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Review

A circular economy framework for seafood waste valorisation to meet challenges and opportunities for intensive production and sustainability

Ronan Cooney [a,b], David Baptista de Sousa [c], Ana Fernández-Ríos [d], Sinead Mellett [e], Neil Rowan [e], Andrew P. Morse [f], Maria Hayes [g], Jara Laso [d], Leticia Regueiro [c], Alex HL. Wan [a,b,h], Eoghan Clifford [a,b,*]

[a] School of Engineering, University of Galway, Galway City, H91 HX31, Ireland
[b] Ryan Institute, University of Galway, Galway City, H91 TK33, Ireland
[c] ANFACO-CECOPESCA, Department of Circular Economy, Campus University 16, 36310, Vigo, Spain
[d] Department of Chemical and Biomolecular Engineering, University of Cantabria, Av. de Los Castros, s.n., 39005, Santander, Spain
[e] Bioscience Research Institute, Technological University of the Shannon, Midlands Midwest Athlone Campus, N37 HD68, Ireland
[f] School of Environmental Sciences, University of Liverpool, Liverpool, UK
[g] Department of Food BioSciences, Teagasc Food Research Centre, Ashtown, Dublin, D15 DY05, Ireland
[h] Aquaculture Nutrition Research Unit (ANRU), Carna Research Station, Ryan Institute and School of Natural Sciences, University of Galway, Carna, Connemara, Co. Galway, H91 V8Y1, Ireland

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ABSTRACT

There is a growing concern among societies and consumers over food security and the sustainability of food production systems. For seafood, it has been highly advocated as a healthy food source and its sustainability credentials. However, the increasing global demand for seafood and the need to supply the quantities are creating sustainability issues, e.g., the importation of plant and marine proteins for aquafeed production. Consequently, there is a necessary need to analyse the supply chain and life cycle of these systems to determine their sustainability merits and how to enhance them. The circular economy (CE) aims to reduce processing by-product underutilisation, increase the rate of reuse, and reduce pressure on natural resources and systems. For seafood, there are large quantities of biomass that are being lost through bycatch/discards, waste from aquaculture (e.g., sludge and wastewater), and by-products generated through processing (e.g., trimmings and offal). These can all be valorised for the generation of feeds, value-added products, or further food production. This review will focus on seafood by-products generated during the processing into consumer products, and the current methods that could be used to manage or treat these waste streams. The review presents a stepwise framework that outlines valorisation opportunities for seafood by-products. This framework can enable producers, operators, regulators, and investors to integrate with the principles of the CE with the consideration of achieving economic viability. The challenges of seafood loss due to climate change and emerging recycling strategies will also need to be considered and integrated into the valorisation pathways. Communication, education, and engagement with stakeholders are key to transitioning to a circular economy. Where increase awareness and acceptance will create drivers and demand for seafood by-product valorisation. Overall, the impact of such a circular production system will potentially lead to higher production efficiency, reduce demand for natural resources, and greater seafood production. All of which addresses many of the United Nation's Sustainable Development Goals by contributing towards future food security and sustainability.

1. Introduction

Human activities contribute to the significant decline in environmental quality and biodiversity. To the present date, interactions between humanity and the environment have been based on a model of extraction, processing, production, and discarding the unused products and the by-products produced along the core product as waste back into the environment (Tan and Lamers, 2021). This linear economy model is

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* Corresponding author. School of Engineering, University of Galway, Galway City, H91 HX31, Ireland.
E-mail addresses: rcooney@nuigalway.ie (R. Cooney), eoghan.clifford@universityofgalway.ie (E. Clifford).

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no longer compatible with the current capacities of this planet (Borrello et al., 2020; European Commission, 2020b; Laso et al., 2018; Regueiro et al., 2021). With a growing population compounded by a growing middle class with increased spending power, the global demand for food is increasing (Belton et al., 2020; Béné et al., 2015; Fernández-Ríos et al., 2021; Rohm et al., 2017). In particular, the demand for seafood and seafood products is rising also due to the advocacy as part of a healthy diet (Bohnes et al., 2020; Regueiro et al., 2021).

Seafood is a colloquial and highly broad food category. For example, in much of Europe, this often encompasses both freshwater and marine finfish species (e.g., farmed salmon, trout, carp, seabass, seabream), bivalves, (e.g., mussels, clams and oysters), decapods, (e.g., crabs, shrimp, and lobsters), cephalopods (e.g., squid and octopus), but also algae (macro and micro) and cyanobacteria. These diverse groups of seafood are considered to have a better environmental performance than other protein-rich foods, such as terrestrially farmed animals (European Commission, 2019, 2020a). Their production is either derived through farming (aquaculture) or wild caught (fisheries). Together these food production systems produced 214 million tonnes of global seafood in 2020 and over half of this production was from aquaculture (FAO, 2022). The Food Agricultural Organisation of the United Nation has estimated that the seafood trade is worth USD 151 billion and is projected that this will further grow by over 13% in production value in 2030. Much of this growth will be driven by aquaculture due to its increasing efficiency, farmed species diversification, and new production opportunities.

Like many other food production systems, seafood must employ the concepts of life cycle thinking and the circular economy (CE) to increase production efficiency and mitigate its environmental impact (Cortés et al., 2021b; Ruiz-Salmón et al., 2021). This is either through valorisation strategies or nutrient recovery technologies (de la Caba et al., 2019; Venugopal, 2021). Within the EU, policies for increased seafood consumption are being introduced to increase food and seafood circularity (European Commission, 2020b). The Circular Economy Action Plan (European Commission, 2020b) was launched by the European Union (EU) as part of the European Green Deal. The plan aims to transition the European economic bloc from a linear to a circular economy. This transition has been advocated to open new avenues for resource efficiency and places the concept of life cycle thinking as its core action (Gheewala and Silalertruksa, 2021; Ruiz-Salmón et al., 2020). This drive for circularity in value chains and processes will help to support (Raimondo et al., 2021; Regueiro et al., 2021; Zilia et al., 2021).

(i) Greater use of renewable energy,
(ii) More responsible use of resources and, crucially,
(iii) Reuse and valorisation of by-products and residue streams generated from seafood processing.

To combat the seafood nutrients, energy, and elemental loss along the supply chain, there is a need to identify value in this lost material. Thereafter, there is a need for novel designs for the valorisation and exploitation of seafood by-products, as well as the promotion of more environmentally, socially, and economically sustainable business models. Furthermore, any proposed solutions should contribute to increasing seafood circularity by maximising the potential value that can be derived. The underutilisation of by-products is regarded as a wasted opportunity. Therefore, the present review aims to identify the opportunities for CE within seafood production chains. This will be achieved by using a stepwise valorisation framework, with a particular focus on.

(i) The current protocols for seafood by-product treatment,
(ii) Opportunities for CE,
(iii) Emerging seafood loss, and
(iv) Emerging strategies for CE and opportunities.

Furthermore, this review will evaluate the barriers that prevent or limit seafood circularity and potential solutions. Overall, this review will form a catalyse in allowing researchers, industry, and policymakers in focusing key innovations to drive a CE in seafood.

2. Research methodology

The present review was carried out by searching for peer-reviewed studies relevant to the area of seafood waste, by-product valorisation, and the circular economy. Relevant literature was reviewed using academic databases (inc. Scopus, Google Scholar, Web of Science and Science Direct). The terms used for the literature search were “seafood loss”, “seafood waste”, “seafood nutrient recovery”, “aquaculture waste/loss”, “fisheries waste/loss”, “seafood circular economy” and “seafood circularity”. The inclusion criteria for the results were that the articles had to be peer-reviewed and published in the English language and must have been published in the last 10 years (2010–2022). The exclusion criteria that were applied focused on the thematic relevance of the article and that it not be an opinion article, conference article, or from the grey literature. Further refinement of the results was reached by implementing the stepwise approach to key areas of seafood waste that the article aimed to review. These areas were (i) seafood waste streams and (ii) current waste treatment protocols. The next thematic area focused on approaches which incorporate the circular economy into seafood waste management, (iii) nutrient recovery technologies, (iv) nutrient recovery strategies and management practices, (v) seafood loss, (vi) recycling strategies and (vii) bio-based resources.

Using these search terms and criteria, 142 articles derived from these searches were then broken down into the relevant thematic areas. This critical analysis of this article concludes with a discussion of the challenges with recommendations for implementation and actualisation, which will transform societies from a linear into a circular economy. This analysis will be European-centric due to the over-exploitation of aquatic environments and the economic bloc’s 88 million tonnes of food waste per annum (European Commission, 2022).

3. Current practices for seafood by-products

Within seafood production systems, large quantities of by-products are generated from both wild capture fisheries and farmed aquatic species-aquaculture. Very frequently these by-products are disposed of as waste or discharged into the aquatic environment. This brings the need to implement effective and novel treatment and utilisation protocols to reduce any environmental impact on aquatic environments or land and promote more efficient production practices that reduce biomass, energy, or nutrient losses (Caruso, 2016).

Within the seafood category, there are significant volumes of by-products being generated from the production, processing, distribution, consumption, and disposal stages (Hayes and Gallagher, 2019; Venugopal, 2021). It has been estimated that as much as 36% of seafood can be lost or wasted (FAO, 2018; Gustafsson et al., 2013). These losses are often complex and each by-product streams are unique from different seafood production systems which leads to varying composition, quantities, and quality (Fig. 1). Consequently, this results in the need for different technological requirements in its management after its produced.

In terms of by-product generation, there are a variety of sources from the seafood sector, particularly depending on the level being studied. By-product volumes, value and quality can vary from species to species, between regions, availability, and at different stages of the supply chain. For example, the use of pond culturing systems (flow through aquaculture) are extensively used for freshwater aquaculture across the world (Bohnes et al., 2019; Bohnes and Laurent, 2019; FAO, 2018). Its attractiveness to farmers is the low technology required to set up and maintain but more importantly can be easily built with limited cost in relation to aquatic farm systems. In many instances, pond systems may

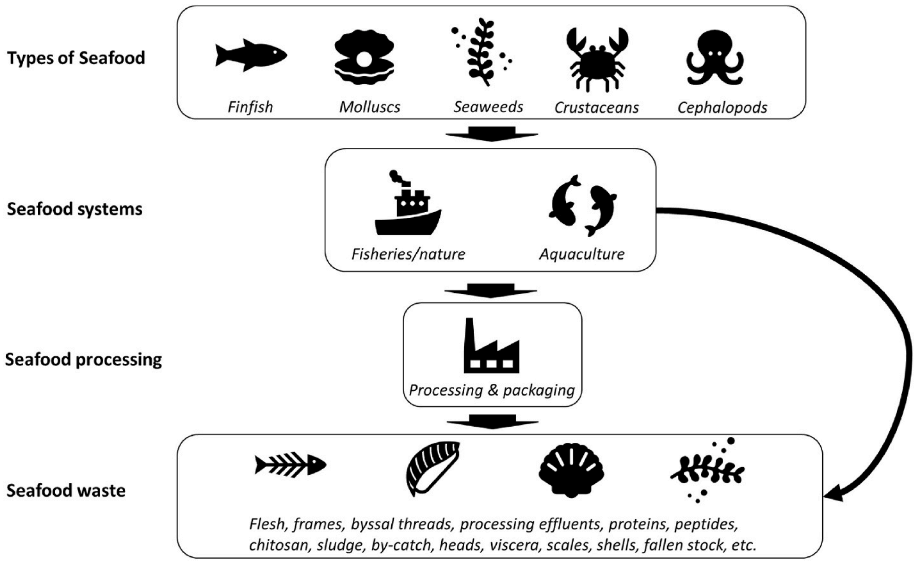

Fig. 1. An overview of the several types of seafood, their production/capture systems, and the types of by-products that are generated.

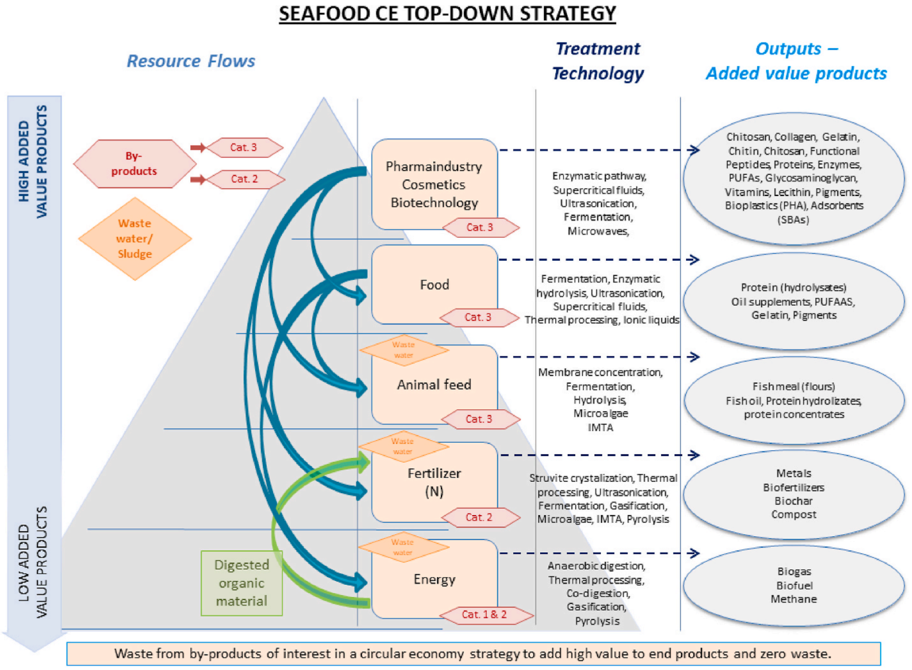

Fig. 2. A proposed framework for top-down CE strategies for seafood by-product valorisation. Animal by-products categories are presented as Cat. The triangle indicates the added value of the products and volume needed.

not allow for efficient process control, this can result in wasted and uneaten feed that can settle and accumulate over time on the pond floor. This uneaten feed can become a nutrient-rich layer that provides a substrate for microbes to convert and breakdown down biochemically (Dauda et al., 2019). This layer can also reduce process efficiencies by consuming oxygen, thus requiring larger amounts of supplementary aeration (Tahar et al., 2018). The low technology requirements of pond-based aquaculture are in contrast to the high technology requirements of recirculating aquaculture systems. These closed or semi closed aquaculture systems re-use a large proportion of the water by undergoing treatment processes. Commercial recirculating aquaculture systems as mechanical solids removal, bioreactors, heating, and cooling, and ozonation and/or ultraviolet sterilisation (Martins et al., 2010). From the solid's removal, sludge which comprises uneaten feed and biogenic wastes is captured and stored on the site for further treatment. Generally, this sludge is treated in centralised facilities such as publicly owned treatment works used for the treatment of other livestock waste as well as domestic and industrial waste (van Rijn, 2013). Other routes of food loss and waste in open aquaculture systems can be due to disease outbreaks and environmental events such as jellyfish blooms, and algal blooms which can result in mortality events (Brooks et al., 2022; Clinton et al., 2021).

Within fisheries, the main by-products are by-catches and discards. The former is classified as non-targeted caught species which can impact marine food webs, e.g., cetaceans, echinoderms, and molluscs (Bielli et al., 2020). While the latter are species that are captured which may not be of suitable grade (e.g., below harvest size), or economic value, or the fishers may not have a quota for the species. It has been estimated by the EU that between 7 and 10 million tonnes of fish are discarded annually across the world (EC, 2022). Like bycatches, discards are returned to the sea dead which has led to a significant negative public image of fisheries (FAO, 2020). In recent years there has been a growing trend to utilise these fish for the production of fishmeal, fish oil, fertilisers, biostimulants, and even food ingredients for human consumption (Dineshbabu et al., 2013; Madende and Hayes, 2020). This trend is supported by several mitigation strategies, e.g., the EU's Common Fisheries Policy on discards ban and landing obligation. They aim to reduce the levels of bycatch and discards through modifications that include the mesh size, use of fisheye devices (FAO, 2020), implementation of circle hooks, alternate baits in longline fisheries, improvements in remote sensing, and animal tracking technologies on vessels (Komoroske and Lewison, 2015).

While the volumes of by-products from aquaculture and fisheries seem high, the major source of lost or unused material can be found in the processing stage. By-products generated during processing typically consist of biomass produced during filleting and preparation of processed seafood products direct to the end consumer. For fish by-products, there is the skin, bones, trimmings, heads, offal, shells and byssal threads from bivalve and mollusc species (Table 1). By-products should be treated on-site as food grade if required for food ingredient generation or feed grade if processed further by approved animal by-product operators. In some instances, these may be discharged to the marine environment, sent to sewage treatment plants, or disposed of in landfills (Cadavid-Rodríguez et al., 2019). For example, "stick-water" produced from the processing of fish (e.g., blood, mucus, and residue muscle proteins) can be an issue due to their quantities being generated and the requirement for sanitary disposal. However, in a number of countries, actions have been taken to reduce and valorise these by-products into food-grade and value-added food ingredients, such as collagen, chitosan, and proteins (Erasmus et al., 2021; Mathew et al.,

Table 1
Current seafood by-products and waste sources for valorisation, biorefining, or disposal.

Stage	Treatment/Process	Current waste hierarchy option	Seafood by-products	Current management strategy	Reference
Aquaculture	Use of pond systems	Disposal	Uneaten feed and sludges	Accumulation of organic by-products at the bottom of the system, where microbes act converting it to less toxic material	Dauda et al. (2019)
	Use of recirculating aquaculture systems	Disposal	Uneaten feed and sludges	Partial removal of organic by-products from aquaculture water through sedimentation and filters. Subsequent treatment in publicly owned wastewater treatment plants.	Martins et al. (2010)
Fishing	No treatment	Disposal	Bycatch	Return of the dead catch to the sea	FAO (2020)
	Fishmeal production	Valorisation	Fish bycatch	Production of fishmeal in processing plants destined for aquafeed products	Dineshbabu et al. (2013)
	Fertiliser production	Valorisation	Fish bycatch	Production of liquid or solid fertilizer, silage, or compost through fermentation or composting	
	Mitigation	Prevention	Fish bycatch	Modifications in mesh size Use of fisheye devices Implementation of circle hooks and alternate baits in longline fisheries Improvements in remote sensing and animal tracking technologies	FAO (2020) Komoroske and Lewison (2015)
Processing	No treatment	Disposal	Heads, bones, offal, and skin	Waste is eliminated through its discharge into the ocean or its disposal in landfills	Cadavid-Rodríguez et al. (2019)
	Bait	Valorisation/ biorefining	Heads, bones, offal, and skin	Valorisation of by-products for fish bait	Masilan et al. (2021)
	Silage production	Valorisation	All fish and selfish by-products	Production of silage (protein-rich liquid) through enzymatic hydrolysis of fish by-products for aquatic and terrestrial animals feeding	Islam and Peñarubia (2021)
	Fishmeal production (human consumption)	Valorisation	Heads	Production of meal in fishmeal processing plants for human consumption, such as fish mince, fish smoked sausages, or fish patties	Erasmus et al. (2021)
	Fishmeal production (animal feeds)	Valorisation	All fish by-products	Production of aquafeed for a low trophic level or warm water fish (like carp or tilapia)	Saleh et al. (2020)
	Functional food	Valorisation/ Biorefining	All fish by-products	Production of functional foods or products such as collagen, peptides, chitin, enzymes, and gelatin for human consumption	Coppola et al. (2021)
	Fertilizers production	Valorisation	Bones, heads, viscera, and wastewater (blood water)	Production of biostimulants and liquid fertilisers through degradation of viscera, biological treatment of wastewater for agricultural application	Kim et al. (2010) Kim (2011) Ching and Redzwan (2017)
	Biofuels production	Valorisation/ Biorefining	Offal and bones	Extraction of oils from fish waste and subsequent biogas or biodiesel production and by-production of glycerine for pharmaceutical, food and cosmetic applications	Karkal and Kudre (2020) Jayathilakan et al. (2012) El-Gendy et al. (2014)
	Omega-3 fatty acids extraction	Valorisation/ Biorefining	All fish by-products	Extraction of omega-3 fatty acids through anaerobic digestion for food applications (food supplements)	Mbatia et al. (2010) Nges et al. (2012)
	Collagen extraction	Valorisation/ Biorefining	Skin, scales, fins, and bones	Extraction of collagen for food, cosmetic, pharmaceutical, tissue engineering, and biomedical industries	Bhuimbar et al. (2019) Araujo et al. (2021)
	Chitin and chitosan extraction	Valorisation/ Biorefining	Shellfish shells	Extraction and purification of chitin and production of chitosan for chemical and food applications	Mathew et al. (2020)
	Protein hydrolysates extraction	Valorisation/ Biorefining	All fish and selfish by-products (especially skin and bones)	Isolation and purification of proteins for human nutrition, cosmetics, and pharmaceutical purposes	Anal et al. (2013)
Consumption	No treatment	Disposal	Bones, viscera, heads, and skin	Waste is eliminated through its disposal in organic recycling bins and later deposited in landfills	Cadavid-Rodríguez et al. (2019)

2020). These products can directly contribute to reducing the environmental impact and production costs of the primary fish product. This may provide an impact positively human health. Whereby, the production of novel, functional food ingredients potentially can reduce the risk of diseases or enhance health (Hayes, 2021).

Markets for these by-products can include low-value animal feeds or agricultural products. A common way to produce low-value feeds is to use seafood by-product-based on ensilage processes. This is used as it is a relatively simple and cheap process, taking advantage of all aspects of the by-product, i.e., protein, lipids, and bone materials (Islam and Peñarubia, 2021; Mousavi et al., 2013). Examples of higher-value alternatives for by-product use include the production of hydrolysates for human consumption, fish mince, fish smoked sausages, fish patties (Erasmus et al., 2021), and aquafeeds (Saleh et al., 2020). The use of by-products for the production of fertilisers and biostimulants has also received attention over the years as a means to increase the economic and ecological sustainability of the fishing industry (Ahuja et al., 2020), by finding avenues to derive value from bones, heads (Kim et al., 2010), viscera (Kim, 2011), and even the wastewater from processing and effluent from aquaculture farms (Ching and Redzwan, 2017; Hayes and Gallagher, 2019).

An area which has been widely studied is the valorisation of fish by-products into high-value products. Some of these studies have assessed the extraction of omega-3 fatty acids, for food supplements because of their preventive role in cardiovascular diseases (Mbatia et al., 2010; Nges et al., 2012), collagen for food, cosmetic, pharmaceutical, tissue engineering, and biomedical industries (Araujo et al., 2021; Bhuimbar et al., 2019), chitin or chitosan from shells for chemical applications (Mathew et al., 2020), and protein hydrolysates (Anal et al., 2013). Other opportunities and strategies for the extraction of oils and the subsequent production of biofuels, like biogas or biodiesel, have also been assessed (Karkal and Kudre, 2020). These valorisation processes make use of by-products generated from seafood production activities such as fishing, aquaculture, processing (e.g., offal and trimmings, Jayathilakan et al., 2012), and waste from consumers (e.g., bones) (El-Gendy et al., 2014). However, research and the uptake of seafood valorisation into commercial practices must be underpinned by the CE model. This would ensure the seafood by-products valorised for further use are sustainable through evidence-based metrics, such as life cycle assessment (LCA).

4. Incorporating the circular economy in seafood value chains

To incorporate CE principles into seafood value chains, there is a need for measurable value(s) from the utilisation of the by-products, e.g., economic, consumer perception, de-risk production portfolio, and legislation compliance. A way in which this can be facilitated is through the use and promotion of eco-design and eco-efficiency (de la Caba et al., 2019; Regueiro et al., 2021; Ruiz-Salmón et al., 2020). The former is integrating environmental attributes into the design of the value chain, while the latter is producing more from fewer resources. Opportunities exist based on a value and volume hierarchy, which can be used to valorise potential products from seafood by-products. Within the seafood industry, there are two main types of by-products that are considered waste. These by-products can be effluents from process water (i.e., sludge, aquaculture wastewater, and processing and cooking effluents) or the biological by-products resulting from the processing (e.g., crustacean, and bivalve shells, offal, fish heads, frame, and trimmings). Some whole fish material could be sourced as discarded from fisheries due to changes in the EU's Common Fisheries policy. Although the quantities are reduced in recent years due to policy changes when compared to a more static and inherent loss from seafood processing for human consumption.

Research activities have identified the potential for the valorisation of liquid effluents from seafood and processing activities, however, these are not yet as extensively applied as they could be (Alkaya and Demirer, 2016; Zilia et al., 2021). For example, it is possible to extract pigments, proteins, or flavour compounds (Tremblay et al., 2020) from processing by-products. Other avenues for the recovery of valuable products include the blood waters from the processing of fish. These waters contain substances which could be valorised into products such as antioxidant peptides, renin, and dipeptidyl peptidase (Hayes and Gallagher, 2019). Other recoverable materials from effluents include sludge or biosolids. Alternative management for sludge could generate novel resources, generating valuable elements such as carbon and different nutrients. Furthermore, as an energy resource in the form of biogas or biodiesel, sludge and recovered solids can be integrated into sustainable solutions that can help mitigate energy consumption in the sector (Gherghel et al., 2019).

With regards to organic processing by-products such as heads, skin, fins, bones, viscera, and scales are often derived into low-value commercial products such as feed, fish meal and oils (Al Khawli et al., 2019; Bruno et al., 2019a). Adhering to the principles of sustainability, these products could be important sources of new high-quality and high-value commercial compounds such as proteins, peptides, vitamins, amino acids, collagen, chitin, enzymes, gelatine, glycosaminoglycans, polyunsaturated fatty acids, minerals, etc. Furthermore, they can provide important functional and bioactive properties for food, agriculture, cosmetics, pharmaceuticals, and/or nutraceutical industries (Al Khawli et al., 2019; Ghalamara et al., 2020; Wang et al., 2019). In addition, different processes have been developed to exploit these by-products efficiently in the form of food packaging, silage, fertiliser enrichers, biofuels, etc. (Nawaz et al., 2020).

In a CE context and to achieve a zero-waste goal, a top-down classification strategy could be established according to the quality or value of the resulting products from liquid or solid by-products. This is with a view to minimising the generation of waste material, which does not result in the recovery of energy or products of interest. It is essential to identify appropriate extraction technologies that will minimise energy consumption, maximise quality and yield, guarantee the safety of the resultant product, and ensure the objectives of sustainable development. However, the valorisation of these by-products may be impacted by certain regulations. Within the EU, the European Commission Regulation (EC) 1774/2002 established the sanitary standards applicable to animal by-products not intended for human consumption (currently repealed by regulation (EC) 1069/2009). For these purposes, by-products are classified into 3 categories based on their risk to human and animal health and specify the conditions under which they can be managed (Table 2). These regulations place a limit on some of the material which can be valorised but does not unduly impact most seafood. Only designated category 3 can re-enter the food chain, typically in the form of farmed animal feed or aquafeeds.

In Fig. 2, the blue arrows represent the flows of by-products or low-value discards that are used in industries with "lower added value". These levels utilise a higher volume of material for a lower value-added product. As the material moves towards the base of the pyramid it is placed in the category below. This is because each time a lower level is used, the less value the resultant product can obtain. In the case of the green arrow, this indicates the co-product that results from energy production that could be reused in the fertilizer category, promoting recirculation of the system (i.e., digestate). The colours for wastewater/sludge (orange) and by-products (red) have no value per se. In the figure, they symbolize the types of by-products and effluents obtained during industrial processes for each of the animal by-products categories.

4.1. *Pharma-industry, cosmetics, and biotechnology opportunities*

There are a number of processing/biorefinery technologies that can be used to extract, concentrate, refine, and transform compounds from seafood by-products into high-value market bioactive/functional products for nutraceutical, pharma-industry, cosmetics, and biotechnology. These technologies can often include the use of supercritical extraction,

Table 2
Animal by-products (ABP) categories in seafood by-products and waste (European Union Regulation EC No. 1069/2009).

ABP Category	Risk level	By-product management	ABP material	Permitted uses
Category 1	High	Disposal only	Diseased fish, fish with notifiable diseases etc.	Incineration or as fuel in approved plants.
Category 2	Med	Not intended for animal consumption	Livestock carcasses and non-disease mortalities	Fertiliser, landfill (after sterilisation), and safe technical use.
Category 3	Low	'fit for human consumption' and derived from processing plants	Fish and shellfish processor by-products, fish trimmings.	Fertiliser, biofuel, petfood, farmed animal feeds, and aquafeeds.

A stepwise seafood by-product valorisation framework is outlined in Fig. 2. This framework is based on five levels of value for seafood by-products using a volume-value relationship (i.e., low volume, high value products at level 1 and high volume, low value products at level 5). High value applications for by-products include (Level 1) pharma-industry, cosmetics, and biotechnology, (Level 2) food. Medium value applications are valorisation as (Level 3) animal feed. Lower value applications include (Level 4) fertilisers (nitrogen, N; phosphorus, P; potassium, K) and (Level 5) energy. The nutrient recovery technologies, the value-added opportunities, and products for each of the levels of seafood by-product valorisation are presented below from high to low-value products.

membrane separation, and/or hydrolysis, inc. chemical and enzymatic. Such use allows compounds such as vitamins, flavours, essential oils, carotenoids, enzymes, amino acids, lecithin, and polyunsaturated fatty acids to be obtained from seafood by-products. The advantages of using technologies such as supercritical fluid extraction eliminates the need for extractive organic solvents that is traditionally used for extracting bioactive compounds. These solvents might not be food-safe, or environmentally friendly, and at elevated temperatures could compromise recovery rates of the compound(s) (Al Khawli et al., 2019; Haque et al., 2014; Kuvendziev et al., 2018; Uddin et al., 2011). Most studies evaluating the potential of supercritical fluids have focused on recovering lipid-soluble and antioxidative compounds. These products can often have the greatest economic value because they can improve certain technological properties in food matrices in novel foods (Al Khawli et al., 2019).

In contrast, the long-chain polysaccharides chitin and chitosan recovered from shrimp and crab shells are typically through the use of microbial proteolytic enzymes to deproteinise crustacean by-products (Wang et al., 2019). The other methodology is through the use of inorganic acids to demineralise the shells, followed by strong alkalis for deproteinisation. While the latter method produces a purer final product than the biological technique, it does however produce waste by-products, and if not removed, it can contaminate the final product.

The use of pressure membrane technology can purify recovered protein/peptide from seafood. The usefulness of this technology can avoid the need for solvents or adsorbents, as Through this technology, it is possible to obtain permeate fractions enriched in small bioactive peptides with bioactive potential as antioxidative, antimicrobial, and angiotensin-converting enzyme inhibitory activity (Chi et al., 2015; Karnjanapratum et al., 2017; Ngo et al., 2014). For example, it has been observed that cod blood can be a potential source of peptides with antioxidative properties and could be exploited as a functional food ingredient (Ghalamara et al., 2020). In addition, peptides purified from fish by-products also showed interesting antimicrobial activity (Ennaas et al., 2015; Song et al., 2012), i.e., peptides purified from cod blood and sardine cooking wastewater against *Escherichia coli* (Ghalamara et al., 2020).

The use of sludge derived from seafood was recently reviewed by Gherghel et al. (2019). The authors reported the obtention of different compounds of interest such as adsorbents obtained using microwave and pyrolysis treatments, high-quality enzymes, and proteins comparable to commercial versions using ultrasound, or bioplastics using activated sludge as raw material during bacterial fermentation. The bycatch small-spotted catshark (*Scyliorhinus canicula*) viscera have been used as a substrate to produce hyaluronic acid by *Streptococcus zooepidemicus* fermentation (Vázquez et al., 2015). Scales have also been used as a substrate to generate collagenase-like enzymes by microbial fermentation (Wang et al., 2019). Cephalopod by-products such as squid skin, it is a source of collagen for the manufacture of cosmetic products. In addition, this by-product has been investigated as a potential plasticiser in the preparation of biofilms in combination with chitosan (Wang et al., 2019).

4.2. Food opportunities

The use of seafood by-products continues to be a challenge due to food safety, their interactions with other ingredients used in the final food product, and public perception and consumer acceptance. Several products of interest can be obtained from fish by-products such as protein hydrolysates and polyunsaturated fatty acids from trimmings, heads, and frames. However, any by-products used for human consumption must be treated as food grade standards during their collection and processing, e.g., HACCP, which meets below limits of foodborne pathogens. Neglecting these standards can result in hygiene issues, spoilage, and food-borne illness due to seafood's inherent highly perishable nature.

Protein hydrolysates are perhaps the most common use of fish by-products, e.g., fish heads, frames, and offal. The generation of functional food ingredients containing bioactive peptides that can provide the consumer with a health benefit that goes beyond basic, human nutrition is a growing area of both research and commercial venture. Protein hydrolysates, concentrates and isolates are distinguished by the level and quality of protein contained in each and can command different market values based on protein content but also techno-functional and sensory attributes as well as health benefits for the consumer (Hayes et al., 2016). Hydrolysates also have applications as functional feed ingredients to improve the health of farmed aquatic species, ruminants, and companion animals (Naik et al., 2021).

Similarly, omega-3 fatty acid-rich oils from fish livers for the food/health supplement market (Al Khawli et al., 2019; Anal et al., 2013; Bhuimbar et al., 2019). Marine-derived oils (e.g., fish oil) are valuable by-products but were once treated as a low-value commodity until the recognition for their high nutritional value and now it is exploited as an omega-3 fatty acid-rich supplement. Besides this, other applications have been tested including the omega-3 fatty acid enrichment of bakery and pasta products (Nawaz et al., 2020). The traditional method of oil extraction is through cooking and separation. Although, there are other technologies such as ultrasound combined with assisted enzymatic extraction that can improve the oil extraction efficiency. Recent studies have shown that waste parts from fish (e.g., heads and frames) that were pre-treated with assisted enzymatic extraction before enzymatic hydrolysis led to a higher level of oil recovery. This included a higher percentage of polyunsaturated fatty acids level and greater oxidative stability, lower apparent viscosity, and an overall sensitivity to temperature-dependent degradation. All these attributes would lead to wider applications in food products (Al Khawli et al., 2019; Bruno et al., 2019b). While marine oils could also be co-produced along with the production of protein hydrolysates, where centrifugation or filtration technologies are typically used for recovery.

Calcium from fish bones has received attention as a natural calcium supplement for individuals that has calcium deficiency or as a health supplement (Nawaz et al., 2020; Venugopal, 2021). Studies have previously reported that calcium bioavailability is higher in tuna bones in comparison to calcium from other sources such as milk, vegetable, and salts.

However, all previous studies suggested pre-treatment, including heating, boiling, tempering, or chemical treatment before adding it to the food matrix (Gupta et al., 2016; Nawaz et al., 2020). The reason is that the bone matrix is composed of a complex inorganic part and an organic part of collagen fibres. These fibres are difficult to break down in simple enzymatic digestion without prior softening of the bones. Likewise, by incorporating boiled fish bones from Nile tilapia (*Oreochromis niloticus*) into biscuits, it was reported that fish bone fortification may be a rich source of calcium and other minerals, along with improved fatty acids (Nawaz et al., 2020).

4.3. Animal feeds opportunities

The majority of animal by-products from fisheries and processing plants have long been used in fish meal production that is destined for animal feeds (Cho and Kim, 2011). Although from a circular business economic model perspective, the aim would be to use these by-products for greater value outputs, specifically Level 1 (pharma-industry, cosmetics and biotechnology and human food) and 2 (human food) categories (Fig. 2). However, not all by-products are suitable for CE implementation. For example, the low production yield of the seafood by-product to be economically viable, loss of quality, sporadic times of production, long distances between the by-product producer and the valorisation plant, or insufficient logistical resources to be valorised under Levels 1 and 2, the by-product could therefore be more suitable for animal feed rendering use that is lower grade. One example can be the red and vascularised fish flesh that is typically produced as waste from the fish filleting plants. It is a high-quality protein source that is often used for animal feed production or discarded without revenue being generated (Herpandi et al., 2011; Nawaz et al., 2020). This is often due to the low quantities being generated and logistical difficulty in attaining Level 1 or 2 use.

However, if it is commercially, technically, and/or logistically viable then seafood waste could undergo a series of biorefinery processes to produce functional ingredients for feed use. For instance, the use of supercritical fluid extraction makes it possible to reduce the fat content of fishmeal without affecting the quality of the protein. When operated under certain extraction conditions (10–40 MPa, 25–80 °C and with CO_2 flows of 9.5 g min^{-1}), it is possible to achieve a 90% reduction in lipid content (Al Khawli et al., 2019). Fish oil is extracted from fish viscera by pressing, microwave-assisted extraction, supercritical fluid extraction, solvent extraction, autolysis, and enzymatic hydrolysis (Wang et al., 2019). The application of supercritical fluid extraction has increased in recent years as CE and resource-efficient practices have been incorporated into commercial production practices (Al Khawli et al., 2019; Venugopal, 2021).

The high cost of fishmeal used in fish feed has prompted alternative ways of obtaining protein for feeds. A low-cost method for processing seafood by-products for feed is fish silage (Islam and Peñarubia, 2021; Mousavi et al., 2013). This process results in excellent protein products and is a valuable source of amino acids for protein biosynthesis, with high amounts of polyunsaturated fatty acids. The resulting biorefined products are widely used as feed ingredients in aquaculture for different aquaculture species. During silage processing, endogenous enzymes hydrolyse proteins and transform them into more soluble forms of nitrogen, this helps contribute to their widespread use (Ahuja et al., 2020; Herpandi et al., 2011; Mousavi et al., 2013).

As a potential solution to liquid by-product streams for aquaculture and fish processing, the cultivation of high nutritional value macroalgae (seaweeds) in integrated multitrophic aquaculture systems presents great potential. Ammonia/ammonium from protein metabolism and uneaten aquafeeds is the main aquaculture effluent. It is also often one of the most difficult nutrients to limit in flow through and open aquaculture systems, e.g., sea cages (Badiola et al., 2012; Liu et al., 2016; Song et al., 2019). In general, intensive aquaculture systems, solids are removed by sedimentation or screening, and the nitrogenous nutrient is converted to nitrate (NO_3), through nitrification in bacterial filters (Milhazes-Cunha and Otero, 2017). Therefore, current effluent treatment technology depends on bacterial systems and does not add value to the process beyond converting the toxic nutrient to a lesser form in the effluent. This is except for some aquaculture facilities possessing additional units where that host anaerobic denitrification bacteria where that convert nitrates into nitrogen gas. Although this process is technically prohibitive, e.g., the conversion process is relatively slow. Microalgae can be used for the efficient collection and recycling of nutrients in aquaculture effluents and can reduce chemical and biochemical oxygen demand concentrations and potentially toxic metals. To further enhance the economic strength of integrated multitrophic aquaculture systems, can be achieved by extracting high-value added compounds from algal biomass (fatty acids, pigments, polysaccharides, etc.) that can be valorised in premium animal feeds or as a feedstock for biobased fuels or plastics (Laurens et al., 2017; Maiolo et al., 2020; Milhazes-Cunha and Otero, 2017; Shah et al., 2018).

4.4. Fertiliser and plant biostimulant opportunities

The use of seafood by-products to produce plant fertilisers and biostimulants (i.e., enhances plant health, crop quality and stress tolerance) can potentially reduce large biomasses into commodity. This is particularly relevant if the biomass has deteriorated in shelf-life quality (i.e., rancid), or not fit for use in human or animal use. Furthermore, the recycling of elements back into food in both fisheries and aquaculture production system can mitigate the need for artificial fertilisers. For example, synthetically produced nitrogenous based fertilisers (e.g., ammonium nitrate), which uses the energy-intensive process of converting nitrogen gas in the air to ammonia using natural gas. More importantly, the generation of potassium and phosphate fertilizer from seafood by-products can also displace the need for finite mined sources, e.g., phosphorite and potash-rich rock. This could be strategically important as there is an increasing concern over the growing need for phosphorus fertilizers as a result of food demand. In addition, there is a rising scarcity of phosphate-rich mines, and more recently, global conflicts and climate impact, all of which threatens future food security (Nedelciu et al., 2020).

The benefits of using seafood by-products to produce fertiliser and biostimulant products include being a natural soil conditioner, improving soil texture, and enhancing growth performance (Radziemska et al., 2019). Different fertilisers based on fish by-products are commercially available (e.g., fish blood and bone) and some are even authorised for ecological or organic agriculture. For example, composted fish by-products with pine bark have been evaluated as organic fertilisers. The results showed that there was a positive enhancement in the nitrogen, phosphorus, potassium, sodium, calcium, and magnesium content in arable plant leaves, i.e., ice lettuce (*Lactuca sativa*) and white mustard (*Sinapis alba*) (Radziemska et al., 2019). Although the calcium: phosphorous ratio simultaneously had worsened as a result of the fertiliser regime. Similarly, the fermentation of squid feather bones inoculated with the *Lactobacillus paracasei* bacteria has been reported as a means of producing biobased fertilisers (Wang et al., 2019). In addition, as a fertiliser, it can increase the carbon storage capacity of the soil, potentially minimising greenhouse gas emissions to the atmosphere (Radziemska et al., 2019).

The recovery of phosphorus (usually as struvite) from waste sludge has been reported after anaerobic digestion, where the recovered phosphorus can be used as fertilisers. In some studies, there has been reported that aquaculture-derived sludge derived from anaerobic digestion has a higher bioavailability of nitrogen than undigested sludge (Aas and Åsgård, 2017; Del Campo et al., 2010). Although these processes involve low investment costs and can remove potentially toxic metals simultaneously, they usually require specialised equipment (e.g., digester vessels), high operating costs, and chemical and energy consumption (Gherghel et al., 2019). While the use of microwave technology at a laboratory scale had been shown to obtain cadmium, chromium, copper, nickel, lead and zinc after anaerobic digestion of sludge, with a total recovery of 95.3–100%. After anaerobic digestion and sludge dewatering, the production of adsorbents for metal ions (Cu^{2+} and Pb^{2+}) has been reported, with improved control of the heating process, energy savings and reduction of equipment and wastes (Gherghel et al., 2019; Madende and Hayes, 2020).

4.5. Energy generation opportunities

Different methods to obtain energy from seafood-derived sludge have been reported. For instance, biogas generation has been investigated through microwaves, ozonation, ultrasound, enzymatic treatment, and treatments with alkalis or acids. Consolidated technologies have been shown to enhance biodegradability and the capacity to obtain methane from sludge (thermal pre-treatments and high pressures), or the co-digestion of food waste with sewage sludge. Although the complexity of the reactors and the process requires a high level of technical expertise for the operation and production optimisation.

In general, biogas is produced through anaerobic digestion, which obtains a varying degree of methane (50–70%) and CO_2 (30–50%) depending on the quality of the substrate and with a minor impurity concentration, e.g., nitrogen and hydrogen sulphide. Although the process can be slow, carried out at higher than ambient temperatures, and can require large bioreactors to produce viable quantities of biogas. Anaerobic processes can remove organic matter (80–90%) (Del Campo et al., 2010; Parvathy et al., 2017). Beyond anaerobic digestion, gasification, pyrolysis, and sludge can also produce useful products such as syngas (carbon monoxide and hydrogen from gasification/pyrolysis), biochar (pyrolysis), and bio-oils. For the latter, calcined flakes have been used as a catalyst for biodiesel synthesis (Wang et al., 2019). While pyrolysis of sludge after the standard anaerobic digestion for energy production can produce biochar, which can be used for soil remediation or as fuel (Gherghel et al., 2019). The combination of anaerobic digestion and aerobic processes can also be an effective approach to reducing negative characteristics in fish processing wastewater, e.g., high biological and chemical oxygen demand, volatile solids, and typically a low pH. Other technologies such as supercritical fluid extraction have also been explored after sludge dewatering. However, they require high capital investment and maintenance costs (Gherghel et al., 2019; Parvathy et al., 2017). In the review by Pan et al. (2015), a more critical analysis of waste-to-energy supply chains was undertaken. The authors identified a series of barriers that could be categorised as technological, financial, institutional, and regulatory for the uptake of waste into energy production systems. Furthermore, evaluated successful and sustainable waste-to-energy businesses.

5. Discussion

Outlined in the previous sections of this article is the current state of the art with regards to seafood by-product materials, the processes, and technologies available and a volume to value valorisation framework. However, to increase the levels of circularity in seafood value chains, a multidisciplinary and holistic approach to its implementation is required. In order to realise this, a number of stages and steps will need to be included, expanded on and developed (Fig. 3).

- Valorisation levels in a circular economy
- Emerging waste recycling strategies
- Beyond waste to bio-based resources
- Climate impact on seafood loss in fisheries and aquaculture as well as along the value chain
- Education and outreach
- Measuring environmental performance for intensive sustainability

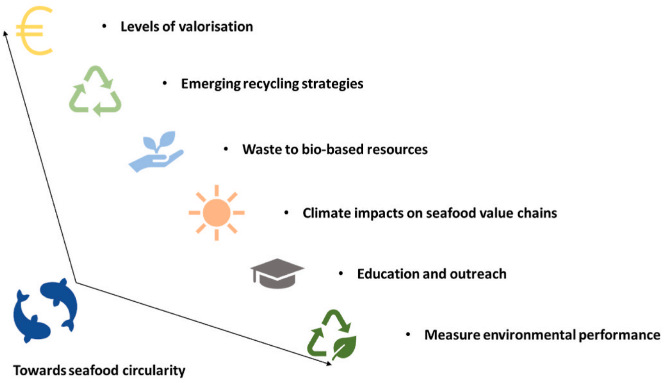

Fig. 3. The thematic areas that require implementation for increased uptake of circularity in seafood value chains.

These thematic areas address some of the key environmental, economic, and social aspects, which will impact on the successful implementation of CE in seafood value chains (Fig. 3). These areas can allow consumers, producers, and waste managers to tackle areas such as seafood loss, prepare climate adaptation measures and find value in almost all aspects of the production chain.

5.1. Valorisation levels in a circular economy

The levels for valorisation and nutrient recovery from seafood waste demonstrate the role of reuse and recovery within the CE, which subsequently adds to the sustainable seafood value chain credentials. These levels offer a decision tree framework which can allow operators, regulators, and investors to comply with the principles of CE while following options that make economic and business sense in their respective cases. For each site, the key considerations will include the volume of available material for valorisation, the distance that the material must travel and indeed, and financial costs that can be considered within this framework and allow economic and environmental considerations to develop viable valorisation strategies.

Feedback loops for by-product material in the various stages of the value chain can contribute to raw material production, in terms of feed, energy, and fertiliser (Fig. 4). By-product material from seafood processing can be valorised as feed ingredients or in higher applications such as food and biopharma products and shifted to the consumption

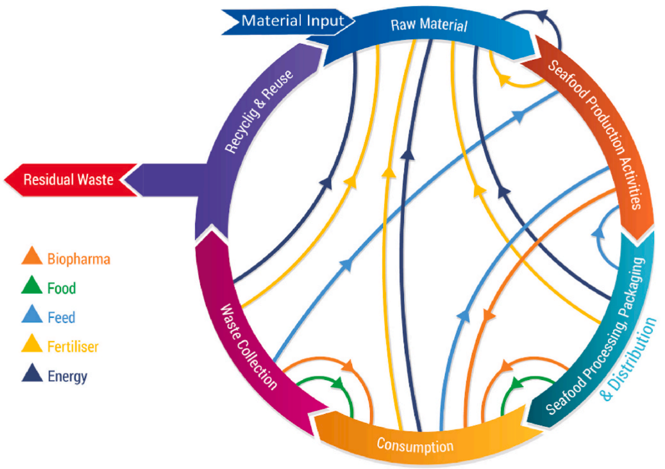

Fig. 4. Seafood circularity using the 5 levels of valorisation potential. Large arrows indicate the bulk material transfer from one step of the value chain to another, while smaller arrows demonstrate potential material transfer for regeneration along the value chain. Omitted from the diagram is the value component for each of the levels.

stage of the value chain. Opportunities for increased valorisation and recovery of lost food and material can be implemented at numerous stages in the seafood supply chain.

The CE model aims to maximise the efficiencies of resource use to reach a high level of return on the energy, time and space invested into the activity and product. The perception that the by-products from these processes are value-less is changing. However, to engage all value chain actors, there are significant knowledge gaps which need to be closed to implement sustainable CE models, which balance the needs of the business with the needs of the environment, i.e., profitability versus limiting environmental impact and sustainability. Therefore, CE practices must be implemented across the product life cycle. Extending beyond the current state of the art, where much of the focus has been on seafood production and processing.

5.2. *Climate impact on seafood loss*

One of the greatest threats to food and seafood security is climate change. Changes in environmental conditions can greatly impact wild fish stocks, and aquaculture productivity.

For instance, there are increasing concerns over emerging frequency and prevalence of infectious diseases, especially amongst farmed aquatic species. Brooks et al. (2022) considered the impacts of emerging infectious diseases in aquatic systems, but the case studies are mostly on tropical and crustacean-farmed species. This suggests aquatic systems elsewhere need to be evaluated against potential future climate-related impacts.

Furthermore, the increasing frequency in extreme weather events caused by climate change may have negative impacts on processing, packaging, and distribution channels, which further contribute to seafood loss. For example, Collins et al. (2020) postulated that climate change may cause an increased flood risk that could impact both shore-based facilities and their access points and routes. While increasing storm and extreme weather events (e.g., heatwaves) may also increase the time required to transport or shorten the life of seafood within and between markets. This consequently brings about a reduced useable life, quality, and value of the seafood product (Maulu et al., 2021).

5.2.1. *Fisheries loss*

Fisheries is one of the food production sectors that face the greatest threat of food loss from climate change. Sainsbury et al. (2021) found that fishers in the southwest region of the UK examined the trade-off of the economic rewards of continued fishing compared with the physical risk at sea when adverse weather conditions impact fishing. They looked at the socio-economic risks and potential benefits across a range of wind speeds and wave heights at sea, and how these influence the decision-making of the ship's skipper on whether to set out to fish or not. There was variability across the types of ships, gear type and other factors but in general, the utility values were seen to reduce with windspeeds above about 40 kph and wave heights >3 m. Other factors which contribute to seafood loss in the fisheries segment of seafood production can also include; discarded catch, poor chilling facilities on board the fishing vessel and damage to stock while being removed from nets (Kruijssen et al., 2020). These factors can broadly be categorised as physical, quality, nutritional and market loss (Kruijssen et al., 2020; Kumolu-Johnson and Ndimele, 2011; Love et al., 2015).

5.2.2. *Aquaculture loss*

The same factors for seafood loss in fisheries apply to aquaculture. Where aquaculture differs from fisheries is that the artificial conditions in which aquatic species are cultured offer little protection from natural events for example, in marine environments, storms and extreme weather events can cause cage structures to fail and in the instance of freshwater flow through systems flood events can cause considerable damage to facilities and lead to the escape of farmed stock. Food loss in aquaculture systems is something which should be mitigated given the artificial nature of the practice, which is similar to the culture of cattle and sheep, where it relies on inputs from the technosphere for production and success. Naylor et al. (2021) recognised in a comprehensive review of global aquaculture and its increasing importance over the last 20 years the impacts and thus potential losses that climate change may have on farmed seafood. They noted that losses (i.e., mortalities) from aquaculture occur mainly due to suboptimal growing temperatures, saltwater intrusion due to sea-level rise, damage to infrastructure, freshwater shortages, and droughts. They also noted climate impacts on rising costs of feed as well as climate-driven risks due to pathogens, parasites, and pests as well as harmful algal blooms.

5.2.3. *Processing and distribution loss*

The processing and packaging sections of seafood value chains are likely to offer the greatest opportunity and impact in recovering lost waste in the short and medium term (Cortés et al., 2021a; de la Caba et al., 2019; Laso et al., 2016; Tan and Lamers, 2021; Venugopal and Sasidharan, 2021). Seafood loss can occur in this stage of the value chain through a number of different challenges. Some of these overlap with losses that have been highlighted in other parts of the value chain. One of the ways in which loss can occur in the processing stage can be through spoilage due to inadequate equipment or equipment failure (i.e. refrigeration and conveyor systems), low levels of processing control (i.e., staff removing too little from the carcass), low use of packaging material, or low processing capacities (Kruijssen et al., 2020; Love et al., 2015; Spang et al., 2019). Another contributing factor to food loss can be the implementation of high-quality food standards. These quality standards, while they present appealing-looking products to consumers can also contribute to food and nutrient loss, by diverting damaged, but safe and healthy seafood products from the food supply (Spang et al., 2019).

From a distribution perspective, losses can occur through poor handling or stocking of the products. Damaged packaging can shorten the shelf life of the products and in cases where there is a sizeable distance to market lead to unsaleable products. Poor road infrastructure and remote landing or production sites can also contribute to seafood loss. Geopolitical events, trade barriers, and disease outbreaks can also shorten the shelf-life and availability of seafood. This can be evident by delays in the delivery of seafood products to continental Europe from Ireland and air freight of seafood from Europe to Far-East Asia and vice versa (Ahearne and Hynes, 2020; Barnes, 2020; Mahfouz et al., 2019).

Improved process control and supply chain management practices can help to reduce food loss and waste in seafood supply chains (Bruno et al., 2019a; de la Caba et al., 2019; Yan and Chen, 2015). With industry and industrial processes moving into the 4th industrial revolution (Industry 4.0), a number of advanced and smart technologies are coming online (Hassoun et al., 2022). These technologies in conjunction with wider smart systems such as energy monitoring can help to reduce the costs of cooling and refrigeration; cooling and freezing being one of the main drivers of cost, energy use, and environmental burden of seafood processing (Avadí and Acosta-Alba, 2021; Cortés et al., 2021a; Hassoun et al., 2022; Vazquez-Rowe et al., 2012). Industry 4.0 is still an emerging vision of how industrial processes and economies can increase their efficiencies. However, the EU has already begun to build capacity for Industry 5.0. It aims to complement Industry 4.0 practices by also transitioning to sustainable, human-centric, and resilient industries (European Commission, 2022).

5.2.4. *Consumption loss*

Some of the greatest losses and waste of seafood occur at the consumption stage. Statistics on seafood loss at the consumer level can range from 10 to 11% (Gustafsson et al., 2013) to 41–56% (Love et al., 2015) and by some estimates can be as high as 70% (Stenmarck et al., 2016). These values can vary from region to region and can reflect the cultural value that is placed on seafood within a nation's diet. Contributing factors to food loss at this stage of the supply chain can include spoilage of the products, excess preparation (the loss of edible parts due to poor preparation), and diet culture, i.e., only eating certain parts of the seafood (Birney et al., 2017; Kruijssen et al., 2020).

Many of the recommendations which have been put forward to reduce the levels of loss and waste generated by consumers have focused on behavioural changes through educational efforts (Kruijssen et al., 2020; Love et al., 2015). These strategies aim to encourage consumers to plan their meals, control the portion size of the meals, and minimise the levels of leftovers. Other suggestions include a switch from fresh to frozen seafood products, which could lead to a decrease in levels of waste through longer shelf-life spans. Action plans are being developed by national and interregional policymakers to raise awareness on the impacts and to highlight the unsustainability of current food consumption practices. This includes the United Nations' Sustainable Development Goals, policies, and actions such as those by the EU, which have incorporated food loss and waste minimisation within many of its plans (Circular Economy, European Green Deal) and strategies (Farm to Fork, European Commission, 2018; 2020a, 200b). These actions will lead to national and interregional initiatives by member states to combat food loss and waste. However, there will also be a need to match these efforts in waste management through novel and emerging waste recycling techniques and strategies throughout seafood supply chains.

5.3. *Emerging waste recycling strategies*

Emerging waste recycling strategies in the seafood supply chain are essential to tackle the growing seafood waste problem. Within the EU trading bloc, the Waste Framework Directive (Commission Decision, 2011/753/EU, EU 2019) outlines some basic waste management principles with the preferred option of preventing waste. However, according to Sharma et al. (2021) and Ghosh et al. (2016), an effective waste management strategy would need to include waste minimisation, characterising the waste, and waste recycling. From a supply chain perspective, some emerging strategies are being introduced to meet sustainability goals. For example, location-based tracking technology is being introduced by the EU's commercial fisheries. This initiative will be a step towards increasing transparency and discernibility in seafood supply chains. Identifying the waste levels and the location of waste within the supply chain allows the development of an effective waste management plan, e.g., the stage, location, type, and volume of seafood waste being generated (Ghosh et al., 2016). Emerging waste recycling plans aim to develop value-added supply chains. For instance, the valorisation of abundant and available bio-wastes (de la Caba et al., 2019; Sorg et al., 2019). These plans can be facilitated through the separation of the waste into liquid/solid streams and using the best available extraction method to retain the nutritional component(s) of interest (Coppola et al., 2021; Lam et al., 2020; Rejula and Mohanty, 2018). There is also a great interest in developing sustainable and biorefinery practices to produce disruptive and high-value bioactive compounds from food waste streams. These range from the use of novel antimicrobials for eco-packaging applications, immune-stimulatory ingredients for health and wellbeing (Murphy et al., 2020; Rowan and Galanakis, 2020), and novel ingredients for fish feed from biorefining fisheries and seaweed by-products into the aquafeed ingredients (Pogue et al., 2021; Colombo et al., 2022).

Some researchers have outlined the importance of reframing what is food and what is waste as a key step in the cradle-to-cradle considering waste as part of the cycle (Martínez-Córdova et al., 2017; Soma, 2020). For example, in aquaculture, the conventional waste that is produced can take a place as a by-product alongside traditional seafood products. This approach can decrease the release of contaminants into the environment and add new revenue streams to the seafood sector (Regueiro et al., 2021).

One of the key challenges in emerging waste management strategies is consumer acceptance of recycling seafood waste and turning it into a new product. These strategies will need to balance several factors to be effective and commercially viable approaches. For example, new market opportunities, market trends, current market developments, and an end product that is competitive in the marketplace (Borrello et al., 2017). The role of the consumer in the success of the product is particularly important, as the consumer has the final say in the economic success of a product (Borrello et al., 2017; Ghosh et al., 2016). Finally, food marketing, consumer education and food labelling by retailers and producers can assist with changing consumer behaviour as a catalyst for waste management plans (Altintzoglou et al., 2021; Aschemann-Witzel et al., 2016, 2016de la Caba et al., 2019).

5.4. *Beyond waste to bio-based resources*

Within CE an emerging field is the circular bioeconomy (CBE). The CBE aims to utilise biomass or biological resources from all industries and economic sectors (Tan and Lamers, 2021). There are a number of definitions in use for the CBE, but it can be accepted as complementary to the CE and can help in the transition to cleaner and sustainable production (Raimondo et al., 2021; Tan and Lamers, 2021; Venugopal and Sasidharan, 2021). One of the core aims of the CBE is the production of biobased materials and products. Bio-based products are often considered to be more sustainable than their conventional counterparts. Although these claims need to be validated using life cycle thinking (Adom et al., 2014; Brunklaus and Riise, 2018; Spierling et al., 2020; Wojnowska-Baryła et al., 2020). Under a CBE framework, there are efforts to develop functional foods, feeds, and additives from seafood by-products.

Recent research and frameworks for the use of machine learning in the processing and production of feeds and food products have identified opportunities for the application of such technologies across seafood supply chains (Cooney et al., 2021; Hassoun et al., 2022; Kang et al., 2017; López-Cortés et al., 2017; Manoharan et al., 2020; Suryawanshi and Eswari, 2022). There are strong roles for machine learning, the internet of things and digitisation in the development and production of efficient, precise food products from raw or waste sources.

5.5. *Measuring sustainability and environmental performance*

One of the most important concepts in the use and implementation of the technologies and approaches for seafood by-product valorisation is sustainability. The sustainability of these interventions and actions needs to balance the economic and environmental needs of society and business operators. One of the approaches that are widely used to assess the environmental performance and sustainability credentials of a system, technology, process, or product is life cycle thinking, primarily in the form of life cycle assessment (LCA, Bohnes and Laurent, 2019; Ruiz-Salmón et al., 2021). Life cycle thinking uses a multimeric approach that can be used to assess the performance of a product across the three pillars of sustainability or triple bottom line: 1) environmental, 2) economic, and 3) social. These assessments can take the form of environmental LCA, social LCA (SLCA) or life cycle costing (LCC). When combined, these distinct aspects of life cycle thinking become a life cycle sustainability assessment (LCSA). LCSA has received growing attention since the early 2010s but to date has not been widely applied (Guinée, 2016). This is in part due to the ongoing development of frameworks and methodological approaches which can be used in LCSA (Lam et al., 2020). While the use of LCSA is the end goal, in the interim the use of key performance indicators (KPI) derived from LCA, LCC and SLCA can help to better inform and support decisions for the valorisation and increased utilisation of seafood by and co-products. For example, under the environmental pillar of sustainability, the use of KPIs such as carbon dioxide (kg CO2 eq. kg-1 of product), water use (m3 kg-1 of product) or energy use (MJ/kg of product) can provide very useful information on the associated environmental burden of operational decisions. Economic KPIs under an LCC approach could take the form of a payback period of the investment, internal rate of return or benefit-cost ratio (Valenti et al., 2018). Social KPIs for example that could be applied in this context could include investment to create direct employment or indices on the seafood circularity (amount of seafood prevented from being wasted) and its contribution to nutrition (using recommended daily allowances for human nutrition or energy content if for feed) (Hallström et al., 2019; Valenti et al., 2018). The use of simple KPIs like those listed above can help to promote the sustainable use of seafood co-products under a circular economy.

Previous studies have demonstrated LCA as a suitable tool to guide and make decisions on selecting and handling strategies in food waste recycling (Lam et al., 2020; Vilariño et al., 2017; Zilia et al., 2021). The use of the water-energy-food nexus can be an effective tool in developing a waste recycling plan applied for seafood by-products. A study undertaken by Chang et al. (2016) found it was particularly useful for identifying synergies, challenges, and opportunities. In particular, the authors noted that some of the outputs which would lead to increased social justice enhanced resource efficiency and reduced environmental impact. Gephart et al. (2017) argued that there was a gap in the 'seafood' water-energy-food nexus literature. They highlighted the importance of looking at water usage in seafood production. In addition, Slorach et al. (2020) conducted a study incorporating 'health' into the water-energy-food nexus, using LCA for each sector to give a true perspective on environmental impacts. The study looked at the impact on the nexus of four treatment options: anaerobic digestion, in-vessel composting, incineration, and landfilling. The results found that anaerobic digestion was the most sustainable and in-vessel composting the least. Similarly, a study carried out by Laso et al. (2016) analysed the environmental impact of anchovy waste valorisation in contrast to incineration and landfilling. The results showed that the valorisation waste management options resulted in the least impact on the environment.

Numerous studies have outlined the benefits of using social, economic, and environmental variables including economic performance assessment tools to assist decision-makers in the waste management of seafood supply chain strategy (Alkaya and Demirer, 2016; Jacob et al., 2021; Zilia et al., 2021). Zilia et al. (2021) demonstrated that by incorporating the three pillars of economic, social, and environmental in the example of reusing sea urchin waste. They did this by presenting the frameworks under a business model canvas approach and identified social opportunities through additional jobs being created as part of CE implementation and reduced environmental burden by valorising the waste material. Vilariño et al. (2017) followed a similar approach in reviewing LCA approaches for food by-product management. A number of recent studies have suggested that the use of technological, social, and political readiness levels to supplement the use of LCA as means of developing new green innovations, including sustainable waste management (Ruiz-Salmón et al., 2020; Stead, 2019; Villanueva-Rey et al., 2018; Voyer and van Leeuwen, 2019).

According to Ghosh et al. (2016) 'undervaluing and 'underreporting' are referred to as the 'hidden costs' in food waste management. Economic benefits are key enablers of green innovation (Kelliher et al., 2020); exploring the true value of these, 'hidden costs' can enable a more accurate assessment of the economic impact of waste valorisation and can act as a facilitator for change (Ghosh et al., 2016). A good example is the use of recirculating aquaculture systems and how they can reduce water usage, increase nutrient recycling, and improve waste management (Martins et al., 2010).

5.6. *Driving a seafood circular agenda through education and outreach*

The linear economy has increased the distance between producers and consumers. As a result, it has affected society across all strands and social classes. In particular, how food is produced, this gap has resulted in a loss of awareness and value for the food being consume and the associated production systems. Given the increasing global demand for seafood, there is an opportunity for many seafood production systems to become "model" CE systems. Applying a multi-stakeholder approach to inform future sustainable waste management will enable an effective and inclusive strategy that will affect behavioural change. The power of the consumer as a catalyst in driving waste management in the seafood supply chain is vital. For example, the raising in public awareness on the environmental impact of single use plastics has led to a drive to prohibit their use, which resulted in the EU passing the Directive 2019/904 and bans certain types of plastics used and sold within the EU. There is a scarcity of literature on gauging socioeconomic impact, and this limits the ability of decision-makers to develop successful and long-term sustainable waste management strategies into existing business models.

Education and communication (vertical and horizontal) using the concept of a Triple Helix (academia-industry-government) ecosystem approach is required to change the behaviour to value waste as a resource in the value-added supply chain. This Triple helix approach will also support and accelerate the societal transition to a low-carbon economy using a bottom-up approach, which will inform future research and enterprise-performing activities regionally and nationally, with a global orientation. A number of emerging waste recycling strategies are reviewed from the seafood supply chain to the consumer. A holistic Triple-Helix framework approach to supporting and enabling sustainable waste recycling and management will provide strategies for by-product resource efficiency incorporating all stakeholders comprising producers, policymakers and consumers in the decision-making process and contribute to sustainable waste recycling goals. There should also be equally public-academia-industry-government driven initiatives for better seafood valorisation innovation and strategic impact. For instance, changing the misconception of fishmeal being used in aquafeeds where it is derived from the fish processing (e.g., trimming, offal, heads, and frames, Colombo et al., 2022) or hydrolysates waste by-products (partially fish protein hydrolysate and cook water, Egerton et al., 2020).

6. Conclusion

This review offers insight into the diversity of seafood by-products being generated as part of current EU and global food production practices. It also presented a stepwise framework which can allow operators to identify valorisation strategies based on a volume-value-based approach. Opportunities exist through the valorisation or reuse, which can reduce environmental impact or loss of resources, i.e., nutrients, energy, and biomass. Some of these opportunities, for example, can include nutrient recovery at the level of production in aquatic farms using polyculture, aquaponics, integrated multitrophic aquaculture, or through mechanical means such as solid waste recovery from the produced sludge. Similarly, there are many opportunities from the fisheries sector, where non-targeted species, over quotas, or poor quality and unsuitable targeted species could be exploited as a valued resource, rather than discarded back into the aquatic environment. There is now a greater need for resource efficiency use as fisheries production levels are plateauing due to over-exploitation and climate impact. However, there are significant barriers that prevent the large-scale regeneration of seafood waste into valued products. A conjunction of incentives, capital investments, policy changes, commercial, and social and consumer acceptance is needed to realise the true potential of seafood waste.

Another key area to address is that many of the technologies which had been discussed remain at the research level. To increase the technological readiness level, there needs to be greater engagement with the industry in discerning the viability and readiness with which these technologies and approaches will be received. The markets for valorised seafood by-products as they move into the higher value levels of the valorisation framework (i.e., food and biopharma). The amounts and quality of by-products that are available for valorisation will also need to be established. Eco-efficiency and eco-design will need to play strong roles in the sustainable development of seafood by-product valorisation. For example, would centralising or decentralising to valorising a particular seafood waste be the most appropriate for commercial exploitation? To measure this environmental impact LCA would need to be employed and allow the decision-making of which valorisation option is the most sustainable. Human development has now reached a critical juncture, where the realisation of many natural resources is finite and incompatible with society's linear production chains. As the global human population increases, the regeneration of nutrients from seafood waste into new foods and products is paramount to creating a future of sustainable and responsible consumption.

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.

Data availability

No data was used for the research described in the article.

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