishmeal	30,000	50,000	0.60	30,000	–	[83]

Values are given in mg/L **, g/L.

effluents affect coastal water quality and hence human life, particularly in the coastal regions [36]. Hypoxia is a condition of low oxygen in the water than can kill fish and other aquatic animals. High level of BOD may cause hypoxia in a receiving environment, leading to anoxia, a condition characterized by an absence of oxygen supply to an organ or a tissue of living organisms. The high levels of nitrogen, phosphorus and FOG may lead to shortage of drinking water, eutrophication (growth of unwanted biota), biotic depletion, algal blooms, habitat destruction, water acidification, disease outbreaks and possible extensive siltation of corals [11] [37] [38].

1.4.1. *Environmental hazards of aquaculture*

The rapid growth of aquaculture has raised questions concerning its environmental sustainability [11]. It is recognized that for normal breathing of the fish and hence their good health CO_2 levels should be maintained at levels below 30 mg/L. During the course of farming operations, the concentrations of gases such as NH_3 and CO_2 increase affecting the survival rate of the fish population. High CO_2 also decreases the pH and enhances the toxicity. Besides, periodically discharged water from farms is often rich in organic materials, including unconsumed feed, fecal matter, shellfish drop-off, and other materials. For healthy aquaculture operations, routine environmental assessment incorporating impacts distinctive to farming is necessary. A study employing standardized methods making use of LCA with respect to 75 seafood species-production systems made estimates of their impacts on six environmental parameters, namely, eutrophication, acidification, climate change, cumulative energy demand, land occupation and biotic depletion The data showed a positive relationship between overall production levels and environmental impacts. Inland pond culture had the greatest impact. Of the different finfish species farmed, carps and eel productions were more environmentally demanding, carp culture significantly contributing to eutrophication. Bivalves and seaweeds had low influence on the environment and even reduced eutrophication, as revealed by LCA analysis [11]. Intensive production systems of species such as rainbow trout in fresh water, sea-bass in sea cages, and turbot in an inland re-circulating system released substantial amounts of nitrogen and phosphorus that can be highly responsible for eutrophication; the bass cage system exhibiting the maximum potential. In the trout and sea-bass systems, feed conversion ratio was the major contributor to climate change and acidification impacts [39]. Effluents from Pacific white shrimp farm influenced density and type of plankton. As the nutrient concentrations increased with the farming period, diatom and Copepoda were replaced by cyanobacteria, protozoan, and rotifers [40]. Chemicals used in shrimp farming, such as antibiotics, organotin compounds, copper compounds, and others leave persistent, toxic residues in the waters. Effluents from salmon farm were characterized by 8–10 % total solids, 60–74 g/L COD, and, 10–15 /L of sodium [41]. Processing by freezing of farmed Pangasius released effluents having values of BOD, 740; COD, 1020; TSS, 2050; phosphorus, 27; and nitrogen, 106 [31]. In the light of the above data, it is imperative that fisheries governance and development should take necessary steps for the protection of the environment, conservation of resources, biodiversity, among others to achieve food security, nutrition and trade [4]. The following discussion will concentrate on the regulatory standards required for treated effluents, various processes for treatments and finally the potentials of algal biotechnology for effluent valorization.

2. Treatment of seafood industry effluents

2.1. *Regulatory requirements*

The global concerns regarding seafood-associated environmental pollution have attracted attention of many national and international regulatory agencies [10–12]. These agencies insist that the effluents are subjected to appropriate treatments so that they can be safely discharged without being responsible for undue hazards to the environment. The regulatory agencies have, therefore, framed directives and regulations to control the environmental impacts of commercial fish processing. These directives specify the quality of effluents and maximum allowable levels of pollutants that may be present in the effluents before discharge by the industry. Recent times have witnessed increasingly stringent standards, particularly with respect to BOD, COD and TSS values. The Environmental, Health and Safety (EHS) Guidelines proposed by the International Finance Corporation of the World Bank are technical reference documents with industry specific examples of Good International Industry Practices (GIIP). Community health and safety impacts of fish processing projects, discussed in the General EHS Guidelines, relate to processing fish and shellfish originating from sea, fresh water or by farming operations [42]. Every country has its own requirements for effluent quality. In the US the Environmental Protection Agency (EPA) promulgated the Seafood Processing Effluent Guidelines and Standards in 1974 and 1975. The Guidelines cover wastewater discharges from facilities that process seafood. The Guidelines and Standards are incorporated into NPDES (National Pollutant Discharge Elimination System) permits [43]. The U.S. Clean Water Act (CWA) stipulates zero discharge of pollutants into the US waters and has also fixed quality standards for surface waters [36]. In the US, however, the state governments generally do not impose wastewater treatment technologies or equipments on the processor (Isdmond, A., personal communication, 2020). In Canada, the Fisheries and Oceans Canada is the federal lead for safeguarding waters and managing fisheries, oceans and freshwater resources to ensure healthy and sustainable aquatic ecosystems (https://www.dfo-mpo.gc.ca/index-eng.htm, accessed July 5, 2020). The EU Commission recommends pasteurization at 70 °C for 60 min to inactivate microorganisms that may be present in the treated waste before their discharge to avoid their environmental impacts [44]. In India, the Environment Protection Agency of the Government of India has prescribed maximum values (mg/L) of 10, 750, 750, 1, 10, and 25 for reactive phosphorus, chloride, sulfate, ammonia nitrogen, nitrate and total Kjeldahl nitrogen, respectively, for food industry effluents prior to their discharge [45].Recently, Shoushtarian and Negahban-Azar [46] made detailed examinations of monitoring parameters of water quality and treatment processes promulgated by as many as 70 regulatory agencies including the US EPA, International Organization for Standardization (ISO), Food and Agriculture Organization, World Health Organization, the individual States of the US, Canada, European Commission, and those of several other countries. These studies concluded that the many regulations and guidelines, although mainly human-health centered, are insufficient to control some of the potentially dangerous and emerging pollutants. Some of the important water quality parameters such as certain pathogens, heavy metals, and salinity are included only in a small group of regulations and guidelines. Besides, there are also large discrepancies in country-wise guidelines when compared with each other. Specific treatment processes have been mentioned only in some of the regulations and guidelines [46].

Aquaculture, being a potential cause of environmental pollution, has attracted attention of regulatory agencies, who have fixed standards for effluents released during farming of finfish, crustaceans and mollusks. The Global Aquaculture Authority stipulates parameters for farm effluents. These include pH, 6 to 9; TSS, 50 mg/L or less, soluble phosphorus, <5 mg/L; total NH_3-N, <5 mg/L BOD_5, <30; FOG, <7 mg, and salinity, <1ppt [47]. In the US, the National Pollutant Discharge Elimination System (NPDES) helps the US EPA to identify ways to decrease unnecessary outflows from aquaculture systems on a case-by-case basis, particularly in larger farming operations [37]. The Aquaculture Activities Regulations (AAR) under the Fisheries Act, Canada, requires operators of marine finfish farms to report on the results of benthic monitoring in accordance with the standards developed by the organization. For finfish farms located over muddy or soft sediments, free sulfide is measured, which is used as an indicator of oxygen in the sediment that influences survival of different microbial species in the sediment. Sometimes visual periodical monitoring for the presence of Beggiatoa sp. or marine worms (class Polychaeta) are used as biomarkers of aquaculture impact (https://www.dfo-mpo.gc.ca/aquaculture/management-gestion/aar-raa-eng.htm, accessed, August 7, 2020). Table 5 gives discharge limits proposed for fishery effluents

2.2. Treatment procedures

Increasingly stringent standards required by regulatory agencies, particularly in terms of BOD, COD and TSS values have resulted in innovative treatment procedures for effluent treatments. The selection of appropriate treatment depends essentially on the type of the effluent, its quality characteristics (BOD, COD, TSS, FOG, the BOD to COD ratio) and influent volume. The challenges of effluent treatment are linked to sustainable seafood processing, clean air and water conservation [48]

The effluents are initially subjected to primary treatments such as screening and sedimentation Screening removes large particles (usually 0.7 mm or larger particles including bones and shells). Pre-treatment of the wastewater with 0.8 mm sieve and a two stage flotation reduced the nitrogen load [14]. FOG can result in clogging, hindrance to sedimentation due to the formation of hydrophobic sludge along with lipids A decanter, used as physical pre-treatment unit, removed fats and allowed elimination of 40 % suspended solids [26]. Sludge removal system ensures rapid removal of settled sludge with minimal sludge blanket disturbance [16]. Methods for treatment of fish wastewater may be grouped into physic-chemical, biological, membrane and other processes. These are briefly discussed below:

2.2.1. Physicochemical methods

Physicochemical methods available for treatment include neutralization (pH adjustment), coagulation, flocculation, chemical precipitation, chemical oxidation such as ozonation, UV irradiation, halogenation, electrolysis, polymeric adsorption, granular activated carbon adsorption, dissolved air flotation (DAF), sludge treatments, and others [49]. Bactericidal agents such as chlorine, ozone (O_3) and UV irradiation cause disinfection of the effluents. Ozonation or UV irradiation coupled with hydrogen peroxide (H_2O_2) treatment lead to more oxygen rich, less hydrophobic and more biodegradable, effluent-rich organic material [50] Coagulation, flocculation, flotation and emulsification are effective methods to reduce FOG and BOD values. Adjustments of the effluents to appropriate pH values remove charges on the colloidal particles, allowing them to settle during coagulation and flocculation. Coagulation of proteins can be effected by the addition of organic acids, non-toxic cationic or anionic polyelectrolytes to the suspension. Chitin and chitosan from wastes of shellfish can be used as flocculation agents. The distinctive advantages of these compounds, particularly chitosan, include their availability, biocompatibility, biodegradability, non-toxicity, antimicrobial properties, ability to chelate heavy metal ions, gel forming properties, ease of chemical modification, and high affinity to proteins [51]. Upstream flocculation using as low as 25–45 mg of food grade chitosan or complexes of chitosan with polysaccharides such as alginate, pectin and carrageenan per liter effluent have removed up to 86 % proteins from shrimp process waters, surimi washwater and fishmeal stickwater. The settled biomass is collected by suitable means such as membrane filtration and centrifugation [52,53]. Flocculation and sedimentation of a protein-rich biomass from shrimp (*Pandalus borealis*) boiling water by food grade polysaccharides (carrageenan, alginate and carboxymethyl cellulose) as flocculants have been reported. recently [54]. Treatment of effluents with 150 mg chitosan per L at pH 6.0 reduced suspended solids by 97 %. The proximate composition of the coagulated solids was 27 % protein, 51.7 % fat and 3.3 % ash. The treatment resulted in 45 % reduction in COD [55].

Dissolved air flotation (DAF) systems are popular to reduce sedimentation time for suspended solids, BOD, and FOG, within a few min of treatment. DAF involves injection of air under pressure into a recycle stream of clarified effluent. DAF is usually operated at pH 5.0 to reduce protein solubility. This recycle stream is then combined and mixed with incoming wastewater in an internal contact chamber where the dissolved air comes out of solution in the form of micron-sized bubbles that attach to the contaminants. The bubbles and contaminants rise to the surface and form a floating bed of material that is removed by a surface skimmer. DAF may also be coupled with additional treatment facilities such as filtration, ion exchange, granular activated carbon adsorption, electro-coagulation, biological treatment processes, among others to improve discharge standards for the treated water [16]. DAF in combination with coagulants and flocculants can remove up to 50 % of TSS and 80 % of FOG. DAF system can be started and shut down easily to accommodate fluctuations in seafood processing [49]. Application of DAF treatment partially reduced acute toxicity of finfish effluents [32].

2.2.2. Biological treatments

Biological treatments use aerobic, anaerobic or facultative microorganisms including bacteria, fungi, and protozoa to degrade organic matter present in the effluents. The common aerobic processes are activated sludge systems, aerobic lagoons, trickling filters and rotating disc contactors. In the commonly used activated sludge treatment system, the sludge consisting of an optimized, mixed flora of microorganisms degrades the organic materials in the wastewater in the presence of excess dissolved oxygen and nutrients including nitrogenous compounds, so that no further oxygen demand is exerted by them. The treatment is highly useful to reduce soluble BOD_5, fats and nutrients. Aerobic treatment methods are however, energy-intensive [24,56]. Anaerobic digestion (AD) has been identified as a potential green technology. The process involves (i) initial hydrolysis, liquefaction, and fermentation of the material in the absence of molecular oxygen, (ii) formation of hydrogen and acetic acid, and, finally, (iii) methane is produced from the reduction of carbon dioxide and acetate by hydrogen. The process parameters include hydraulic retention time (HRT), organic loading rate (OLR), carbon to nitrogen ratio, free NH_3 concentration, pH, temperature, mixing, and pretreatment. Heat pasteurization may be used to inactivate pathogens in AD plants. Anaerobic systems can be modified as per requirements, which include fluidized bed reactor (FBR), anaerobic filter (AF), up-flow anaerobic sludge blanket reactor (UASBR), anaerobic biochemical reactor (ABR), anaerobic fluidized bed reactor (AFBR), up-flow anaerobic sludge fixed-film (UASFF) reactor, anaerobic baffled bioreactor (ABR), modified anaerobic baffled bioreactor (MABB), continuous stirred tank reactor (CSTR), expanded granular sludge bed reactor (EGSBR), membrane anaerobic system (MAS), and the ultrasonic-assisted membrane anaerobic system (UAMAS). The advantages of anaerobic systems are low sludge yield, higher organic loading, production of methane-rich biogas, good process stability, lower nutrient requirements and lower operating costs [9,44,57]. Anaerobic processes such as Ultrasonic-assisted Membrane Anaerobic System (UASBR), AF and AFBR can achieve 80–90% removal of organic compounds, associated with gas production [58]

Biological treatments, briefly mentioned above, have been employed for seafood processing wastewater. Aerobic processes are suitable for removal of organics from seafood wastewater. A laboratory-scale aerobic continuous bioreactor treated high saline fish processing wastewater containing 2.5 % salt. An optimum biomass yield was obtained after 8 days of treatment; the treated wastewater was free of offensive odor. The system can be used as a treatment option in small scale fish processing industries [23]. Choudhury et al. [56] observed that anaerobic treatment followed by aerobic treatment is ideal for the treatment of fish effluents. They also reported that up-flow anaerobic sludge blanket reactor (UASBR), anaerobic filter (AF) and anaerobic fluidized bed reactor (AFBR) can produce biogas together with up to 90 % removal of organic material. Corsino et al. [59] used an AD system that sustained simultaneous nitritation–denitritation at salinities up to 5%. Both COD and BOD removal efficiencies were over 90 %. An activated sludge process with partial nitrification in combination with anaerobic ammonium oxidation process was developed for the treatment of seafood processing wastewater. At pH value of 7.7–8.2, and dissolved oxygen of 0.5 to 0.9 mg /L, the treatment resulted in 85 % reduction of COD and near complete removal of ammonium and nitrite [60].

Mesophilic anaerobic treatment of sludge from effluents of salmon farming in stirred tank reactors (CSTR) at 35 °C stabilized COD between 36–55% with methane yields between 0.114 and 0.184 L/g. Dilution of the sludge with equal volumes of tap water gave a stable process without salt-induced inhibition [41]. Bio-electrochemical process is a green technique to produce electricity from wastewater. Jayashree et al. [61] treated seafood processing waste in an up-flow microbial fuel cell (MFC). At an organic loading rate of 0.6 g per day, the MFC accomplished up to 95 % reduction of COD. Recently, a new technology, hydrodynamic cavitation, was used to treat fish processing wastewater. In the process, an orifice plate was used in the reactor to generate a cavitation effect. The intensification of this technique was carried out with the help of H_2O_2 and titanium oxide. At 15 g/L of H_2O_2 about 70 % reduction of COD in 120 min of treatment was observed. The treatment increased biodegradability of the effluent [62].

2.2.3. Membrane processes

Membrane-based separation processes (MBSPs) have emerged as novel tools to efficiently separate organic matter. MBSPs can also remove endotoxins, bacteria, viruses, and other pathogens from biowastes. Some of the major MBSPs are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), microfiltration (MF), reverse osmosis (RO), and forward osmosis (FO). MF, UF, NF, RO, and FO methods as well as hybrid technologies have good prospects to provide clean water from wastewater streams at an affordable cost with minimum energy requirement. There are potentials for use of NF in water softening, wastewater treatment, vegetable oil and other industries [63]. Recently, hybrid RO/NF membranes have been successfully used for sewage and industrial wastewater treatments. FO is becoming more popular for wastewater treatment because it is less vulnerable to fouling, operates at normal pressure and utilizes osmotic gradients created by the high concentration solution across the membrane. Nano-materials-based treatments, however, are yet to reach full commercial potential due to current unreliability in terms of sensitivity and selectivity, higher cost, and field-level issues during operation. A wide framework of integrated membrane technology and its advantages in wastewater treatment, environmental benefits and recovery of high value compounds have been pointed out recently [43,64–66].

Membrane processes have been used for treatment of seafood processing wastewater. UF is plausible to recover significant quantities of proteins. Up to 96 % of the proteins of shrimp shell were dissolved by incubating them in dilute alkali for 2 h at 45 °C at a solid to solvent ratio of 1:2 (w/v). The dissolved proteins were recovered by UF [67]. UF recovered proteins and lipids up to 97 % and 90 %, respectively, from process waters of cuttlefish, shrimp, sardine, surimi and fishmeal industries. However, due to the high concentration of suspended matter in these effluents, it is advisable microfiltration as a pre-treatment prior to UF to reduce the protein contents in the effluents. Fouling of the membrane can be controlled by caustic washing [68]. Protein and fat were removed from brine used for herring marination employing MF (polypropylene bag, 25 μm) and UF (ceramic membrane) [21]. The highest rejection coefficients for protein and fat contents were obtained by membrane having150 kDa cut-off. Gringer et al. [69] reported that UF of brine from herring processing through ceramic membrane reduced COD, TSS, and nitrogen contents. Retention values of up to 42 % COD, and 95 % TSS were recorded.

2.2.4. Combination processes

In most situations, a single procedure may not be effective for successful treatment of a particular effluent. Combinations of different processes can provide improved efficiency that may exhibit synergistic benefits with respect of quality, yield and costs. For example, an integrated system, which included a decanter to remove the fats and TSS, an anaerobic digester and an activated sludge aerated bio-reactor removed up to 95 % of the COD of tuna processing effluents with minimal energy consumption and sludge production, while individual processes were only partially successful to reduce the COD [26]. Supplementation of low quantities (0.2 %, w/v) of fungal lipase in up-flow anaerobic sludge blanket bioreactor (ASBR) reduced 91 % of COD of seafood wastewater containing 1500 mg oil and grease per L [70]. Recently, Mannacharaju et al. [71] observed that baffled moving bed biofilm reactor (BMBBR), up-flow anaerobic sludge blanket reactor (UASBR), fluidized immobilized cell carbon oxidation reactor (FICCOR), and chemoautotrophic activated carbon oxidation reactor (CAACOR) in series almost completely removed COD, proteins, lipids and FOG from fish processing wastewater

Membrane processes can be integrated with conventional biological methods for better efficiency. An anaerobic membrane bioreactor,which has the advantages of AD and membrane filtration can yield effluents of high quality [72]. Membrane filtration of effluents initially treated to coagulation–flocculation–sedimentation, reclaimed water for reuse in industrial cooling systems [73]. Growth of salt tolerant bacteria in fish processing wastewater containing 5.5 % salt followed by treatment of the bacteria-grown effluent in a membrane bioreactor (MBR) reduced COD up to 99 %. Nevertheless, salinity with increasing organic loading rate aggravated fouling that required more cleaning for a membrane in MBR [74]. Large amounts of biomass are currently lost per ton of processed herring, equivalent to ~9.2 kg proteins and ~4.1 kg fatty acids. Electro-flocculation followed by UF in series recovered up to 80 % proteins and fatty acids from the brine [69]. An economical membrane process for treatment of high saline fish processing effluents makes use of photosynthetic bacteria and membrane photo-bioreactor in combination with heterogeneous. Fenton fluidized bed to remove non-biodegradable organic compounds. The membrane, fabricated by chemical grafting of nano-sheets exhibited enhanced hydrophilicity, better permeability and flux recovery. The COD and NH_3-N removal efficiency of the system were 95 and 98 %, respectively [75]. Fish processing wastewater could be effectively treated in photo-bioreactors inoculated with microalgae from a lagoon containing aerobically treated swine slurry and with sludge from a membrane submerged bioreactor treating winery wastewater. The combination treatment reduced the hydraulic retention time from 10 to 5 days, with complete removal of NH_3-N together with up to 70 % reduction of COD and phosphate [76].

2.2.5. Treatment of aquaculture effluents

Sustainable aquaculture demands care to avoid the farm waters causing environmental hazards including loss of fish species and likely reduction of aquatic production [3,77]. Good practices need to be employed in pond construction, feed selection, proper feeding the fish/shellfish, erosion control, maintenance of moderate stocking densities, and the use of settling basins to improve the quality of effluents discharged [37]. Methods for removing waste within the aquaculture effluents include sedimentation, filtration, mechanical separation, chemical and biological treatments. The use of cleaner production technologies and the development of wastewater treatment plants could be applied to large farms and processing facilities to reduce water pollution [31]. Shrimp farmers need to reduce the use of chemicals and biological products to minimize risks to the environment and human health [78]. A recent, cost-effective, electrochemical oxidation (EO) process has potential to treat marine aquaculture wastewater for removal of multiple pollutants to meet regulatory requirements. The process makes uses flow of aquaculture effluents through EO reactor, when oxidation removes up to 90 % of NH_3-N and nitrate nitrogen, phosphate and COD. The treatment enhances formation rate of chlorine and degradation rate of pollutants. The EO process has good bactericidal effect, which also removed antibiotics such as sulfadimidine and norfloxacin [79]. Wet land systems are popular for treatment of wastewaters from seafood industry. There are two major types of wetlands, free water surface and surface flow. In both the systems BOD is decreased as organics are consumed by microorganisms; and ammonia is microbiologically oxidized near the water surface. The resulting nitrate can be removed in anoxic metabolism deeper in the wetland. Three emergent plant species were planted in surface flow wetland, which were fed with seafood wastewater diluted with equal amounts of fresh water. Growth of the plants was associated with uptake of 1.4–2.3 g nitrogen/m^2/d and 0.17 to 0.29 g phosphorus/m^2/d together with removal of BOD_5, TSS, total nitrogen and phosphate, at average maximum removal efficiencies of 99, 90, 92 and 77 %, respectively. Treatment for 5 day resulted in meeting quality standards required for the discharged water [80]. Potential climate change and acidification impacts of aquaculture can be largely reduced by improved energy efficiency throughout production and value chain [39] It has been generally noted that compared with post-harvest processing operations, aquaculture is less responsible for environmental pollution as the farm effluents generally contain relatively lower nutrient loads [81]. Nevertheless, it is important that for aquaculture to remain sustainable future growth should not adversely affect natural biodiversity or place unacceptable demand on ecology [11], Apart from effluent treatment options, ideally, an effective and efficient approach for safe aquaculture would be to avoid pollution at the source. This requires cleaner production methods based on the principles of green and sustainable chemistry in such a way that treatment systems and water environments cope successfully with the challenge of micro-pollutants globally [36]. Table 4 summarizes the different types of treatment options for wastewaters generated during finfish and shellfish processing and salient benefits of each treatment

The above discussion suggests various treatment options for seafood effluents. The success of treatment may differ depending upon the nature of effluent and the process employed. For example, aquaculture effluents may require milder treatments against effluents released from fish canning operations. Physico-chemical methods can have only limited efficiency. Flocculation by food-grade polysaccharides is more feasible. There is potential to use chitin and chitossan for flocculation, considering their seafood origin, biocompatibility, user-friendly nature, and efficiency at low concentrations. DAF is a plausible technology.

Table 4
Some treatments for seafood processing wastewater and their benefits.

Process	Salient benefits	References
Dissolved air flotation (DAF)	Major treatment process	[49]
Flocculation of effluents of shrimp, fishmeal and surimi processing by polysaccharides	Recovered ≤86 % protein	[54,52]
Combo of sieving flotation and activated sludge	Removed biological nitrogen	[14]
Integrated physico-chemical and biological processes	Reduced COD and yielded gas Good treatment	[152]
Activated sludge, rotating biological contactor, trickling filter, lagoons	Better efficiency	[56].
Up-flow microbial fuel cell (MFC)	Removal of COD with power	[61]
Aerobic granular sludge(AGS) for fish canning wastewater having salt up to 5%	AGS significantly removed. COD	[59]
Aerobic laboratory-scale bioreactor for saline waste water	Optimum biomass removal in 8-day HRT	[23]
Bioreactors in series	Removed COD up to 99 %	[71]
Anaerobic digestion (AD) with lipase	Enhanced effluent quality	[70]
Waste-to-energy technology (DAF, AD, nitrification-denitrification, clarification)	Reduced treatment cost by 50 %, 40 % energy supply	[82]
DAF treatment of effluent	Reduced toxicity	[32]
A 'GEM' system with screens, DAF, coagulation, flocculation, dechlorination	Removed COD and FOG up to 99%	[83].
Activated sludge process, partial denitri-fication system, anaerobic NH_4^+ oxidation	Near complete removal of ammonium and nitrite	[60]
Integrated system of AD and activated sludge aerated bio-reactor	Removed up to 95 % of the COD of tuna processing water	[26]
Continuous stirred-tank reactor (CSTR) or membrane bioreactor (MBR), salt-tolerant bacteria	MBR was better than CSTR. Removed 98 % organic carbon	[74]
Seaweed-associated bacteria	Bacterial consortia treatment option	[146]
Photosynthetic bacteria-membrane photo-bioreactor (MPBR) with Fenton fluidized bed reactor	Successful in seafood wastewater treatment.	[75]
Combination treatments	Reduced HRT to 5 days, removal of NH_3-N and 70% COD	[76]
Growth of *R.sulfidophilum in* settled undiluted and non-sterilized sardine effluent	Reduced COD	[140]
Cultivation of *Chlorella* sp. in aerated effluent	Treatment associated with algal biomass production	[141] [135]
Coupling of UF and enzyme treatment	Nutritive protein product	[104]
Hydrodynamic cavitational reactor with biodegradability improvement	Up to 71 % reduction in COD in presence of H_2O_2	[62]
Fenton reaction step after an activated sludge biological treatment	Treated organic matter of fish canning wastewaters	[153]

Table 5
Discharge limits for BOD_5, TSS and FOG) for some fishery effluents.

Seafood	BOD_5		TSS			FOG		
	EPA	WB	EPA	WB	Wang[a]	EPA	WB	Wang[a]
Tuna	20.0	2.2	3.3	2.2	–	2.1	0.27	–
Salmon	2.7	11	26	2.8	26	11	2.8	11
Other finfish	1.2	4.7	3.1–3.6	4.0	–	1.3–43	0.85	–
Crabs	0.3–10.0	3.6	2.2–19	3.3	–	0.6–1.8	1.1	
King crab, Sea cucumbers, Snails, Skates	–	–	–	–	3.9	–	–	0.42
Flounder, Arrowtooth, Rockfish, Halibut, Red snapper, Pacific cod	–	–	–	–	12	–	–	3.9
Salmon			1.6		26	0.19		11
Shrimp	63–155	52	110–320	22	210	17	4.6	19
Clams, oysters, canned	–	41	190	41	–	1.7	0.62	–
Bottom fish	–	–	1.9		12	0.56	–	3.9
Fishmeal/ waste Stream	3.9		7.0		3.7	1.4		1.4
Effluents from aquaculture	30 (COD, 100)		30		–	–		–
Seafood*	30		50		–	100		–
Seafood**	25		25		–	–		–

Monthly average values.
Source: References [1], [24], [43]l [a] [45]; *[49]; **Fisheries and Oceans, Canada; -, not given.

Biological treatments including the activated sludge treatment, however, may have limitations due to the presence of salt and potential high pollutant loadings. Variations in characteristics of seafood effluents require standardization of AD processes on a case by case basis for risk assessment. Hydrodynamic cavitation, although feasible, requirements of considerable amounts of hydrogen peroxide for its use can influence the costs. Membrane processes are novel cost-effective technologies. Their commercial level applications may take time. There is good scope for designing processes that combine biological treatments with membrane processes for resource recovery and energy production (see Section 3.0)

2.3. Examples of industrial scale effluent treatments

Industrial level treatments of seafood processing wastewater have been reported from some parts of the world to prevent effluent-related environmental hazards. These plants have been designed taking into considerations the type of raw materials, their seasonal or batch to batch variations, proximate composition and freshness. A few examples may be pointed out. An effluent treatment unit in Ecuador, operated by EUROFISH for the last few years, is attached to a plant that daily processes roughly about 200 tons of tuna. The challenges in installation of the treatment plant included a need to accommodate both existing operations and the intended expansion with a provision to increase effluent production from 600 to 1300 m^3/d and the high organic loading of the effluents, having a COD of about 8,000 mg/L. The treatment consisted of separation of effluent in the DAF system, further treatment of clarified water in a double nitrification-denitrification stage, anaerobic digestion of solids separated during the DAF process, and final clarification to ensure the treated wastewater meets regulatory requirements before it is discharged. Making use of approximately 1,300 m^3/d of methane generated by the plant as energy source, the waste-to-energy technology helped reduction of wastewater treatment costs by 50 % and energy consumption by 35–40 % [82]. A full scale experience of one of the largest fish-processing factories in Germany with a yearly production capacity of about 50,000 tons herring and a maximum daily wastewater discharge of 1,500 m^3 has been pointed out [14]. Another full scale treatment plant for seafood processing wastewater at the Ocean Gold Seafood plant, Westport, US, installed in collaboration with Clean Water Technology Inc. (www.cwt-global.com) has been in operation since 2004. The system included an underground equalization tank, rotating drum screens and DAF facilities. The plant was able to almost completely remove salinity and provide chlorination - dechlorination to remove fecal coliform. Novel polyacrylamide flocculants used in the process enabled TSS and FOG removal even at high salinity [83]. A biodegradation system to treat the discharged concentrated liquid effluents from a tuna-processing unit included a decanter, an anaerobic digester and an activated sludge aerated bio-reactor. The anaerobic system transformed 45 % of the dissolved COD into methane gas with a production of about 0.25 m^3 methane per kg of degraded COD. The aerated treatment unit achieved 85 % reduction of COD Achour et al. [26]. There is scope for incorporation of membrane processes in commercial treatment plants. Ceramic membranes made from silicon carbide have recently been certified for effluent treatment by the food industry [21].

2.4. Advantages of effluent treatment

There are three major advantages of treatment of seafood industry wastewater, namely, (i).alleviation of effluent-related environmental hazards, (ii) conservation of water, and, (iii) isolation of commercially valuable ingredients. Increasing demands for freshwater have encouraged use of treated water as a beneficial practice, especially in the agricultural sector, the largest water consumer worldwide. This appears possible with advancements in wastewater treatment technologies, which can now give water of almost any desired quality [84]. The potentials of seafood effluent treatments to improve water security, sustainability and resilience of water resources is much relevant in the face of the current scenario of global drinking water crisis [10,85]. The treated effluents from seafood sources, however, may not be directly used for seafood processing, essentially due to possible presence of unacceptable levels of BOD, microorganisms, and chlorine. Nevertheless, it can be used for landscape irrigation, and also to replenish ground water basin, depending upon its pH and BOD value (which needs to be ideally less than10 per L), contents of trace elements and free chlorine. Such water can also be used for irrigation. For surface irrigation, the sodium and chloride levels need to be less than 3 and 4 mg/L, respectively [46]. In a study conducted at six fish processing plants, water from the freezing tunnel and cooling chamber was recycled after subjecting it to disinfection. This reduced the total average water consumption of the processing unit by 11 % and, if the effluents from the cooling tower purges were also to be reused for other administrative ends, the savings could be as high as 22 % [85]. A case study related to water minimizing and recycling opportunities in anchovy industry showed that both environmental benefits and economic advantages were achievable through effluent treatment. The consumption of water required by the fish thawing and gutting processes could be reduced by 65 % and 77 %, respectively, leading to total water saving of 45 %, with an annual total water saving of about 29,000 m^3 [86]. A recent study showed that treatment of aquaculture wastewater with heterotrophic microorganisms reduced requirement for water replacement by as high as 82 % [87]. By adopting best available technology, water consumption and wastewater generation could be reduced to 7 m^3 per ton in the fish canning industry, with significant reductions in BOD, loads of nitrogen and phosphate together with reductions in energy consumption [12].

Cleaner production is defined as continuous application of an integrated preventive, environmental strategy applied to products, processes and service to reduce risks to humans and the environment [12]. It has been well recognized that cleaner production in seafood industry helps conservation of resources, reduction of wastes and elimination of toxic materials. Such measures in frozen fish installations helped reduction of up to 40 % wastes [88]. Imlementation of effluent treatment and recovery solutions are challenges facing the food processing industry including seafood industry, the success of which can satisfy the 'Water-Energy-Food –Nexus [89].

3. Resource recovery from effluents

Seafood processing discards including waste streams are rich in valuable ingredients having potential applications in food, pharmaceutical and allied industries. Besides environmental protection, valorization of fishery wastes can be a key factor in conservation of marine resources and cost reduction of product development. Sustainability of seafood processing demands that seafood solid discards as well as wastewater be recognized as resources of various ingredients, water and energy [84,86] Treatment options of food process effluents aimed to control environmental hazards also open up opportunities to recover valuable bio-compounds that can have interesting applications in nutrition, healthcare, pharmaceutical and other industries Whereas both valorisation process and waste treatments presented similar impacts, a significant benefit can be achieved through valorisation of fish by-products [90]. However, unlike the effluents, solid wastes have attracted more attention as resources for diverse high-value bioactive ingredients such as fish oils, proteins and peptides, collagen, gelatin, enzymes, chitin, and minerals [91–93] Isolations of these compounds have been facilitated by developments in green technology and biotechnology. Some of the plausible techniques include microwave, ultrasound, super-critical fluid extraction, enzyme extraction, fermentation-dependent extraction, membrane-filtration and other techniques [94,95]. The biorefinery approach, as discussed in Section 4, integrates biomass conversion processes to recover useful ingredients and also produce fuel that may lead to zero discharge of both solid wastes and effluents. The US EPA [96], which focuses on recycling resources apart from treating waste products, noted that the high levels of nitrogen and phosphorus in wastewater could be used as nutrient resources for farming. Holistic secondary processing of the effluents can help recovery of nutrients, re-usable water and energy ultimately leading to total utilization of the marine resources.

In general, the seafood wastewaters can be sources of four categories of ingredients, namely nitrogenous compounds, lipids and lipid-derived compounds, polysaccharides and minerals. As depicted in Fig. 2, these compounds can have diverse applications, which include their uses as (i) food ingredients, (ii) ingredients for agro-industry, and (iii) production of bio-energy. These aspects will be discussed.

3.1. Food ingredients

Many ingredients useful for the food industry can be made available from seafood industry effluents. For recovery of these ingredients it is highly preferable to use effluents fresh from the industry; since the longer the detention time of fishery effluents, the greater the BOD and COD with corresponding reduced recovery of good quality products. Methods for the recovery of various ingredients, their properties and applications are discussed below:

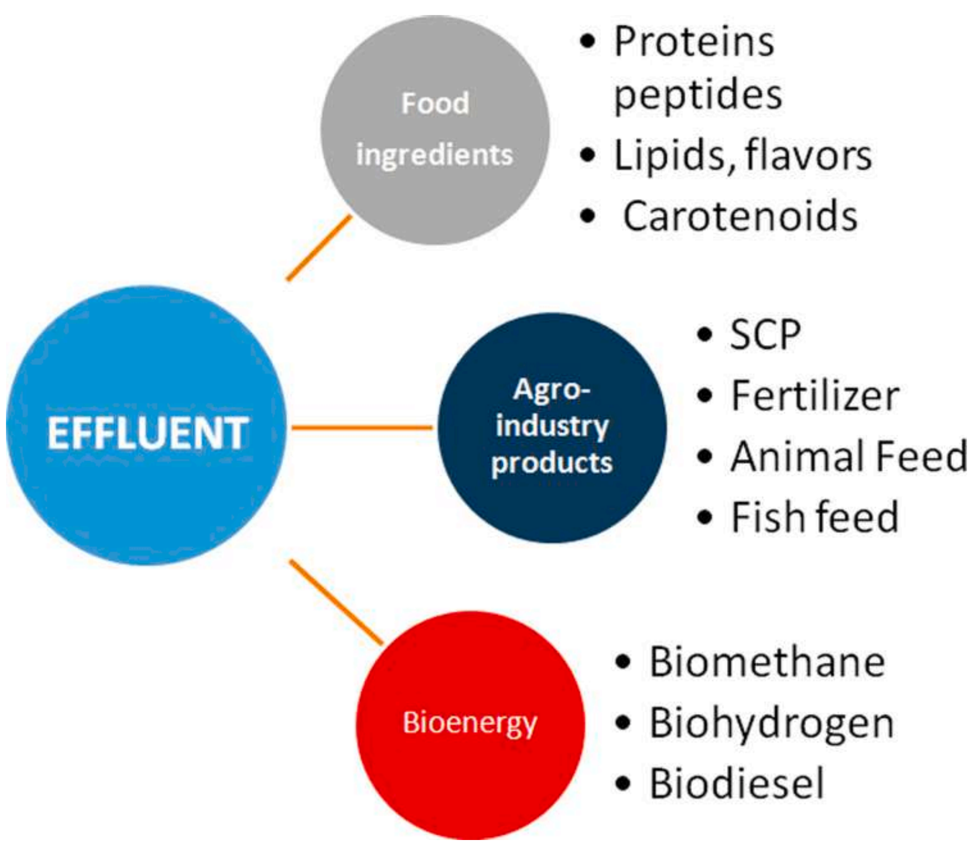

Fig. 2. Major classes of products recoverable from seafood industry effluents.

3.1.1. Proteins

Protein scarcity especially in third world countries is a major problem, associated with rise in demand for human and animal requirements. Therefore economically feasible processes are required to recover proteins from novel sources, which should meet food and environmental safety standards and also consumer acceptance [97]. Recovery of proteins (and also other bio-molecules) from effluents, however, can be difficult due to their relatively low concentrations. Recent developments in membrane technology coupled with flocculation can be highly beneficial in this respect. Upstream flocculation using food grade polysaccharides such as carrageenan, alginate and carboxy methylcellulose followed by dewatering techniques such as filtration, sedimentation and centrifugation recovered up to 77 % proteins from shrimp boiling waterrs [54]. Generation of large amounts of sludge during treatment of highly nitrogenous-wastewater contains significant amount of proteins, which can be recovered by initial disintegration of the sludge by alkali followed by ultra-sonication, precipitation and drying [98]. Membrane processes such as UF have been successful in recovering proteins from cuttlefish wastewater [99], alkali-treated shrimp shell [67], snow crab cooking effluents [18], surimi wash water [100], and. pre-salting brine used for marination of herring [21, 66].

Proteins isolated from seafood processing effluents invariably retain their natural properties. Isolates obtained by acid and alkali treatments of fishmeal stickwater from processing of sardine had a chemical composition of 76 ± 4 and 16.9 ± 3.1 % protein, 12 ± 6.2 and 2.9 ± 1.9 % fat, 7.9 ± 2 and 75.4 ± 2.6 % ash, respectively. The proteins were more water soluble than egg albumin and sodium caseinate. The isolates had also good Ca^{++}, Mg^{++}, P^{3-}, K^{+} and essential amino acid contents [101] Freeze-dried stickwater of pollock, cod and salmon contained 70.5–86% proteins and 10.6–13.9% ash, with variable amounts of lipids. Major proteins corresponded to molecular weights (kDa) of 198, 120, and 39, containing high levels of proline and hydroxyproline, indicative of connective tissues in the preparation. The proteins had more than 95 % digestibility and their calculated protein efficiency ratios from amino acid analysis data ranged from 1.6 to 1.8 [19]. A functional concentrate from an industrial shrimp cooking juice had 11.6 % protein and also 13.5 % crude fat and ash with predominance of Na ions [102].

Proteins recovered from effluents can have interesting applications. Proteins having molecular weights of 50 kDa recovered from herring industry wastewaters could function as natural emulsifying agents in food products. They also showed oaming capacity and stability at pH 10. The 50–10 kDa and 10–1 kDa peptide fractions showed good antioxidant activities [103]. Foaming and emulsifying properties of the proteins were improved or unaffected during their recovery by EF/UF membrane processes [69]. Isolates from effluents of cooked snow crab were composed of 59 % proteins, 38.6 % minerals, 27.3 % carbohydrates, 6.4 % lipids, and also about 30 flavor compounds. The proteins had good solubility, water-holding, emulsion capacity, antioxidant activities. Essential amino acids (EAAs) made up 24.6 % of the total amino acids; particularly leucine and valine. The isolate has potential as an additive [18]. Hydrolysis of proteins from shrimp cooking effluent by enzymes such as Alcalase gave peptides in the range of 1–6 kDa having antioxidant and iron-binding capacities. Hydrolysis at 75 °C and pH of 9.0 gave hydrolyzates having EAAs that can satisfy the recommended daily needs. The bioactive peptide in the hydrolyzate had significant antioxidant and ACE-inhibitory activities The peptides were of size 1355–502 Da, with a predominance of glycine, proline, glutamine, aspartic acid and arginine [102]. Tonon et al. [104] prepared protein hydrolyzate from proteins of shrimp cooking water, by coupling UF and enzymatic hydrolysis under optimum conditions, namely,: temperature of 75 °C, pH of 9.0 and E/S ratio of 0.1 %. Bioactive peptides have also been prepared from proteins of cuttlefish effluents [99] and wash water of surimi processing [100]. UF through 4 kDa membrane isolated a peptide of lower than 1 kDa having potential antioxidant and hypotensive activities from saith proteins [105]. Similarly, UF and NF isolated peptides having 1–4 kDa from tuna dark muscle protein hydrolyzate. The peptide fractions can be used in human nutrition [106]. Proteins recovered from effluents can also be converted into aqueous dispersions for use as edible and biodegradable packaging [107,108]. These results suggest potential applications of proteins of seafood process effluents.

3.1.2. Carotenoids

Carotenoids protect cells from oxidative stress by quenching singlet oxygen. There has been considerable interest in dietary carotenoids for their ability to control incidences of some chronic diseases through their antioxidant action. Fluids from shrimp cooking can be concentrated by UF to isolate the carotenoid, astaxanthin, which mostly remains bound to 300 kDa proteins. Response surface analysis showed that astaxanthin can be extracted from the fraction using sunflower oil (3:1 *v/v*) at 40 °C. The shrimp astaxanthin has low thermal stability in oil at 60° and 70 °C [13,99] Free astaxanthin (cis and trans isomers) and derived esters, having antioxidant activities were detected in shrimp cooking juice [102].

3.1.3. Lipids

Many finfish species are known for their good contents lipids rich in n-3 PUFA [109] Therefore, effluents of these fish also contain n-3 PUFA-rich lipids. The stickwater from processing of fish such as pollock, cod and salmon had variable amounts of lipids [19]. Sardine stickwater was concentrated to get up to 18 % fat [101]. Lipids, particularly, n-3 PUFA, can be extracted from the effluents by low temperature crystallization, enzymatic methods, urea complexation, alkaline hydrolysis, supercritical fluid extraction, molecular distillation, microwave-assisted extraction, among others [51,109]. High hydrostatic pressure extraction yielded 333 mg% n-3 PUFA from fish canning effluents. The extraction presented the lowest environmental impact and costs. The isolated lipids can have food, pharmaceutical and cosmetic applications [110]. Flocculation by chitosan has recovered lipids up to 51.7 % [55]. In Sweden, the Nordic project NoVAqua (dealing with extraction of novel values from aqueous seafood side streams) developed a two-step method that recovered up to 99 % lipids (and also 98 % of proteins) from seafood processing effluents. Flotation and dehydration yielded a semi-solid biomass and a nutrient-rich liquid. Biomass from shrimp boiling water proved to be a useful ingredient as feed for salmon [111]. The water recycling system introduced in the gutting process yielded valuable fish oil/grease by-product [86].

3.1.4. Flavor compounds

Flavor compounds can be divided into two categories: aroma compounds and taste compounds. Aroma compounds usually have molecular weights less than 400 Da, such as ketones, and aldehydes are volatile in nature, whereas compounds responsible for taste are mostly water soluble, consisting of amino acids, organic acids and sugars [18,112]. The cooking juices of oysters are rich in volatile compounds like alcohols, aldehydes, ketones, and alkanes. Their concentration by pervaporation resulted in enrichment of 1- octen-3-ol by a factor of 35 [113]. Flavor compounds from crab boiling juice have been concentrated by pervaporation [114]. A flavor concentrate rich in proteins and lipids was obtained from industrial shrimp cooking juice. The preparation contained glucose, glycerol, polyalcohols and acetate [102]. Solids present in squid cooking effluent could be recovered for use as flavor ingredients in squid-analog production. Sixty percent of the totals free amino acid contents, which imparts flavor to the shellfish, corresponded to glutamic acid, serine, glycine, arginine, alanine, leucine and lysine [28]. Sanchart et al. [17] employed a microbial process in which Candida and Lactobacillus sp., encapsulated in sodium alginate, converted glutamine present in tuna condensate to gamma-amino-butyric acid (GABA), with a productivity of 135 mg/l/hr. The GABA could be used as a flavoring agent or in animal feed.

The process design and economic evaluation of membrane extraction was illustrated by a case study on concentration of shrimp aromas by reverse osmosis [105]. In another study, flavoring compounds from shrimp cooking juice were concentrated initially by a pre-concentration step by NF to reduce volume by 10-fold followed by osmotic evaporation. The process gave a 52 % dry matter concentrate. The preparation could be used as flavor additive at 2.5 % level in foods [115]. Diafiltration (DF) and electro-dialysis (ED) recovered flavor compounds from salted shrimp processing wastewater. The DF process removed about 93 % of salt and recovered less than 50 % of free amino acids and nucleotides, while the ED process removed 85 % of salt and recovered more than 70 % of flavor compounds [116]. A two-step integrated membrane process, combining desalination by electro-dialysis and concentration by RO recovered volatile organic compounds from the cooking juices of shrimp and mussels [117]. A UF step followed by a RO treatment concentrated the flavor compounds of lobster cooking wastewater. The UF membrane with a cut-off: of 20 kDa retained proteins, whereas RO retained all dissolved solids of smaller size. The major flavor compounds were glutamic acid, glycine, arginine, uridine 5′-monophosphate, succninic acid, and glucose [112]. Spray drying followed by freeze drying gave flavor additive from clam processing water, which contained glucose and amino acids such as glutamic acid, aspartic acid, glycine and alanine [118]. These flavor concentrates can be used to enhance natural aroma of selected foods. Table 6 gives summary of components recovered from effluents from different seafood sources by different processes

Table 6
Components recovered from effluents from different seafood sources.

Recovered component	Effluent source	Recovery process	References
Proteins, Bioactive peptides	Shrimp boiling water	Flocculation by carrageenan followed by sedimentation and centrifugation recovered 77 % proteins	[54]
	Cuttlefish	Ultra filtration. Hydrolysis of the proteins gave bioactive peptides	[99]
	Fishmeal	Ultrafiltration	[68]
	Shrimp	Ultrafiltration and enzymatic hydrolysis gave bioactive peptides	[104]
	Surimi	Regenerated cellulose membrane (10 kDa)	[78]
	Shrimp	UF of shrimp shell protein extract removed 96 % of proteins	[67]
	Shrimp	Centrifugal separator gave a functional concentrate rich in proteins and lipids. Protein hydrolysis gave bioactive peptides	[102]-
	Sardine	Centrifugation step followed by pH adjustment	[101]
	Herring	Electro-flocculation followed by UF in series	[21,69,13]
Carotenoids	Herring	Oil extraction Ultra filtration	[13] [154]
Lipids including omega-3 fatty acids	Fish canning	Conventional and pressurized extraction processes	[110]
	Sardine	Centrifugation step followed by pH adjustment	[101]
	Fish, shrimp	Flotation and dehydration	[111]
Flavor compounds	Oyster	Concentrated by pervaporation	[113]
	Crab	Concentrated by pervaporation	[155]
	Tuna condensate	A two-step microbial process using immobilized Candida rugosa and Lactobacillus futsaii	[17]
	Mussel	Centrifugation, electrodialysis and reverse osmosis	[117]
	Jumbo squid	Conventional processes	[28]
	Shrimp	Coupled nanofiltration and osmotic evaporation	[115] [102];
	Various seafood	Membrane processes, reverse osmosis	[105]
	Snow crab	Membrane filtration	[9,18]

3.2. Agro-industry applications

Ingredients recovered from seafood processing effluents can have interesting agricultural applications, as pointed out below:

3.2.1. Fish feed

The sludge obtained from effluent treatment is a good source of proteins, which can be recovered through disintegration, alkali treatment followed by ultra-sonication, precipitation and drying. The process removed heavy metals and toxins such as aflatoxin B1, ochratoxin A. The proteins could be used as toxicologically safe animal feed having nutritional value comparable with that of commercial protein feeds [98]. Fermentation of seafood wastewater by Saccharomyces sp. and *Lactobacillus plantarum* in presence of molasses at 22 °C for 5–7 days gave a stable product that could be used as feed [119]. Ensilation of squid processing wastes for 14 days in presence of 3% formic acid resulted in hydrolysis of proteins and also lipids. The silage can be used as animal feed supplement [120]. The insoluble fraction from stickwater of fishmeal production from sardine can be recovered for use as feed/-food ingredients because of its nutritional value [101].

3.2.2. Fertilizer

Fish processing wastewater, being rich in nutrients, has high potential for use as a liquid fertilizer in agriculture [23]. However, caution must be exercised in direct use of effluents to ensure that they contain pathogenic organisms within acceptable limits only [85]. Besides, commercial marketing of recovered nutrients as 'green' fertilizers also can be attempted. The organic components such as nitrogen, phosphorus, and potassium are useful in fertilizing the soil when applied in limited concentrations. However, while using effluents, the impacts of soil prokaryotic community shifts over plant growth remain to be determined [33]. Sludge is in liquid form and can be used as a liquid fertilizer on cultivated land and meadows [72]. Salt-containing effluents have potential for salt-tolerant plant irrigation. Bio-solids isolated from wastewater has found applications as fertilizer in the U.S. and the U.K [84]). A Swedish project aimed to recover nutrients from seafood processing waters, entitled 'Extracting Novel Values from Aqueous Seafood Side Streams'' ('NoVAqua' in short) observed that the processing waters from the seafood industry contain valuable nutrients that can be recovered for use as food or in aquaculture feed [13].

3.2.3. Bio-stimulants

Bio-stimulants are not fertilizers as they do not provide nutrients directly to plants, but can facilitate the acquisition of nutrients by supporting metabolic processes in soil and plants. Protein hydrolyzates can function as bio-stimulants for improvement of plant growth, chlorophyll synthesis and to abate the negative effects of abiotic stresses in vegetables. The active ingredients in protein hydrolyzates include various proteins, peptides and free amino acids. Application of fish protein hydrolyzates in horticultural practices has resulted in increased crop yields and better quality of fruit and vegetables compared to chemical fertilizers. The EC and USDA have now provided framework for the regulation and use of bio-stimulants in Europe and the US, respectively [121]; http://www.cfish.ie/plant-biostimulants/, accessed July 2020). Table 7 gives some applications of ingredients recovered from seafood process effluents.

3.3. Bio-energy

Global concerns of energy security have attracted interests in biological materials as novel energy resources. Bioenergy, also termed as biofuels, mainly focus on biogas, bio-hydrogen, bioethanol, and biodiesel. Biogas consists of CH_4 (50–75 %), CO_2 (25–50 %), 1–2 % of H_2S,

Table 7
Major potential food applications of recovered ingredients.

Ingredients	Function/bioactivities
Proteins	As food additives, modify gelling, water retention, and textural properties of restructured foods (sausages, fish balls, cutlets, nuggets, pate, patties, pastes, composite fillets, imitation products), among others Animal, aquaculture feed supplements
Protein hydrolyzates	As supplements provide nutritional values to food, health food for patients, sources of peptides having various bioactivities, which make them function as nutraceuticals Animal, aquaculture feed supplements
Lipids	Rich in n-3 PUFA, function as nutraceuticals for various benefits
Carotenoids	Coloring agents useful for food and aquaculture, antioxidants
Flavoring additives	Flavor enhancers of food formulations

H_2, NH_3 each and traces of oxygen and nitrogen. CH_4, the major component of the biogas, has a calorific value of 39,800 kJ/ m^3 Bio-hydrogen is a sustainable form of energy as it can be produced from organic waste through fermentation processes involving dark fermentation and photo-fermentation [122]. The sludge obtained after treatments of fishery effluents can be sources of fuel. Anaerobic digestion of fish waste and the fish sludge gave specific CH_4 yields of 742 and 828 CH_4 m^3 /ton substrate, respectively. The high concentrations of light metals together with high fat and protein contents in the sludge could be inhibitory to methanogenic bacteria. Co-digestion of fish sludge with a carbohydrate-rich residue from crop production could address this problem [123,124]. Vivekanand et al. [124] observed that anaerobic digestion of single substrate may be inefficient due reasons such as imbalances in the carbon-nitrogen ratio, high contents of lipids, metals, degree of biodegradability and other reasons. Co-digestion of fish ensilage, manure and whey synergistically improved CH_4 yield to 470 L/kg, which was 84 % higher than the yields obtained from individual substrates. Co-digestion of effluents from Nile perch processing with 10 % of brewery wastewater enhanced CH_4 yield to 66 %. Pretreatment of the wastewater with aerobic microbial cultures isolated from a fish waste stabilization pond enhanced methane yield to a maximum value of 76 % [125]. The anaerobic treatment of sludge from salmon smolt hatchery in a continuous stirred tank reactor at 35 °C significantly reduced TSS of wastewater. An ion-exchange column further improved quality of the effluent. Furthermore, the CH_4 content in biogas was stabilized at 60.5 %, with a CH_4 yield of 0.14 to 0.15 per COD [72].The Up-flow Anaerobic Sludge Blanket Reactor (UASBR) can be modified for the treatment of industrial wastewater or high CH_4 production [58]. Seafood processing wastewater was treated in an up-flow microbial fuel cell for simultaneous power generation and wastewater treatment. A maximum power density of 105 mW m^{-2} was achieved at an organic loading rate of 2.6 g/d. The predominant bacterial communities of anode biofilm belonged to genera Stenotrophomonas [61]. Fluence [82] reported that use of waste-to-energy technology helped Eurofish reduce its wastewater treatment costs by 50 % and its energy consumption by 35–40 %. Anaerobic process has been adopted to produce biogas equivalent to 4 GW of energy, employing approximately 8000 plants [44].

Fish oil can be source of bio-energy. Kato et al. [126] subjected fish oil to ozonation in presence of iron oxide and calcium phosphate as catalysts. The treated oil had properties suitable for use in diesel engines, such as comparable or higher heating value and density compared with commercial diesel fuel, lower flash and pour points. Yahyaee et al. [127] produced biodiesel employing trans-esterification reaction between methanol and oil from fish waste. The octane and cetane numbers of the biofuel were influenced by the contents of oleic acid and other fatty acids including palmeitoleic, palmitic, stearic, linoleic and linolenic acids, present in the oil.

4. Bio-refining of seafood processing effluents: the algal biorefinery approach

Biotechnological processes offer an economic and versatile way to concentrate and transform resources from waste/wastewater into valuable products [72]. 'Biorefining' is the sustainable processing of biomass into a spectrum of marketable products and energy. International Energy Agency Bioenergy defined biorefining as 'sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, materials) and bio-energy [128]. Bioremediation, a part of the biorefinery process, makes use of fast growing algae and also heterotrophic, photosynthetic bacteria, as well as terrestrial plants, which are allowed to grow in the waste when degradation of the components present in the wastes, thereby reducing their potentials to cause environmental hazards. Microalgae, which belong to the largest primary producers of oxygen in the ocean through their significant photosynthetic activity, have attracted increasing attention in this respect. Some of the major classes of marine microalgae include Chlorella, Spirulina, Dunaliella, diatoms, and cyanobacteria, commonly referred as blue green algae. Microalgal species can be grown under strictly phototrophic conditions (light and CO_2) or in heterotrophic conditions or under both conditions The major advantages of cultivation of microalgae over land based crops are their high growth rate and also their high oil contents [129]. Traditionally, microalgae are cultivated in open ponds having large amounts of surface area for economical viability. The ponds must be maintained at low densities of the organism being cultivated in order to allow the light to penetrate into the system. Some of the open systems are shallow ponds, which may be unstirred or paddle-wheeled, slopping cascade, tubular or laminar reactors. Growth of microalgae under heterotrophic conditions in stirred tank bioreactors have shown to provide more biomass than under auto-phototrophic conditions [95]. Cultivation in photo-bioreactors under required stringent conditions also provide diverse range of extractible products such as β-carotene, phycocyanin, phycoerythrin and others.

4.1. Algal-biotechnology for wastewater bioremediation

The algae based bio-technology is a plausible method for utilization of food industry wastes including aquaculture effluents [130]. Microalgae can effectively utilize wastewater nutrients for growth and biomass production, when grown in open ponds, thereby improing the environmental impacts of the currently used wastewater treatment methods [131]. Recently, Shahid et al. [132] recognized that microalgal cultivation in wastewater offered the highest atmospheric carbon fixation rate (1.83 kg CO_2/Kg biomass) and rapid biomass productivity (40–50 % higher than terrestrial crops) with almost complete removal of pollutants Further, this approach also gives a low-cost process for production of biomass rich in bioactive compounds [133]. In view of their digestive action, and photosynthetic activities aquatic green algae can accomplish degradation of organic contents, unused food, and excretory products together with removal of CO_2, NH_3-N, CO_2, and H_2S thereby providing environmentally safe effluents. Therefore, the phycoremediation potentials of these organisms are reflected in the production of biomass, fixation of CO_2, and extent of removal of pollutants. The purple phototrophic bacteria under anaerobic conditions coupled with infrared irradiation removed 63 % COD, 99 % NH_3-N, and 88 % of phosphate from primary settled domestic wastewater. Almost all the COD removed was assimilated into biomass rather than oxidized to CO_2. The productivity of biomass is 40–50%, higher than that of terrestrial crops [134]. Optimal growth of C. vulgaris resulted in the removal of up to 98.5 % and 90 % of TSS and nutrients, respectively. The biomass formed contained 107.2 ± 5.6 g·/L dry matter with a chlorophyll content of 25.5 mg·/L [135]. It would be ideal to pasteurize the effluents before its use for algal cultivation to prevent putrefaction by contaminant microorganisms and also to inactivate pathogens.

The algal biomass can be used as whole cells or as sources of various bioactive compounds. The biomass has significant amounts of proteins, which are comparable to conventional vegetable proteins. The biomass of marine microalgae, *Chlorella* vulgaris, *Tetraselmis suecica, Isochrysis galbana, D. tertiolecta* and *C. stigmatophora* are considered single cell protein (SCP), due to their high (39–54%) protein contents. Peptides derived from algal proteins may possess one or more bioactivities antibacterial, antiviral, antifungal, antioxidative, anti-inflammatory, antitumor and other functions. Interestingly, stringent nitrogen limitations stimulate the organisms to produce more lipids ranging from 15–75% (on dry weight basis), depending upon the organism and cultivation conditions. The lipids have high contents of n-3 PUFA. Many species of microalgae are also good sources of carbohydrates, and pigments including chlorophylls, carotenoids and phycobiliproteins and minerals. Algal pigments have commercial value as natural colorants. Some strains of Dunaliella are well known for their β-carotene contents. Because of these bioactive compounds, microalgal biomass have found wide applications as sources of nutraceuticals (defined as a food or food product that provides health and medical benefits, including the prevention and treatment of disease), plant growth stimulants, animal feeds, food additives, cosmeceuticals, and drugs. Spirulina is considered as one of the greatest super-foods, a few species such as *C. vulgaris* are consumed in Europe. Many algal extracts and preparations are used in nutritional supplements and cosmetics, notably Dunaliella, Spirulina, Chlorella, and Haematococcus [95,136–138]. Microalgae are promising source of alternative carbon neutral biofuels including biomethane and biohydrogen [139].

4.2. Algal biotechnology for valorization of seafood industry effluents

The algal biotechnology offers interesting options for treatment of seafood processing wastewaters. Microalgal production of SCP is an interesting method for the bioconversions of seafood processing effluents into valuable compounds. Growth of microalgae has been estimated to consume water in a ratio 200–1000 kg water/kg of dry biomass [128]. This suggests comparable volumes of seafood industry effluents could be treated giving a yield one kilogram of microalgae as SCP. The growth of the purple bacterium *Rhodovulum sulfidophilum* in non-sterilized sardine processing wastewater caused significant reduction of COD [140]. Batch cultivation of *Chlorella* sp. in seafood processing water gave a biomass yield of 896 mg/L. Aeration reduced the amount of toxic unionized ammonia, while most of the nutrients were retained in the wastewater giving a higher daily biomass productivity of 77.7 mg/L and lipid productivity of 20.4 mg/L [141]. The algal SCP can be used to replace expensive soy meal and fishmeal in animal feeds. Further, the biomass can also be sources of bio-energy [127,140]. Smárason et al. [142] reported that up to 68 % of expensive fishmeal in a tilapia feed could be replaced with SCP for improved fish growth.

Cultivation of oleaginous microorganisms in fish industry wastewater has potential for biofuel production [129,143]. Vadivel et al., [144] reported that biomass production by two fresh water microalgae species belonging to *Scenedesmus* in agricultural media supplemented with nitrogenous compounds resulted in high accumulation of neutral lipids composed of saturated, mono unsaturated and PUFA at 53, 24 and 20 % (w/v), respectively. The trans-esterification of microalgal lipids with absolute ethanol medium in the presence of nickel/hydrogen catalyst and nickel–Schiff base chelate promoter provided biodiesel having required oxidation stability and cetane number [144]. Anaerobic digestion of the lipid-exhausted algae (*Tetraselmis* sp.) biomass gave 236 mL CH_4 /g VS added [145]. *Bacillus* sp., *Brevibacterium* sp. and *Vibrio* sp associated with seaweed (*Ulva* sp.) having a consortia of hydrolytic enzymes including cellulase, protease, and chitinase biodegraded seafood wastes and effluents. Sugars released during the process can be utilized for ethanol fermentation by Saccharomyces cerevisiae [146]. The anaerobic growth of Chlorella sp. in seafood processing wastewater supports biogas production. Methane yield with 10–50% (v/v) of the algal biomass ranged between 131–193 ml CH_4/g VS, with an average methane of 44 mL per g of the microalgae [147]. Commercial potentials of production of biofuel making use of algal growth depends on the size of the processing plant, type of fuel requirements, and characteristics of the fish waste [148]. These studies, in general, suggest that algae could be useful for bioremediation of seafood processing effluents and production of SCP as a resource material. Sustainable, effective, and economic processes for bioconversion processes related to seafood processing effluents requires integration of microalgal biology including strain selection, genetic engineering, reactor designs, among others. A guide towards conceptual positioning and planning of microalgal plants has been pointed out [128]. The algae-dependent effluent treatment also requires evaluation of nutrient dissipation by abiotic methods, LCA and techno-economic evaluation [131]. Fig. 3 summarizes potentials for commercial products that can be recovered from SCP generated by cultivation of microalgae in seafood effluents.

4.3. Seafood effluents as feedstock towards circular bioeconomy

Circular bioeconomy, which relies on the concepts of 'reduce, reuse and re-cycle' encompasses production of renewable biological resources from waste streams and conversion of these resources into value added products [149]. Efforts to minimize food waste are major challenges for a circular economy, which aims at maximizing the value of resources with a belief that virtually no unrecoverable waste occurs. The approach promises safe and nutritious food, food supplements, functional ingredients, healthy animal feed, and bio-energy [150,151]. Wastewater treatment is a key platform in this respect. The use of seafood effluents as feedstock of resources helps recovery of nutrients and water for recycling, making significant contribution towards a successful circular bioeconomy. An interesting operational program towards this goal can be algal biotechnology, which makes use of algae-dependent bioconversion processes leading to production of algal biomass from the nutrient-rich effluents [73]. Secondary processing of the biomass into various material products and biofuel from a biorefinery angle can significantly contribute towards a circular economy in the realm of seafood processing.

5. Conclusions

In a world of stagnating oceanic resources and declining environmental quality, it is imperative that seafood processing needs to be sustainable, cost effective and safe for overall food security and environment protection. In this review we pointed out that the seafood industry can do much in this regard. The industry including aquaculture releases voluminous amounts of wastewater, which can be detrimental to the environment, if discharged without any treatment. It is essential that the effluents are treated well to alleviate their adverse environmental impacts. It was pointed out that effective and economically viable treatments are now available, which are based on the principles of biotechnology, membrane technology, green chemistry and related disciplines. It is ideal that effluent treatment should be linked to resource recovery for economic viability of the industry. Recent developments in algae based phyco-remediation from a biorefinery perspective can benefit significant reductions in environmental hazards, recovery of resources as food additives, nutraceuticals, animal feeds, agricultural products, and also biofuels. It is ideal to link the treatment and valorization processes. It is tempting to subject the effluents initially to membrane processes for recovery of resources such as protein, follows by its use for algal cultivation. Further a anaerobic treatments can make the effluents more environment savvy. These processes however, may depend on the nature of the effluents. Judicious applications of these options for commercial level treatments and valorization can lead to cleaner seafood production, conservation of water, reduction of wastes and lower emissions, eventually favoring a circular bioeconomy. Management of effluents can significantly help seafood industry realise objectives of safer environment, food security and nutrition towards

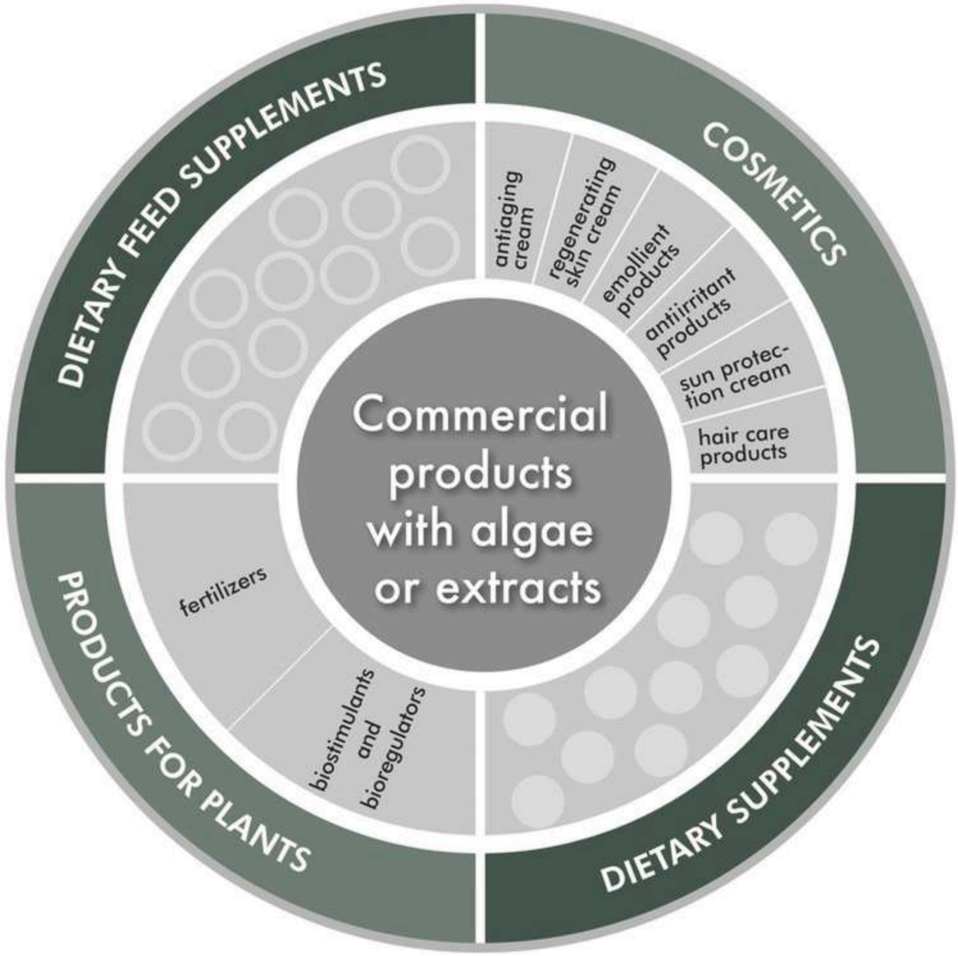

Fig. 3. Potentials for SCP-derived commercial products through the microalgal cultivation in seafood processing effluents. Source: Ref. [137], with permission from Wiley.

sustainable seafood production.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors thank Srikant V. Menon for technical support.

The article is dedicated to the late Prof. A. Ramachandran, Former Vice-Chancellor, Kerala University of Fisheries and Ocean Studies, Kochi, Kerala, India.

References

[1] World Bank, World Development Indicators: Fresh Water, 2014. Http://Wdi. Worldbank.Org..

[2] A. Gustavsson, J. Cederberg, C. Sonesson, U. van Otterdijk, R. Meybeck, Global Food Losses and Food Waste: Extent Causes and Prevention, FAO Food Agric. Organ, Rome, 2011.

[3] N. Ahmed, S. Thompson, The blue dimensions of aquaculture: a global synthesis, Sci. Total Environ. 652 (2019) 851–861, https://doi.org/10.1016/j.scitotenv.2018.10.163.

[4] R. FAO Food and Agriculture Organization of the United Nations, The State of World Fisheries and Aquaculture: Sustainability in Action, 2020.

[5] V. Venugopal, Seafood processing: adding value through quick freezing. Retortable Packaging and Cook-Chilling, CRC Press, Boca Raton, Fl, 2006.

[6] E. Weichselbaum, S. Coe, J. Buttriss, S. Stanner, Fish in the diet: a review, Nutr. Bull. 38 (2013) 128–177, https://doi.org/10.1111/nbu.12021.

[7] K. Kelleher, Discards in the world's marine fisheries: an update, in: FAO Fish. Tech. Pap., 470, 2005, p. 134.

[8] M.S. Islam, S. Khan, M. Tanaka, Waste loading in shrimp and fish processing effluents: potential source of hazards to the coastal and nearshore environments, Mar. Pollut. Bull. 49 (2004) 103–110, https://doi.org/10.1016/j.marpolbul.2004.01.018.

[9] I.S. Arvanitoyannis, A. Kassaveti, Fish industry waste: treatments, environmental impacts, current and potential uses, Int. J. Food Sci. Technol. 43 (2008) 726–745, https://doi.org/10.1111/j.1365-2621.2006.01513.x.

[10] D. Ottaviani, S. Tsuji, C. De Young, Lessons learned in water accounting: the fisheries and aquaculture perspective in the system of environmental-economic accounting (SEEA) framework, in: Fish. Aquac. Tech. Pap., 599, FAO Food Agric. Organ., 2016.

[11] S.J. Hall, A. Delaporte, M.J. Phillips, M. Beveridge, M. O'Keefe, Blue Frontiers. Managing the Environmental Cost of Aquaculture, The World Fish Center, Penang, 2011, 92 p.

[12] United Nations Environment Program and Danish Environmental Protection Agency, C.J. Matcon, K. Christiansen, B. Hummrlmose, Cleaner Production Assessment in Fish Processing, 2000. Http://Www.Unep.Fr/Shared/Publications/Pdf/2481-CPfish.Pdf..

[13] M. Malmstedt, Recovering Nutrients from Seafood Processing Water, 2019, in: Https://Www.Aquaculturealliance.Org/Advocate/Recovering-Nutrients-Seafood-Processing-Water/..

[14] M. Steinke, M. Barjenbruch, Full-scale experiences of nitrogen removal of fish-processing wastewater with flotation and anoxic-aerobic activated sludge system, Water Sci. Technol. 61 (2010) 2227–2233, https://doi.org/10.2166/wst.2010.984.

[15] J.A. Gephart, M. Troell, P.J.G. Henriksson, M.C.M. Beveridge, M. Verdegem, M. Metian, L.D. Mateos, L. Deutsch, The 'seafood gap' in the food-water nexus literature-issues surrounding freshwater use in seafood production chains, Adv. Water Resour. 110 (2017) 505–514, https://doi.org/10.1016/j.advwatres.2017.03.025.
[16] Evoqua, https://www.evoqua.com/en/search-page/?q=seafood+wastewater, (2020).
[17] C. Sanchart, N. Watthanasakphuban, O. Boonseng, T.-H. Nguyen, D. Haltrich, S. Maneerat, Tuna condensate as a promising low-cost substrate for glutamic acid and {GABA} formation using Candida rugosa and Lactobacillus futsaii, Process Biochem. 70 (2018) 29–35, https://doi.org/10.1016/j.procbio.2018.04.013.
[18] A. Tremblay, R. Corcuff, C. Goulet, S.B. Godefroy, A. Doyen, L. Beaulieu, Valorization of snow crab (Chionoecetes opilio) cooking effluents for food applications, J. Sci. Food Agric. 100 (2019) 384–393, https://doi.org/10.1002/jsfa.10066.
[19] P.J. Bechtel, Properties of stickwater from fish processing byproducts, J. Aquat. Food Prod. Technol. 14 (2005) 25–38, https://doi.org/10.1300/j030v14n02_03.
[20] A. Nedzarek, A. Drost, A. Tórz, E. Bogusławska-Wkas, The use of a micro- and ultrafiltration cascade system for the recovery of protein, fat, and purified marinating brine from brine used for herring marination, Food Bioprod. Process. 106 (2017) 82–90, https://doi.org/10.1016/j.fbp.2017.09.001.
[21] A. Osman, N. Gringer, T. Svendsen, L. Yuan, S.V. Hosseini, C.P. Baron, I. Undeland, Quantification of biomolecules in herring (Clupea harengus) industry processing waters and their recovery using electroflocculation and ultrafiltration, Food Bioprod. Process. 96 (2015) 198–210, https://doi.org/10.1016/j.fbp.2015.08.002.
[22] G.K. Sivaraman, S. Visnuvinayagam, A.K. Jha, V. Renuka, S. Remya, D. Vanik, Assessment of microbial quality of fish processing industrial effluent in bar-mouth at Bhidia landing site, Veraval, Gujarat, India, J. Env. Biol. 37 (2016) 537–541.
[23] R. Ching, Y.C. Ghufran, Biological treatment of fish processing saline wastewater for reuse as liquid fertilizer, Sustainability 9 (2017) 1062, https://doi.org/10.3390/su9071062.
[24] J.F. Gonzalez, Wastewater Treatment in the Fishery Industry, FAO Food Agric. Organ. United Nations, Rome, 1995, p. 52p.
[25] P. Bourseau, A. Massé, S. Cros, L. Vandanjon, P. Jaouen, Recovery of aroma compounds from seafood cooking juices by membrane processes, J. Food Eng. 128 (2014) 157–166, https://doi.org/10.1016/j.jfoodeng.2013.12.014.
[26] M. Achour, O. Khelifi, I. Bouazizi, M. Hamdi, Design of an integrated bioprocess for the treatment of tuna processing liquid effluents, Process Biochem. 35 (2000) 1013–1017, https://doi.org/10.1016/s0032-9592(00)00133-3.
[27] B.L. Jamieson, G.A. Gagnon, A.A. Gonçalves, Physicochemical characterization of Atlantic Canadian seafood processing plant effluent, Mar. Pollut. Bull. 116 (2017) 137–142, https://doi.org/10.1016/j.marpolbul.2016.12.071.
[28] Z.G. Rosas-Romero, J.C. Ramirez-Suarez, R. Pacheco-Aguilar, M.E. Lugo-Sánchez, G. Carvallo-Ruiz, G. García-Sánchez, Partial characterization of an effluent produced by cooking of Jumbo squid (Dosidicus gigas) mantle muscle, Bioresour. Technol. 101 (2010) 600–605, https://doi.org/10.1016/j.biortech.2009.08.074.
[29] R.O. Cristóvão, C.M.S. Botelho, R.J.E. Martins, R.A.R. Boaventura, Chemical and biological treatment of fish canning wastewaters, Int. J. Biosci. Biochem. Bioinforma. (2012) 237–242, https://doi.org/10.7763/ijbbb.2012.v2.108.
[30] A. Tukker, B. Jansen, Environmental impacts of products: a detailed review of studies, J. Ind. Ecol. 10 (2006) 159–182, https://doi.org/10.1162/jiec.2006.10.3.159.
[31] P.T. Anh, C. Kroeze, S.R. Bush, A.P.J. Mol, Water pollution by Pangasius production in the Mekong Delta, vietnam: causes and options for control, Aquac. Res. 42 (2010) 108–128, https://doi.org/10.1111/j.1365-2109.2010.02578.x.
[32] B.L. Jamieson, A.A. Gonçalves, G.A. Gagnon, Toxicology evaluation of Atlantic Canadian seafood processing plant effluent, Environ. Toxicol. 25 (2009) 137–146, https://doi.org/10.1002/tox.20479.
[33] M.B. Vallejos, M.S. Marcos, C. Barrionuevo, N.L. Olivera, Fish-processing effluent discharges influenced physicochemical properties and prokaryotic community structure in arid soils from Patagonia, Sci. Total Environ. 714 (2020) 136882, https://doi.org/10.1016/j.scitotenv.2020.136882.
[34] R.D. Astuti, H. Hadiyanto, Estimating environmental impact potential of small scale fish processing using life cycle assessment, J. Ecol. Eng. 19 (2018) 65–74, https://doi.org/10.12911/22998993/91879.
[35] U.S.E.P.A. US EPA, Ocean Disposal Of Fish Wastes, 2017a, 2017, Https://Www.Epa.Gov/Ocean-Dumping/Ocean-Disposal-Fish-Wastes..
[36] K. Kümmerer, D.D. Dionysiou, O. Olsson, D. Fatta-Kassinos, Reducing aquatic micropollutants - increasing the focus on input prevention and integrated emission management, Sci. Total Environ. 652 (2019) 836–850, https://doi.org/10.1016/j.scitotenv.2018.10.219.
[37] G. Ozbay, G. Blank, T. Thunjai, Impacts of aquaculture on habitats and Best management practices (BMPs). Sustain. Aquac. Tech., InTech, 2014, https://doi.org/10.5772/57471.
[38] T.J.R. Quimpo, C.A. Ligson, D.P. Manogan, J.N.C. Requilme, R.L. Albelda, C. Conaco, P.C. Cabaitan, Fish farm effluents alter reef benthic assemblages and reduce coral settlement, Mar. Pollut. Bull. 153 (2020) 111025, https://doi.org/10.1016/j.marpolbul.2020.111025.
[39] J. Aubin, E. Papatryphon, H.M.G. van der Werf, S. Chatzifotis, Assessment of the environmental impact of carnivorous finfish production systems using life cycle assessment, J. Clean. Prod. 17 (2009) 354–361, https://doi.org/10.1016/j.jclepro.2008.08.008.
[40] M. Casé, E.E. Leça, S.N. Leitão, E.E. Sant′Anna, R. Schwamborn, A.T. de Moraes Jr., Plankton community as an indicator of water quality in tropical shrimp culture ponds, Mar. Pollut. Bull. 56 (2008) 1343–1352, https://doi.org/10.1016/j.marpolbul.2008.02.008.
[41] R. Gebauer, Mesophilic anaerobic treatment of sludge from saline fish farm effluents with biogas production, Bioresour. Technol. 93 (2004) 155–167, https://doi.org/10.1016/j.biortech.2003.10.024.
[42] World Bank Group, International Finance Corporation, Environment, Health and Safety Guidelines for Fish Processing, 2020.
[43] U.S.E.P.A. US EPA, Seafood Processing Effluent Guidelines, 2014, 2014, Https://Www.Epa.Gov/Eg/Seafood-Processing-Effluent-Guidelines..
[44] R. Nag, A. Auer, B.K. Markey, P. Whyte, S. Nolan, V. O'Flaherty, L. Russell, D. Bolton, O. Fenton, K. Richards, E. Cummins, Anaerobic digestion of agricultural manure and biomass - critical indicators of risk and knowledge gaps, Sci. Total Environ. 690 (2019) 460–479, https://doi.org/10.1016/j.scitotenv.2019.06.512.
[45] EPA India, http://www.cpcbenvis.nic.in/scanned%20reports/PCL%204%20Environmental%20Standards.pdf, (2000).
[46] F. Shoushtarian, M. Negahban-Azar, Worldwide Regulations and Guidelines for Agricultural Water Reuse: A Critical Review, Water 12 (2020) 971, https://doi.org/10.3390/w12040971.
[47] GAA, Global Aquaculture alliance, Best Aquaculture Practice, Seafood Processing Standard, 2009. www.gaalliance.org.
[48] L.T. Antelo, C. Lopes, A. Franco-Uría, A.A. Alonso, Fish discards management: pollution levels and best available removal techniques, Mar. Pollut. Bull. 64 (2012) 1277–1290, https://doi.org/10.1016/j.marpolbul.2012.04.005.
[49] L.K. Wang, D.B. Aulenbach, N.K. Shammas, Treatment of seafood processing wastewater. Flotat. Technol., Humana Press, 2010, pp. 567–592, https://doi.org/10.1007/978-1-60327-133-2_17.
[50] W.T.M. Audenaert, D. Vandierendonck, S.W.H. Van Hulle, I. Nopens, Comparison of ozone and {HO} induced conversion of effluent organic matter ({EfOM}) using ozonation and {UV}/H2O2 treatment, Water Res. 47 (2013) 2387–2398, https://doi.org/10.1016/j.watres.2013.02.003.
[51] A. Balano, Recovery of biomolecules from food discards–a review, Molecules 17 (2014) 14821–14842.
[52] Y. Hao, L. Liu, G. Feng, Q. Jin, X. Zou, D. Xie, X. Wang, Polysaccharides as coagulants for the recovery of protein in fish meal wastewater, J. Aquat. Food Prod. Technol. 25 (2016) 1086–1095, https://doi.org/10.1080/10498850.2015.1011796.
[53] S. Wibowo, G. Velazquez, V. Savant, J.A. Torres, Effect of chitosan type on protein and water recovery efficiency from surimi wash water treated with chitosan-alginate complexes, Bioresour. Technol. 98 (2007) 539–545, https://doi.org/10.1016/j.biortech.2006.02.014.
[54] B. Forghani, R. Bordes, A. Ström, I. Undeland, Recovery of a protein-rich biomass from shrimp (Pandalus borealis) boiling water: a colloidal study, Food Chem. 302 (2020) 125299, https://doi.org/10.1016/j.foodchem.2019.125299.
[55] H.K. No, S.P. Meyers, Crawfish chitosan as a coagulant in recovery of organic compounds from seafood processing streams, J. Agric. Food Chem. 37 (1989) 580–583, https://doi.org/10.1021/jf00087a002.
[56] P. Chowdhury, T. Viraraghavan, A. Srinivasan, Biological treatment processes for fish processing wastewater - a review, Bioresour. Technol. 101 (2010) 439–449, https://doi.org/10.1016/j.biortech.2009.08.065.
[57] A.N. Bal, A.S. Dhagat, Upflow anaerobic sludge blanket reactor–A Review, Ind. J. Env. Heal. 43 (2001) 1–82.
[58] M.K. Daud, H. Rizvi, M.F. Akram, S. Ali, M. Rizwan, M. Nafees, Z.S. Jin, Review of upflow anaerobic sludge blanket reactor technology: effect of different parameters and developments for domestic wastewater treatment, J. Chem. 2018 (2018) 1–13, https://doi.org/10.1155/2018/1596319.
[59] S.F. Corsino, M. Capodici, C. Morici, M. Torregrossa, G. Viviani, Simultaneous nitritation - denitritation for the treatment of high-strength nitrogen in hypersaline wastewater by aerobic granular sludge, Water Res. 88 (2016) 329–336, https://doi.org/10.1016/j.watres.2015.10.041.
[60] A. Lamsam, S. Laohaprapanon, A.P. Annachhatre, Combined activated sludge with partial nitrification ({AS}/{PN}) and anammox processes for treatment of seafood processing wastewater, J. Environ. Sci. Heal. Part A. 43 (2008) 1198–1208, https://doi.org/10.1080/10934520802171766.
[61] C. Jayashree, K. Tamilarasan, M. Rajkumar, P. Arulazhagan, K.N. Yogalakshmi, M. Srikanth, J.R. Banu, Treatment of seafood processing wastewater using upflow microbial fuel cell for power generation and identification of bacterial community in anodic biofilm, J. Environ. Manage. 180 (2016) 351–358, https://doi.org/10.1016/j.jenvman.2016.05.050.
[62] P. Dhanke, S. Wagh, A. Patil, Treatment of fish processing industry wastewater using hydrodynamic cavitational reactor with biodegradability improvement, Water Sci. Technol. 80 (2019) 2310–2319, https://doi.org/10.2166/wst.2020.049.
[63] F. Salehi, Current and future applications for nanofiltration technology in the food processing, Food Bioprod. Process. 92 (2014) 161–177, https://doi.org/10.1016/j.fbp.2013.09.005.
[64] A. Nagar, T. Pradeep, Clean water through nanotechnology: needs, gaps, and fulfillment, ACS Nano 14 (2020) 6420–6435, https://doi.org/10.1021/acsnano.9b01730.
[65] S.P. Dharupaneedi, S.K. Nataraj, M. Nadagouda, K.R. Reddy, S.S. Shukla, T. M. Aminabhavi, Membrane-based separation of potential emerging pollutants, Sep. Purif. Technol. 210 (2019) 850–866, https://doi.org/10.1016/j.seppur.2018.09.003.
[66] R. Castro-Muñoz, B.E. Barragán-Huerta, V. Fíla, P.C. Denis, R. Ruby-Figueroa, Current Role of Membrane Technology: From the Treatment of Agro-Industrial

by-Products up to the Valorization of Valuable Compounds, Waste Biomass Valorization 9 (2017) 513–529, https://doi.org/10.1007/s12649-017-0003-1.
[67] M.S. Benhabiles, N. Abdi, N. Drouiche, H. Lounici, A. Pauss, M.F.A. Goosen, N. Mameri, Protein recovery by ultrafiltration during isolation of chitin from shrimp shells Parapenaeus longirostris, Food Hydrocoll. 32 (2013) 28–34, https://doi.org/10.1016/j.foodhyd.2012.11.035.
[68] M.D. Afonso, R. Bórquez, Review of the treatment of seafood processing wastewaters and recovery of proteins therein by membrane separation processes – prospects of the ultrafiltration of wastewaters from the fish meal industry, Desalination 142 (2002) 29–45, https://doi.org/10.1016/s0011-9164(01)00423-4.
[69] N. Gringer, S.V. Hosseini, T. Svendsen, I. Undeland, M.L. Christensen, C.P. Baron, Recovery of biomolecules from marinated herring (Clupea harengus) brine using ultrafiltration through ceramic membranes, LWT - Food Sci. Technol. 63 (2015) 423–429, https://doi.org/10.1016/j.lwt.2015.03.001.
[70] V.M.F. Alexandre, A.M. Valente, M.C. Cammarota, D.M.G. Freire, Performance of anaerobic bioreactor treating fish-processing plant wastewater pre-hydrolyzed with a solid enzyme pool, Renew. Energy 36 (2011) 3439–3444, https://doi.org/10.1016/j.renene.2011.05.024.
[71] M. Mannacharaju, A.K. Villalan, B. Shenbagam, P.M. Karmegam, P. Natarajan, S. Somasundaram, G. Arumugam, S. Ganesan, Towards sustainable system configuration for the treatment of fish processing wastewater using bioreactors, Environ. Sci. Pollut. Res. 27 (2019) 353–365, https://doi.org/10.1007/s11356-019-06909-x.
[72] D. Puyol, D.J. Batstone, T. Hülsen, S. Astals, M. Peces, J.O. Krömer, Resource recovery from wastewater by biological technologies: opportunities, challenges, and prospects, Front. Microbiol. 7 (2017), https://doi.org/10.3389/fmicb.2016.02106.
[73] M.I. Queiroz, M.O. Hornes, A.G. da Silva Manetti, L.Q. Zepka, E. Jacob-Lopes, Fish processing wastewater as a platform of the microalgal biorefineries, Biosyst. Eng. 115 (2013) 195–202, https://doi.org/10.1016/j.biosystemseng.2012.12.013.
[74] M. Jemli, F. Karray, F. Feki, S. Loukil, N. Mhiri, F. Aloui, S. Sayadi, Biological treatment of fish processing wastewater: a case study from Sfax City (Southeastern Tunisia), J. Environ. Sci. 30 (2015) 102–112, https://doi.org/10.1016/j.jes.2014.11.002.
[75] C. Li, X. Li, L. Qin, W. Wu, Q. Meng, C. Shen, G. Zhang, Membrane photo-bioreactor coupled with heterogeneous Fenton fluidized bed for high salinity wastewater treatment: pollutant removal, photosynthetic bacteria harvest and membrane anti-fouling analysis, Sci. Total Environ. 696 (2019) 133953, https://doi.org/10.1016/j.scitotenv.2019.133953.
[76] B. Riaño, B. Molinuevo, M.C. García-González, Treatment of fish processing wastewater with microalgae-containing microbiota, Bioresour. Technol. 102 (2011) 10829–10833, https://doi.org/10.1016/j.biortech.2011.09.022.
[77] Issues for the 21st century - results of the {UNEP} foresight process on emerging environmental issues, Environ. Dev. 2 (2012) 150, https://doi.org/10.1016/j.envdev.2012.03.005.
[78] S. Graslund, B. Bengtsson, Chemicals and biological products used in south-east Asian shrimp farming, and their potential impact on the environment – a review, Sci. Total Environ. 280 (2001) 93–131, https://doi.org/10.1016/s0048-9697(01)00818-x.
[79] Z. Lang, M. Zhou, Q. Zhang, X. Yin, Y. Li, Comprehensive treatment of marine aquaculture wastewater by a cost-effective flow-through electro-oxidation process, Sci. Total Environ. 722 (2020) 137812, https://doi.org/10.1016/j.scitotenv.2020.137812.
[80] P. Sohsalam, A.J. Englande, S. Sirianuntapiboon, Seafood wastewater treatment in constructed wetland: tropical case, Bioresour. Technol. 99 (2008) 1218–1224, https://doi.org/10.1016/j.biortech.2007.02.014.
[81] F. Páez-Osuna, S.R. Guerrero-Galván, A.C. Ruiz-Fernández, Discharge of nutrients from shrimp farming to coastal waters of the Gulf of California, Mar. Pollut. Bull. 38 (1999) 585–592, https://doi.org/10.1016/s0025-326x(98)00116-7.
[82] Fluence, Waste-to-energy Technology Helps Fish Processor Save on Operating Costs, 2019, in: Https://Www.Fluencecorp.Com/Case/Waste-to-Energy-for-Fish-Processing-Plant/..
[83] M. Colic, W. Morse, J. Hicks, A. Lechter, J.D. Miller, Case study: fish processing plant wastewater treatment, Proc. Water Environ. Fed. 2007 (2007) 1–27, https://doi.org/10.2175/193864707787781557.
[84] J.S. Guest, S.J. Skerlos, J.L. Barnard, M.B. Beck, G.T. Daigger, H. Hilger, S. J. Jackson, K. Karvazy, L. Kelly, L. Macpherson, J.R. Mihelcic, A. Pramanik, L. Raskin, M.C.M. Van Loosdrecht, D. Yeh, N.G. Love, A new planning and design paradigm to achieve sustainable resource recovery from wastewater, Environ. Sci. Technol. 43 (2009) 6126–6130, https://doi.org/10.1021/es9010515.
[85] J.T. Guimarães, A.L.M. Souza, A.I.S. Brígida, A.A.L. Furtado, P.C.M.S. Chicrala, V. R.V. Santos, R.R. Alves, D.B. Luiz, E.F.M. Mesquita, Quantification and characterization of effluents from the seafood processing industry aiming at water reuse: a pilot study, J. Water Process Eng. 26 (2018) 138–145, https://doi.org/10.1016/j.jwpe.2018.10.006.
[86] E. Alkaya, G.N. Demirer, Minimizing and adding value to seafood processing wastes, Food Bioprod. Process. 100 (2016) 195–202, https://doi.org/10.1016/j.fbp.2016.07.003.
[87] K. Kim, J.W. Hur, S. Kim, J.-Y. Jung, H.-S. Han, Biological wastewater treatment: Comparison of heterotrophs ({BFT}) with autotrophs ({ABFT}) in aquaculture systems, Bioresour. Technol. 296 (2020) 122293, https://doi.org/10.1016/j.biortech.2019.122293.
[88] A. Bezama, H. Valeria, M. Correa, N. Szarka, Evaluation of the environmental impacts of a Cleaner Production Agreement by frozen fish facilities in the Biob {\'{\i}}o Region, Chile, J. Clean. Prod. 26 (2012) 95–100, https://doi.org/10.1016/j.jclepro.2011.12.029.
[89] I.A. Udugama, L.A.H. Petersen, F.C. Falco, H. Junicke, A. Mitic, X.F. Alsina, S. S. Mansouri, K.V. Gernaey, Resource recovery from waste streams in a water-energy-food nexus perspective: toward more sustainable food processing, Food Bioprod. Process. 119 (2020) 133–147, https://doi.org/10.1016/j.fbp.2019.10.014.
[90] C. Lopes, L.T. Antelo, A. Uría, A.A. Alonso, R. Pérez-Martín, Valorisation of fish by-products against waste management treatments - comparison of environmental impacts, Waste Manag. 46 (2015) 103–112, https://doi.org/10.1016/j.wasman.2015.08.017.
[91] A. Sasidharan, V. Venugopal, Proteins and co-products from seafood processing discards: their recovery, functional properties and applications, Waste Biomass Valorization 11 (2019) 5647–5663, https://doi.org/10.1007/s12649-019-00812-9.
[92] A. Shavandi, Y. Hou, A. Carne, M. McConnell, A.E.A. Bekhit, Marine waste utilization as a source of functional and health compounds. Adv. Food Nutr. Res., Elsevier, 2019, pp. 187–254, https://doi.org/10.1016/bs.afnr.2018.08.001.
[93] V.V. Menon, S.S. Lele, Nutraceuticals and bioactive compounds from seafood processing waste. Hb25_Springer Handb. Mar. Biotechnol., Springer, Berlin Heidelberg, 2015, pp. 1405–1425, https://doi.org/10.1007/978-3-642-53971-8_65.
[94] S.F. Bruno, F.J.A.A. Ekorong, S.S. Karkal, M.S.B. Cathrine, T.G. Kudre, Green and innovative techniques for recovery of valuable compounds from seafood by-products and discards: a review, Trends Food Sci. Technol. 85 (2019) 10–22, https://doi.org/10.1016/j.tifs.2018.12.004.
[95] A.C. Freitas, D. Rodrigues, T.A.P. Rocha-Santos, A.M.P. Gomes, A.C. Duarte, Marine biotechnology advances towards applications in new functional foods, Biotechnol. Adv. 30 (2012) 1506–1515, https://doi.org/10.1016/j.biotechadv.2012.03.006.
[96] US EPA 2017b United States Environmental Protection Agency, Nutrient Research, 2017. Https://Www.Epa.Gov/Water-Research/Nutrients-Research..
[97] M. Henchion, M. Hayes, A. Mullen, M. Fenelon, B. Tiwari, Future protein supply and demand: strategies and factors influencing a sustainable equilibrium, Foods 6 (2017) 53, https://doi.org/10.3390/foods6070053.
[98] J. Hwang, L. Zhang, S. Seo, Y.-W. Lee, D. Jahng, Protein recovery from excess sludge for its use as animal feed, Bioresour. Technol. 99 (2008) 8949–8954, https://doi.org/10.1016/j.biortech.2008.05.001.
[99] I.R. Amado, J.A. Vázquez, M. González, M.A. Murado, Production of antihypertensive and antioxidant activities by enzymatic hydrolysis of protein concentrates recovered by ultrafiltration from cuttlefish processing wastewaters, Biochem. Eng. J. 76 (2013) 43–54, https://doi.org/10.1016/j.bej.2013.04.009.
[100] J. Dumay, S. Radier, G. Barnathan, J.P. Bergé, P. Jaouen, Recovery of valuable soluble compounds from washing waters generated during small fatty pelagic surimi processing by membrane processes, Environ. Technol. 29 (2008) 451–461, https://doi.org/10.1080/09593330801983912.
[101] C. Garcia-Sifuentes, R. Pacheco-Aguilar, M. Lugo-Sánchez, G. Garcia-Sánchez, J. C. Ramirez-Suarez, F. Garcia-Carreño, Properties of recovered solids from stick-water treated by centrifugation and {pH} shift, Food Chem. 114 (2009) 197–203, https://doi.org/10.1016/j.foodchem.2008.09.064.
[102] E. Pérez-Santín, M.M. Calvo, M.E. López-Caballero, P. Montero, M.C. Gómez-Guillén, Compositional properties and bioactive potential of waste material from shrimp cooking juice, LWT - Food Sci. Technol. 54 (2013) 87–94, https://doi.org/10.1016/j.lwt.2013.05.038.
[103] A. Taheri, K.H.S. Farvin, C. Jacobsen, C.P. Baron, Antioxidant activities and functional properties of protein and peptide fractions isolated from salted herring brine, Food Chem. 142 (2014) 318–326, https://doi.org/10.1016/j.foodchem.2013.06.113.
[104] R.V. Tonon, B.A. dos Santos, C.C. Couto, C. Mellinger-Silva, A.I.S. Brígida, L.M. C. Cabral, Coupling of ultrafiltration and enzymatic hydrolysis aiming at valorizing shrimp wastewater, Food Chem. 198 (2016) 20–27, https://doi.org/10.1016/j.foodchem.2015.11.094.
[105] A. Chabeaud, L. Vandanjon, P. Bourseau, P. Jaouen, M. Chaplain-Derouiniot, F. Guerard, Performances of ultrafiltration membranes for fractionating a fish protein hydrolyzate: Application to the refining of bioactive peptidic fractions, Sep. Purif. Technol. 66 (2009) 463–471, https://doi.org/10.1016/j.seppur.2009.02.012.
[106] S. Saidi, A. Deratani, M.-P. Belleville, R. Ben Amar, Production and fractionation of tuna by-product protein hydrolyzate by ultrafiltration and nanofiltration: Impact on interesting peptides fractions and nutritional properties, Food Res. Int. 65 (2014) 453–461, https://doi.org/10.1016/j.foodres.2014.04.026.
[107] P.K. Mishra, R.K. Gautam, V. Kumar, A.S. Kakatkar, S. Chatterjee, Synthesis of biodegradable films using gamma irradiation from fish waste, Waste Biomass Valorization (2020), https://doi.org/10.1007/s12649-020-01143-w.
[108] V. Menon, Fish protein coating to enhance the shelf life of fishery products. Seaf. Sci., CRC Press, 2014, pp. 90–116, https://doi.org/10.1201/b17402-6.
[109] V. Venugopal, Marine Products for Healthcare: Functional and Bioactive, Nutraceutical Compounds From the Ocean, CRC Press, Boca Raton, Fl, 2009.
[110] A. Monteiro, D. Paquincha, F. Martins, R.P. Queirós, J.A. Saraiva, J. Švarc-Gajić, N. Nastić, C. Delerue-Matos, A.P. Carvalho, Liquid by-products from fish canning industry as sustainable sources of $\upomega$3 lipids, J. Environ. Manage. 219 (2018) 9–17, https://doi.org/10.1016/j.jenvman.2018.04.102.
[111] S. Himmelstein, Nutrient Recovery From Seafood Processing Effluent, 2018, in: Https://Insights.Globalspec.Com/Article/10376/Nutrient-Recovery-from-Seafood-Processing-Effluent..

[112] C.N. Jayarajah, C.M. Lee, Ultrafiltration/reverse osmosis concentration of lobster extract, J. Food Sci. 64 (1999) 93–98, https://doi.org/10.1111/j.1365-2621.1999.tb09868.x.
[113] L.S. Soares, A.C.F. Vieira, F. Fidler, A.R.M. Fritz, M. Di Luccio, Pervaporation as an alternative for adding value to residues of oyster (Crassostrea gigas) processing, Sep. Purif. Technol. 232 (2020) 115968, https://doi.org/10.1016/j.seppur.2019.115968.
[114] R. S.M.T, B.S. Martinez, Pervaporation investigation of recovery of volatile compounds from brown crab boiling juice, Food Sci. Ence Technol. Int. 20 (2014) 511.
[115] C. Jarrault, M. Dornier, M.-L. Labatut, P. Giampaoli, M.-L. Lameloise, Coupling nanofiltration and osmotic evaporation for the recovery of a natural flavouring concentrate from shrimp cooking juice, Innov. Food Sci. Emerg. Technol. 43 (2017) 182–190, https://doi.org/10.1016/j.ifset.2017.07.035.
[116] C.Y. LIN, B.H. CHIANG, Desalting and recovery of flavour compounds from salted shrimp processing waste water by membrane processes, Int. J. Food Sci. Technol. 28 (2007) 453–460, https://doi.org/10.1111/j.1365-2621.1993.tb01294.x.
[117] S. Cros, B.L. Ignot, C. Razafintsalama, P. Jaouen, P.B. Ourseau, Electrodialysis desalination and reverse osmosis concentration of an industrial mussel cooking juice: process impact on pollution reduction and on aroma quality, J. Food Sci. 69 (2006), https://doi.org/10.1111/j.1365-2621.2004.tb10985.x. C435–C442.
[118] N.R. Reddy, G.J. Flick, H.P. Dupuy, G.D. Boardman, Characterization and utilization of dehydrated wash waters from clam processing plants as flavoring agents, J. Food Sci. 54 (1989) 55–59, https://doi.org/10.1111/j.1365-2621.1989.tb08566.x.
[119] M. Faid, A. Zouiten, A. Elmarrakchi, A. Achkari-Begdouri, Biotransformation of fish waste into a stable feed ingredient, Food Chem. 60 (1997) 13–18, https://doi.org/10.1016/s0308-8146(96)00291-9.
[120] K.A.M. Xavier, V. Geethalekshmi, S.R. Senapati, P.T. Mathew, A.C. Joseph, K.G. R. Nair, Valorization of squid processing waste as animal feed ingredient by acid ensilaging process, Waste Biomass Valorization 8 (2016) 2009–2015, https://doi.org/10.1007/s12649-016-9764-1.
[121] M. Madende, M. Hayes, Fish by-product use as biostimulants: an overview of the current state of the art, including relevant legislation and regulations within the EU and USA, Molecules 25 (2020) 1122, https://doi.org/10.3390/molecules25051122.
[122] M.R. Atelge, D. Krisa, G. Kumar, C. Eskicioglu, D.D. Nguyen, S.W. Chang, A. E. Atabani, A.H. Al-Muhtaseb, S. Unalan, Biogas production from organic waste: recent progress and perspectives, Waste Biomass Valorization 11 (2018) 1019–1040, https://doi.org/10.1007/s12649-018-00546-0.
[123] I.A. Nges, B. Mbatia, L. Björnsson, Improved utilization of fish waste by anaerobic digestion following omega-3 fatty acids extraction, J. Environ. Manage. 110 (2012) 159–165, https://doi.org/10.1016/j.jenvman.2012.06.011.
[124] V. Vivekanand, D.G. Mulat, V.G.H. Eijsink, S.J. Horn, Synergistic effects of anaerobic co-digestion of whey, manure and fish ensilage, Bioresour. Technol. 249 (2018) 35–41, https://doi.org/10.1016/j.biortech.2017.09.169.
[125] R. Gumisiriza, A.M. Mshandete, M.S.T. Rubindamayugi, F. Kansiime, Enhancement of anaerobic digestion of Nile Perch fish processing wastewater, Afr. J. Biotechnol. (2009) 328–333.
[126] S. Kato, K. Kunisawa, T. Kojima, S. Murakami, Evaluation of Ozone Treated Fish Waste Oil as a Fuel for Transportation, J. Chem. Eng. Jpn. 37 (2004) 863–870, https://doi.org/10.1252/jcej.37.863.
[127] R. Yahyaee, B. Ghobadian, G. Najafi, Waste fish oil biodiesel as a source of renewable fuel in Iran, Renew. Sustain. Energy Rev. 17 (2013) 312–319, https://doi.org/10.1016/j.rser.2012.09.025.
[128] C.E. de Farias Silva, E. Barbera, A. Bertucco, Biorefinery as a promising approach to promote ethanol industry from microalgae and~Cyanobacteria. Bioethanol Prod. From Food Crop, Elsevier, 2019, pp. 343–359, https://doi.org/10.1016/b978-0-12-813766-6.00017-5.
[129] H.U. Cho, J.M. Park, Biodiesel production by various oleaginous microorganisms from organic wastes, Bioresour. Technol. 256 (2018) 502–508, https://doi.org/10.1016/j.biortech.2018.02.010.
[130] B. Subhadra, Grinson-George, Algal biorefinery-based industry: an approach to address fuel and food insecurity for a carbon-smart world, J. Sci. Food Agric. 91 (2010) 2–13, https://doi.org/10.1002/jsfa.4207.
[131] D. Nagarajan, D.-J. Lee, C.-Y. Chen, J.-S. Chang, Resource recovery from wastewaters using microalgae-based approaches: a circular bioeconomy perspective, Bioresour. Technol. 302 (2020) 122817, https://doi.org/10.1016/j.biortech.2020.122817.
[132] A. Shahid, S. Malik, H. Zhu, J. Xu, M.Z. Nawaz, S. Nawaz, M.A. Alam, M. A. Mehmood, Cultivating microalgae in wastewater for biomass production, pollutant removal, and atmospheric carbon mitigation$\mathsemicolon$ a review, Sci. Total Environ. 704 (2020) 135303, https://doi.org/10.1016/j.scitotenv.2019.135303.
[133] D.B. Stengel, S. Connan, Marine Algae, A source of biomass for biotechnological applications. Methods Mol. Biol., Springer, New York, 2015, pp. 1–37, https://doi.org/10.1007/978-1-4939-2684-8_1.
[134] T. Hülsen, D.J. Batstone, J. Keller, Phototrophic bacteria for nutrient recovery from domestic wastewater, Water Res. 50 (2014) 18–26, https://doi.org/10.1016/j.watres.2013.10.051.
[135] T.D.P. Nguyen, T.V.A. Le, P.L. Show, T.T. Nguyen, M.H. Tran, T.N.T. Tran, S. Y. Lee, Bioflocculation formation of microalgae-bacteria in enhancing microalgae harvesting and nutrient removal from wastewater effluent, Bioresour. Technol. 272 (2019) 34–39, https://doi.org/10.1016/j.biortech.2018.09.146.
[136] M.P. Caporgno, A. Mathys, Trends in microalgae incorporation into innovative food products with potential health benefits, Front. Nutr. 5 (2018), https://doi.org/10.3389/fnut.2018.00058.
[137] I. Michalak, K. Chojnacka, Algae as production systems of bioactive compounds, Eng. Life Sci. 15 (2015) 160–176, https://doi.org/10.1002/elsc.201400191.
[138] K.W. Gellenbeck, Utilization of algal materials for nutraceutical and cosmeceutical applications – what do manufacturers need to know? J. Appl. Phycol. 24 (2011) 309–313, https://doi.org/10.1007/s10811-011-9722-z.
[139] R. Wirth, G. Lakatos, T. Böjti, G. Maróti, Z. Bagi, G. Rákhely, K.L. Kovács, Anaerobic gaseous biofuel production using microalgal biomass - a review, Anaerobe 52 (2018) 1–8, https://doi.org/10.1016/j.anaerobe.2018.05.008.
[140] S.A. Azad, S. Vikineswary, V.C. Chong, K.B. Ramachandran, Rhodovulum sulfidophilum in the treatment and utilization of sardine processing wastewater, Lett. Appl. Microbiol. 38 (2004) 13–18, https://doi.org/10.1046/j.1472-765x.2003.01435.x.
[141] F. Gao, Y.-Y. Peng, C. Li, G.-J. Yang, Y.-B. Deng, B. Xue, Y.-M. Guo, Simultaneous nutrient removal and biomass/lipid production by Chlorella sp. in seafood processing wastewater, Sci. Total Environ. 640–641 (2018) 943–953, https://doi.org/10.1016/j.scitotenv.2018.05.380.
[142] B.Ö. Smárason, B. Alriksson, R. Jóhannsson, Safe and sustainable protein sources from the forest industry - the case of fish feed, Trends Food Sci. Technol. 84 (2019) 12–14, https://doi.org/10.1016/j.tifs.2018.03.005.
[143] C.-Y. Chen, K.-L. Yeh, R. Aisyah, D.-J. Lee, J.-S. Chang, Cultivation, photobioreactor design and harvesting of microalgae for biodiesel production: a critical review, Bioresour. Technol. 102 (2011) 71–81, https://doi.org/10.1016/j.biortech.2010.06.159.
[144] M. Vadivel, S. Arvindnarayan, G. Kumar, S. Shobana, J. Dharmaraja, D. D. Nguyen, S.W. Chang, K.K.S. Prabhu, Biodiesel potentiality of microalgae species: evaluation using various nitrogen sources, Waste Biomass Valorization 11 (2019) 1671–1679, https://doi.org/10.1007/s12649-018-00552-2.
[145] D. Hernández, M. Solana, B. Riaño, M.C. García-González, A. Bertucco, Biofuels from microalgae: Lipid extraction and methane production from the residual biomass in a biorefinery approach, Bioresour. Technol. 170 (2014) 370–378, https://doi.org/10.1016/j.biortech.2014.07.109.
[146] S. Samant, M.M. Naik, D.C. Vaingankar, S.Y. Mujawar, P. Parab, S.N. Meena, Biodegradation of seafood waste by seaweed-associated bacteria and application of seafood waste for ethanol production. Adv. Biol. Sci. Res., Elsevier, 2019, pp. 149–159, https://doi.org/10.1016/b978-0-12-817497-5.00010-0.
[147] A. Jehlee, P. Khongkliang, S. O-Thong, Biogas production from Chlorella sp. {TISTR} 8411 biomass cultivated on biogas effluent of seafood processing wastewater, Energy Procedia 138 (2017) 853–857, https://doi.org/10.1016/j.egypro.2017.10.095.
[148] P. Jayasinghe, K. Hawboldt, A review of bio-oils from waste biomass: focus on fish processing waste, Renew. Sustain. Energy Rev. 16 (2012) 798–821, https://doi.org/10.1016/j.rser.2011.09.005.
[149] Innovating for sustainable growth: a bioeconomy for Europe, Ind. Biotechnol. 8 (2012) 57–61, https://doi.org/10.1089/ind.2012.1508.
[150] M. Carus, L. Dammer, The circular bioeconomy - concepts, opportunities, and limitations, Ind. Biotechnol. 14 (2018) 83–91, https://doi.org/10.1089/ind.2018.29121.mca.
[151] J. Sherwood, The significance of biomass in a circular economy, Bioresour. Technol. 300 (2020) 122755, https://doi.org/10.1016/j.biortech.2020.122755.
[152] L.P. Sunny, N. Mathai, Physico-chemical process for fish processing wastes water, Int. J. Inn. Res. Sci. Technol. 2 (2013) 901–905.
[153] R.O. Cristóvão, C. Gonçalves, C.M. Botelho, R.J.E. Martins, R.A.R. Boaventura, Chemical oxidation of fish canning wastewater by Fenton{\textquotesingle}s reagent, J. Environ. Chem. Eng. 2 (2014) 2372–2376, https://doi.org/10.1016/j.jece.2013.12.023.
[154] I.R. Amado, J.A. Vázquez, M.A. Murado, M.P. González, Recovery of Astaxanthin from Shrimp Cooking Wastewater: Optimization of Astaxanthin Extraction by Response Surface Methodology and Kinetic Studies, Food Bioprocess Technol. 8 (2014) 371–381, https://doi.org/10.1007/s11947-014-1403-x.
[155] R. Martínez, M.T. Sanz, S. Beltrán, Pervaporation investigation of recovery of volatile compounds from brown crab boiling juice, Food Sci. Technol. Int. 20 (2013) 511–526, https://doi.org/10.1177/1082013213496092.