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Mitigation of Seafood-Related Environmental Pollution: A Green Chemistry Perspective

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Abstract: The seafood industry discharges voluminous amounts of discards, consisting of fishery by-catch, process discards, and effluents. Traditional disposals of these side stream materials by landfill, ocean dumping, and incineration are responsible for serious environmental pollution. Emission of greenhouse gases including carbon dioxide, methane, and nitrous oxide from the discards significantly contributes to global warming, while hydrogen sulfide, ammonia, methane, nitrous oxide, and other gases have detrimental effects on the health of living systems. These environmental hazards can be abated by eco-friendly remedial solutions. Green chemistry-based valorization of seafood side streams has potentials to lower environmental hazards simultaneously minimizing volume of the discards. These operations transform the discards to interesting products. Integration of the green methods within the framework of a biorefinery within a circular economy protocol allows a zero-waste strategy for the mitigation of environmental pollution by seafood discards. Possible industrial applications of the recovered ingredients such as proteins, peptides, polyunsaturated fatty acids rich lipids, chitin, chitosan, and others make the fishery discards a valuable resource. The green chemistry approach allows optimal mitigation of seafood-related environmental hazards paving the way for responsible and economically viable conservation of resources for a resilient, sustainable, low-carbon seafood industry.

Keywords: seafood side streams, environmental pollution, carbon footprint, circular economy, green chemistry

1. Introduction

Modern food production systems leave a heavy environmental burden, due to emission of greenhouse gases (GHG) responsible for rise in average global temperature, besides causing significant consumptions of energy, water, and other subsystems. In 2019, the global net anthropogenic GHG emissions were 59 ± 6.6 $GtCO_2$-eq, about 54% (21 $GtCO_2$-eq) higher than in 1990. Food production is responsible for a third of global GHG emissions consisting of CO_2, CH_4, and N_2O involved in global warming [1–6]. Annual global food loss and waste (FLW), which amounts to approximately 1.6 billion tons, emitted 9.3 $GtCO_2$-eq in 2017, which were about half of the annual GHG emissions from the whole food system. Animal products including seafood products which are rich in proteins release almost twice GHG than plant-based foods. The concerns in global warming encouraged the 2015 Paris Agreement to call for 42% reduction of GHG emissions by 2030 with an aim to limit the rise in global average temperature by 1.5°C by the end of 21st century. Besides GHG emissions, FLW also emits hydrogen sulfide, ammonia, methane, nitrous oxide, and others, which affect living systems, besides being responsible for huge loss of nutrients. The serious concerns of climate change, environmental degradation, and food waste-associated nutrient loss call for a synergistic combination of measures to address the problems.

2. The Environmental Burden of Seafood Production

The total fishery and aquaculture production in the year 2020 was 214 million tons (Mt), with a contribution of 122.6 Mt from aquaculture. Seafood production is likely to increase by 21 to 44 Mt by 2050, provided favorable factors such as policy reforms and technological innovation are available [7–9]. Fishery resources, however, in recent times, are affected by overfishing, pollution, loss of biodiversity, poor management, and other factors. Global warming of modern times has also adverse influences on marine ecosystems affecting fish species distribution, catch potential, and consumer availability of proteins and other nutrients. Although climate change may adversely affect ocean's ability to supply food, this can be prevented by sufficient measures to reduce emissions.

The carbon footprint value of a product dictates its environmental impact. The value represents CO_2 emissions generated by the product or supply chain per unit of output on a life cycle basis [10–16]. While aquatic foods form only 1.1% of total food products, they contribute to about 9.9% of global environmental footprints. Information on carbon footprints of aquatic foods is essential to make the seafood industry environmentally, socially, and economically sustainable. The emission hotspots are spread over-fishing operations and post-

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landing product manufacture. Carbon footprint values are high for fishing activities due to heavy fuel consumption. Overfishing increases the carbon footprint of seafood production. Mariculture has about 40% lower carbon footprints than freshwater aquaculture, with emissions intensities for CH_4 and N_2O ranging from 1 to 6 g and 0.05 to 0.2 g, respectively, per kg carcass weight. Capture fisheries predominantly GHG emissions, with small pelagic fishes generating lower emissions than all fed aquaculture. Bivalve production provides a protein source with the lowest GHG emissions. The bivalve shells sequester atmospheric CO_2 and therefore can be environmentally sustainable Studies showed that more than 20 Norwegian seafood products had their carbon footprints varying between 0.7 to 14.0 kg CO_2-eq per kg.

Generation of voluminous discards, also referred as side streams, is characteristic of seafood processing industry. The industry operates on a linear and throw-away model, based on the paradigm, “produce now, clean up later”. Such an attitude results in buildup of discards as high as 70% of the raw materials. The discarded biomass organic matter originating from living tissues, include by-catch, process discards, and effluents are referred as side streams. The by-catch forms low-value fish and shellfish species that are caught during commercial fishing having smaller size than prescribed, poor quality, or that is caught in quantities in excess of specified by regulatory quota. Processing generates up to 70% of shrimp, lobster, and other crustaceans as discards containing heads and shells. These have proteins, minerals, and chitin up to 40%, 50%, and 30%, respectively, besides small amounts of lipids and carotenoids. Fins, heads, bones, and scales comprise up t 50% of the raw materials [17–24]. The action of endogenous enzymes and contaminant microorganisms make seafood discards susceptible for rapid spoilage causing serious environmental pollution. Disposal of the discards by landfilling is responsible for heavy pollution of soil and water. Waste from a seafood processing industry contributed to 66% of total emissions of 19,144 tons of CO_2-eq in 2023. Landfilling of the waste released approximately 410 tons methane per year, equivalent to about 95% of the total emissions. Rapid spoilage of landfilled discards causes heavy release of ammonia (NH_3), nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), methane, hydrogen sulfide (H_2S), and other volatile gases, which are responsible for obnoxious odor, contamination of surface and groundwater causing several health issues. Ocean dumping of by-catch adversely affects oxygen levels at the ocean bottom, causing smothering of living organisms, disturbance of water acidity, making the sea floor ecosystem susceptible to diseases. Incineration of fishery discards generates CO_2, NO_2, and sulfur dioxide (SO_2), adversely impacting global freshwater use, chemical pollution, biodiversity loss, and others, has caused ban of incineration by several countries. Composting, on a limited extent, has been used to develop organic manure. Seafood process effluents contain significant quantity of nutrients, particularly proteins oils, and others affecting the environment.

2.1. Managing environmental hazards of seafood discards

The rising concerns of global environmental hazards particularly global warming have come to a realization that *climate action cannot wait*, requiring industries to prioritize investing in technologies and processes to cut the GHGs of value chains [6, 25, 26]. At COP29, Baku, Azerbaijan, held in November 2024, the **WorldFish**[1] observed a need for urgent action to incorporate aquatic foods into climate action plans, since integration of fisheries and aquaculture into climate strategies can offer both climate adaptation and sustainable economic growth. In this respect, food waste management and process optimization need effective mitigation strategies. In the US, food waste comprises of 24 and 22%, respectively of landfilled and incinerated municipal solid waste. The US Environment Protection Agency has called for cutting food waste into half in the country to increase food security, control environmental pollution, reduce climate change, and accrue other benefit of landfilled and incinerated municipal solid waste. The objective is to increase food security, foster productivity and economic efficiency, promote resource and energy conservation, and address climate change (https://www.epa.gov/land-research/farm-kitchen-environmental-impacts-us-food-waste, accessed October 26, 2024). Significant reduction of food waste has also been suggested by the European Union. The Committee on Fisheries of the Food and Agriculture Organization (FAO) has recognized the importance of reduction of seafood loss and waste, including by-catch.

Saving food is essential to mitigate climate change [2, 10, 27–29]. Attempts to save food need to be ideally built up on a zero-waste strategy. The Zero Waste International Alliance defined zero waste as “the conservation of all resources by means of responsible production, consumption, reuse, and recovery of products, packaging, and materials, without burning and with no discharges to land, water, or air that threaten the environment or human health” (https://zwia.org/contact-zwia/, accessed April 2, 2024). Mitigation of carbon emission should be at the center of zero-waste strategy for maximum reduction of environmental pressures on the ecosystem, marine conservation and health of the seafood industry. The global carbon emissions have been classified as Scopes 1, 2, or 3 emissions. Emissions from the food chain are designated Scope 3 emissions, which account for more than 70% of total emissions, while Scope 1 and Scope 2 emissions arise from sources owned by the industry such as electricity, fuel combustion, and others, whereas food factories have better control over Scope 1 and Scope 2 emissions, minimizing Scope 3 emissions can have a significant contribution to a carbon neutral future. Challenges and opportunities for mitigation of carbon emission in the food industry have been discussed. The environmental protocols to manage food waste are *decarbonization*, to remove CO_2 and other GHG gases from the atmosphere to reduce global warming; detoxification, to reduce impacts of pollutants; and *dematerialization* to extract resources to reduce environmental impacts of the waste.

Decarbonization of food and beverage industries to reduce global warming employing current and emerging practices including potential transformations have been pointed out [2, 30–32]. These processes, ideally, require cleaner production strategies and resource-intensive technologies. Such approaches essentially involve upcycling (replacing the old terminology “recycling”, which is implied as “down-cycling”) and are highly beneficial to address environmental pollution through minimization of waste. An interesting process related to upcycling is transformation of the food waste into acceptable and valuable products and is built on the “trash to treasure” concept, i.e., what is considered waste can become useful materials including food in a new product cycle. The strategy has huge potentials to minimize waste, lower waste disposal expenses, abate environmental hazards, and enhance sustainability and financial returns of the industry. The European Union’s Green Deal is a comprehensive set of policy initiatives aimed to significantly reduce GHG emissions by 2030 compared to 1990 levels (commission.europa.eu’ European-green-deal en, accessed November 2, 2024). The FAO has proposed a “Blue Transformation Framework” for efficient, inclusive, resilient, and sustainable management of aquatic resources. The framework aims improving fisheries management through environment-friendly

[1]WorldFish, https://worldfishcenter.org/cop29

policy as well as technological practices. Emerging biotechnological strategies are able to provide a green leap for environmental abatement through recovery of high-value products. This article discusses potentials of green chemistry-based protocols for transformation of seafood discards in order to mitigate environmental hazards.

3. Green Chemistry to Address Environmental Hazards of Seafood Side Streams

Nature-friendly solutions are essential to decouple economic growth from adverse environmental impacts. The International Union of Pure and Applied Chemistry is involved in identification of emerging technologies to find chemistry-based solutions for a more sustainable future [33–37]. The green chemistry (also known as sustainable chemistry) emerged in the 1990s. Its aims include design, development, and implementation of products and processes that reduce the use and generation of hazardous substances. In 1998, Anastas and Warner elaborated on 12 principles of green chemistry for design, development, and implementation of chemical products in order to reduce or eliminate the use and generation of hazardous materials. These principles were complimented by 12 principles of chemical engineering. Green chemistry-related approaches are powerful leverage points to minimize environmental hazards by designing products and processes, which use only minimal amounts of hazardous substances. Green chemistry is well-placed to benefit the bottom line, with less waste and faster, more energy-efficient manufacturing processes. It has ample potentials to address seafood-related environmental pollution. The operational protocol essentially involves biotransformation of seafood discards, relying on ""waste to wealth" concept, namely, what is considered waste can be transformed into new beneficial products. The advantages of green chemistry-based processes are summarized in Table 1.

3.1. Green processes

The traditional chemical treatment of seafood waste releases hazardous chemicals such as hydrochloric acid and alkali, causing serious environmental hazards [17, 24, 36–41]. In contrast, green chemistry-based innovative processes are environmentally friendly and can be a roadmap to alleviate seafood-borne environmental issues. These processes essentially involve initial biotransformation of the discards followed by recovery of valuable materials from the transformed materials. One such method is fermentation, which besides reducing the environmental burden can also produce value-added products from the seafood discards. The process leverages cultivation of bacteria, fungi, microalgae, and protozoa, and may be operated under aerobic, anaerobic, or facultative conditions. The fermentation efficiency depends on the starter culture, pH, and substrate composition. The process can be either solid state fermentation (SSF), submerged, batch, continuous, or fed-batch fermentation. The advantages of SSF are lower sterility requirements, lower water demand, and higher production volume. Precision and biomass fermentation make use of recent advances in genomics and synthetic biology to produce specific ingredients. Downstream processing of fermented products can yield valuable food ingredients from abundant and inexpensive substrates.

The products of seafood fermentation include microbial biomass, proteins including collagen and gelatin, lactic and other organic acids, chitin, fish oil, bioactive peptides, hyaluronic acid, liquid fertilizer, vitamins, enzymes, and others having interesting applications [42–52]. The popular fermentation using lactic acid bacteria in SSF or fed-batch modes can be useful to develop food, feed, flavors, enzymes, fuel, industrial chemicals, and biomaterials. Non-thermal extraction and ultrafiltration are greener approaches for extraction of collagen from suitably fermented fishery products. Fermentation and enzymatic action have emerged for valorization of shrimp discards for its use in agriculture, pharmaceutical, cosmetic, and food industry to foster environmental sustainability and green economy. A novel microbial process for complete biodegradation of shrimp waste with co-production of chitinase and chitin oligosaccharides has been reported. Single-stage co-fermentation using proteolytic and chitinolytic bacteria gave 90% deproteinization and demineralization of crustacean crab shell wastes, with production of N-acetyl glucosamine and amino acids. Cultivation of oleaginous microorganisms is promising for biofuel production from organic waste. Cultivated seafood making use of cells harvested from salmon and other popular fish reduces environmental impact of fishing and pressure on fisheries besides helping seafood sustainability.

Biomass fermentation using microalgae can transform seafood resources into valuable ingredients. Growth of phototropic microalgae such as Galdieria spp., Chlorella spp., Spirulina spp., Dunaliella spp., diatoms, and cyanobacteria (commonly referred to as blue-green algae) in seafood process effluents or media enriched with nutrients from seafood discards results in 40–50% higher yield of biomass than that from terrestrial crops [24, 53, 54]. The algal biomass, referred as single cell proteins, has protein contents as high as 60% on dry weight basis, besides lipids, polysaccharides, minerals, pigments, and others. These ingredients can be recovered by green downstream processes, for their uses in food, feed, cosmetics, and medicine.

Table 1
General advantages of green chemistry-based processes

Parameters	General advantages
Reaction conditions	Reactions at ambient temperature and pressure
Extraction of materials	Green solvents are mostly inert, recyclable, and sustainable. Therefore, they are ideal for extraction
Energy requirements	Generally low energy requirements
Catalysts	Microorganisms and enzymes serve as low-cost, biocatalysts in comparison with traditional metal catalysts, which are generally used for reactions
Advantages with respect to resources	Degradation is part of design causing "triggered instability"
Functionality of the product	Functionality is mostly enhanced by a modified structure
Type of processes	Ideally circular in nature
Management approach	Waste upstreaming and utilization, not waste disposal
Profitability	Maximum chemical production with minimum use of benign material for increased profitability

Anaerobic digestion (AD) is useful for waste management, biofertilizer production, and renewable energy generation. AD of aquaculture and fish processing waste is a promising for effective material-energy recycling. Salinity, low-carbon/nitrogen ratio, high lipid content, and others can influence AD of waste from aquaculture and seafood processing [10, 32, 55, 56]. The synergistic effects of co-substrates, characterization of microbial communities, the prediction of biogas production, and future research directions for the development of AD-based sustainable biorefinery have been discussed. Cultivation of microorganisms in wastewater results in a reduction of GHG emissions as high as 96%.

Enzymes, because of their catalytic specificity and appreciable activities at moderate temperatures, make economically viable bioconversions to give proteins, chitin, chitosan, chitooligomers, oil rich in polyunsaturated fatty acids, and others from seafood discards [57–71]. Immobilized enzymes can efficiently convert waste streams. Seafood side streams themselves are rich sources of enzymes like proteases, lipases, chitinase, transglutaminase, hyaluronidase, and others. These enzymes can be used for biotransformation of seafood side streams for the recovery of ingredients including proteins, chitin, and lipids, textural modification, removal of allergens, flavor modification and others. Green extraction techniques including fermentation, enzyme-assisted extraction, and non-thermal extractions can extract polysaccharides, proteins, carotenoids, and fatty acids from shrimp waste. Novel enzymatic and other green methods are available for extraction of chitin and its conversions into chitosan and chitooligosaccharides. Chitinases are valuable biocatalysts for waste management, biofuel production, food preservation, and other applications. Chitin and chitosan have innumerable industrial, medicinal, and other applications. The 3-acetamido-5-acetylfuran (3A5AF), prepared from chitin via chemo-enzymatic protocol, is a platform chemical. Proteins recovered from side streams and process effluents can be sustainably used for nutritional and other purposes. Lipid-rich seafood discards can be resource materials for biodiesel and biogas. A new synergy between marine chitinases from Bacillus magnesia and bioethanol production has been reported. Sustainable materials from fishery wastes have been developed for energy storage and other uses. Rearing of insects such as black soldier fly is an innovative bioprocess to manage food waste nitrogen. The cycled protein-rich material can be used as animal feed and soil fertilizer.

Green solvents such as ionic liquids and deep eutectic solvents are ideal to extract compounds released through biotransformation of seafood discards. These solvents have remarkable thermal stability, low viscosity, and low vapor pressure under ambient conditions. They are also less corrosive compared to mineral acids and bases. These solvents can efficiently extract proteins, chitin, lipids, and polyphenols [37, 43, 72, 73].

Ultrasound-assisted extraction (UAE), microwave-assisted extraction, supercritical fluid extraction (SFE), pressurized liquid extraction, and pulsed electric field extraction are efficient eco-friendly non-thermal processes for extraction of proteins, minerals, polysaccharides, flavor compounds, and others [24, 40, 74–79]. UAE and SFE demonstrated high extraction yields and purity levels of carotenoids and other pigments. Coagulation by electro-flocculation can recover suspended proteins and other particles from seafood processing effluents. The coagulated particles can be concentrated by techniques such as microfiltration, ultrafiltration, nanofiltration, reverse osmosis, or forward osmosis. Table 2 summarizes potential benefits of green systems in the recovery of components from seafood side streams.

3.2. Enhancing efficiency of green chemistry-based processes

3.2.1. Integration of green processes through biorefinery

Biorefineries allow a holistic approach for maximum utilization of biowaste and to minimize environmental pollution. Optimization of innovative green technologies within the framework of a biorefinery platform can facilitate zero-waste transformation of food side streams into high-value products [17, 90–96]. These biorefineries, depending on the green processes, have potentials to recover chitin, chitosan, astaxanthin from crustacean shells with significant efficiency and production yield. An anchovy biorefinery extracted PUFA-rich lipids, vitamin D_3, and zeaxanthin from the fish discards. The AD of the leftover sludge produced methane as biogas. Technoeconomic studies on microalgae-based biorefineries suggested biomass processing in a cascading manner can achieve a zero-waste operational benefit. An example for practical success is the WaSeaBi project of the European Union, which through innovative technologies recover proteins, bioactive peptides, mineral supplements, and other marketable products from fishery and aquaculture side streams accruing benefits of environmental conservation and economic value.

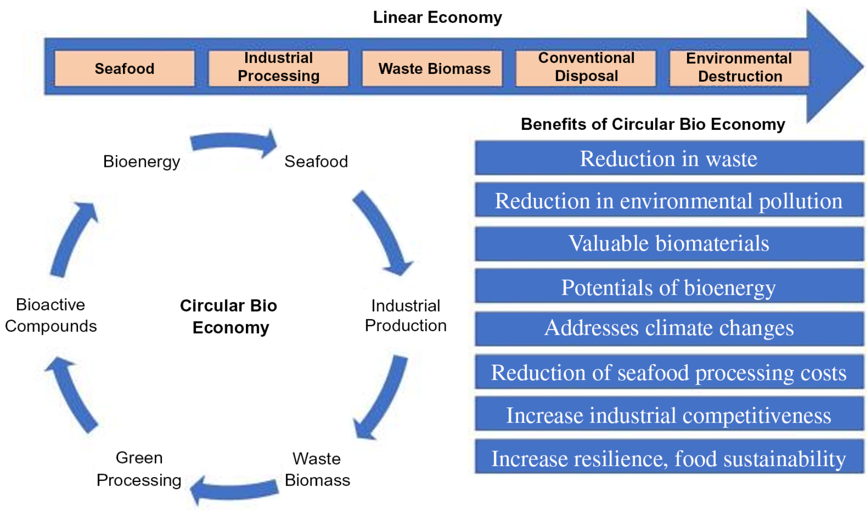
3.2.2. Circular economy approach

A circular economy (CE) approach efficiently utilizes resource through regeneration of products in a sustainable and environmentally friendly manner thereby minimizing waste and emissions. It has advantages compared to the conventional linear take-make-dispose systems [18, 97]. The CE is built on a 3R protocol, namely, Reduce-Reuse-Recycle and aims elimination of waste, circulation of materials, and regeneration of natural systems. The operational strategy of CE is recycling. In the process, the used goods are collected at the end of their life and are used as feedstock to develop new products. These products are safe for humans, animals, and the environment. Muscat et al. [26, 38, 60, 86, 97–105] suggested five ecological principles to guide the use of biomass towards a circular bioeconomy. These encompass prioritizing biomass streams for basic human needs; utilizing and recycling by-products; using renewable energy, and safeguarding and regenerating the health of the ecosystems. The environmental, social, and economic advantages of CE are reduction in carbon footprints, conservation of resource, waste reduction, and others. The European Green Deal points out the importance of transforming Europe's economy into a circular one to achieve a climate-neutral economy by 2050. The benefits are environmental protection, optimal resource utilization for food security, sustainability, and resilience of the industry. The environmental and other benefits of CE-based recovery of by-products from shrimp and bivalves have been reported. The benefits are also with respect to recovery of umami-rich seasoning from tilapia and collagen, chitin/chitosan, gelatin, and hydroxyapatite from fish scales. Circularity principles supported waste recycling practices and also nutrient-supplemented feed formulations offering environmental benefits to aquaculture. Green chemistry in conjunction with CE and waste recycling have potentials to efficiently convert seafood waste into carbon nanomaterials, which had large surface area, porous structure, high reactivity, and abundant active sites. Figure 1 summarizes the advantages of CE in the valorization of seafood discards in comparison with conventional linear economy strategy.

Table 2
Potential benefits of green processes for seafood side streams

Green processes	Benefits	References
Protein, protein hydrolysates, and bioactive peptides		
Fermentation	Almost total bioconversion, low energy processes	[38, 46–48, 80]
Enzymatic processes	Almost total bioconversion	[81]. [74]
Extraction by green solvents	Inert, recyclable, and sustainable solvents. Optimal and eco-friendly extraction	[72]; [73].
Non-thermal technologies	Shorter processing time, higher extraction efficiency	[78], [40]; [77]; [75]
Iso-electric solubilization precipitation	Almost complete recovery	[82].
Membrane filtration	Complete recovery, low energy processes	[79]
Lipids		
Enzymatic extraction	Almost total bioconversion Degradation is part of design	[74]; [68]
Sub-critical water extraction	Efficient extraction	[83]
Carotenoids		
SC-CO_2 extraction	Astaxanthin and others	[84]
Chitin, chitosan, chitooligosaccharides, 3-acetamido-5 acetyl furan		
Various green processes and strategies	Almost total recovery, entail many advantages	[85]; [37]; [65]; [62]
Other processes		
Calcination, pH activation, heat treatment, etc.,	Nanocarbon materials for energy storage and other uses	[15, 42, 70, 86]
Fish bone calcium by fermentation	Bioavailable calcium	[87]
Enzymatic, pH shift, ultrasound, and other procedures	Development of biofilters from crustacean and mollusk shell waste	[88] [89]
Valorization using biorefineries		
Integrated green processes	Up to 90% waste conversion into products, environmental, and economic viability	[60, 90, 91]

Figure 1
Advantages of circular bioeconomy strategy over linear bioeconomy in the valorization of seafood discards



3.2.3. Other potential supports

The upcoming Industry 4.0 technologies including artificial intelligence, the Internet of Things, smart sensors, and others can encourage minimization of GHG emissions, waste reduction, and recovery of food ingredients [106, 107]. Furthermore, digitalization can support green practices and sustainable economic development. These technologies optimize green chemistry-based valorization of waste through timely interventions for maximum advantage.

3.2.4. Life cycle analysis

Life cycle analysis (LCA) is a powerful methodology to evaluate the environmental benefits of green processing of seafood supply chain [6, 99, 108–113]. LCA in conjunction with material flow analysis is commonly used to quantify environmental impacts of FLW. LCA studies, in general, have shown that fishing activities constituted the highest carbon footprint, while post-landing product development displayed lower carbon footprints. LCA of different biowaste conversion processes revealed benefits with respect to environmental sustainability, and positive environmental impacts with respect to seafood biorefineries. A "cradle-to-grave" LCA showed that the recovery of $CaCO_3$ from oyster shells had a lower environmental impact than landfill.

4. Environmental Benefits of Green Processing

The green chemistry protocols, discussed above, can minimize waste through bioconversion, replacing GHG-intensive materials with recovered products having lower emissions. The supply chain decarbonization reduces scope 3 emissions and carbon footprints to improve carbon credits of the industry, besides minimizing polluting gases and release of other hazardous agents. A low-carbon, resource-efficient transition allows a cleaner, quieter, more secure, and productive economy [29, 114]. Reducing the waste by cleaner production strategies helped to lower up to 35% of the total GHG emissions from two Western Australian finfish supply chains.

The benefits of green processing are due to generally lower treatment costs and generally higher yields of products. Furthermore, the low cost of seafood side streams, their consistent availability, high value of the recovered products offer make green processing foster environmental stewardship. Integration of the green chemistry protocols within a framework of CE can optimize resource utilization in an eco-friendly manner to extend product life span that ultimately realize a sustainable economy [115, 116]. Most of the products obtained through biotransformation protocol can have lower carbon footprints, as shown by LCA studies. Huang et al. [23, 57, 117–122] observed that as many as 24 biochemicals out of a total of 25 ingredients, which were recovered through biorefinery, emitted 88 to 94% less amounts of GHG. It has been reported that for each kilogram of food protein wasted, up to 750 kg of CO_2 end up in the atmosphere. Therefore, comprehensive management of protein-rich waste through transformation by green processing has potentials to greatly reduce its carbon footprints. The environmental benefits of recovering materials from fishery discards have been reported with respect to tilapia, catfish, shrimp, lobster, and snail.

In addition to environmental benefits, green processing can be a new driving force promoting sustainable, economic, and social development [23, 24, 67, 68, 88, 103, 105, 107, 108, 123–127]. These technologies generally offer enhanced yields of ingredients from seafood discards. The recovered proteins including collagen and gelatin retain good functionality such as emulsifying, antimicrobial, antioxidant, and other functional properties. These products command a wide range of applications in multiple industries enhancing values of the seafood supply chain and hence economic returns, simultaneously meeting environmental challenges. For instance, the recovered marine proteins can enhance the value of supply chain as sources of peptides, nutritional supplements, and components in active seafood packaging, biodegradable plastics, water purification, and others. Shrimp-derived ingredients are promising in the development of formulated aquafeed items. Production of biochar and bio-oil from biomass for fuel can help decarbonization. The production of collagen from seafood waste for nutritional or high-value applications is rising. Proteins from squid and cuttlefish, because of their characteristics, have been used to develop adhesives, gels, nano capsules, and microneedles. Crustacean and bivalve processing side streams can be raw materials for developing fast time-to-market products including animal feeds, bio-pesticide/stimulants, and cosmetic ingredient. Some of these products comply with specific EU regulations. Calcined shells from crustaceans and mollusks can sequester CO_2 and remove pollutants such as SO_2, hydrogen sulfide (H_2S), NO_x, and heavy metals. Valorization of effluents from seafood processing by green methods helps recovery of ingredients having wide industrial applications. Recent interests of the seafood industry in waste valorization are indicated by a Finnish company, which upcycled seafood side streams to restructured products that commanded acceptable mouthfeel and texture.

In addition to minimizing environmental hazards, the green approach can meet the 2030 Sustainable Development Agenda of the United Nations (UN), particularly the Sustainable Development Goal 13 that aims minimizing climate change. The zero-waste approach through green processing can help meet SDG 12, which aims to reduce food losses along the production and supply chains. In addition, meeting the SDG 14, which targets to conserve and sustainable use of the oceans, seas, and marine resources can be another advantage of green processing of seafood side streams.

5. Conclusion

Seafood production results in the generation of large amounts of side streams. Traditional disposal of these side streams by landfill, incineration, etc., is responsible for heavy environmental pollution and global warming. The article highlights the prospects of green chemistry-based waste management in mitigation of seafood-related environmental pollution and global warming. Green processing can be natural solution for low-carbon, environmentally viable, resilient, and sustainable seafood supply chain. The biotransformation of the side streams using green chemistry protocols, ideally on a biorefinery platform supported by CE protocol, can abate global warming and other environmental hazards. Multi-disciplinary interactions and collaborative ventures on the lines discussed in the article can be key to mitigate environmental hazards of seafood processing industry that can provide a dynamic, safe, and sustainable seafood supply chain.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The Food and Agriculture Organization of the United Nations data that support the findings of this study are openly available at https://doi.org/10.4060/cc0461en. The Food and Agriculture Organization of the United Nations data that support the findings of this study are openly available at www.fao.org/flw-in-fish-value-chains/overview/objective/en/. The Intergovernmental Panel on Climate Change data that support the findings of this study are openly available at https://doi.org/10.59327/IPCC/AR6-9789291691647.001. The United Nations data that support the findings of this study are openly available at https://sustainabledevelopment.un.org/post2015/transformingourworld/publication. The United Nations Environment Programme data that support the findings of this study are openly available at https://www.unep.org/resources/toolkits-manuals-and-guides/green-and-sustainable-chemistry-framework-manual. The World Economic Forum data that support the findings of this study are openly available at https://www.weforum.org/stories/2021/12/green-chemistry-manufacturing-climate-change/.

Author contribution

Vazhiyil Venugopal: Conceptualization, Methodology, Resources, Writing – original draft, Visualization. **Se-Kwon Kim:** Writing – review & editing, Project administration.

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