Future Foods 14 (2026) 101084

Contents lists available at ScienceDirect

Future Foods

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

Sustainability in the blue bioeconomy: A critical review of technologies and sustainability assessment of aquatic food side-stream valorization

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ARTICLE INFO

Keywords:
Seafood side-streams
Valorization
Sustainability assessment
Life cycle analysis (LCA)
Techno-economic analysis (TEA)
Social LCA (SLCA)

ABSTRACT

Global aquatic food consumption and production are increasing, resulting in growing volume of side-streams which are rich in nutritional and functional compounds. Their valorization offers a circular pathway to transform underutilized materials into high value products. However, valorization requires additional resources, so it is essential to assess whether it genuinely enhances sustainability, across environmental, economic, and social dimensions. This review systematically evaluates 40 peer-reviewed publications on the sustainability of seafood side-stream valorization technologies. The environmental dimension was assessed by 80% of the papers, with 91% using Life Cycle Assessment (LCA) methodology, followed by economic assessments (40%), while the social pillar remains largely underexplored, with only one study attempting to integrate all three. Fish viscera and crustacean exoskeleton were studied by 35% and 20% of the papers. Valorization technologies assessed were mostly at TRL 3 and 4 (82%). Fine chemical applications exhibit greater variety in extraction methods, while food applications generally involve simpler processing. Protein extraction technologies were found to yield 6–53% depending on the side-stream while higher value fine chemicals (e.g. astaxanthin, chitin) results to lower yield of 1–3%. Valorization showed lower global warming potential (GWP) than conventional extraction or current end-of-life options in 80% of scenarios. Economic feasibility was influenced by plant size, product selling price, and process efficiency. This review recommends a harmonized reporting of unit processes, inputs, and outputs from harvesting through valorization, to improve transparency and comparability. Future research should define of economic and social indicators to comprehensively evaluate the sustainability of seafood side-stream valorization.

1. Introduction

In 2021, global aquatic food consumption reached 165 million tonnes, averaging 20.7 kg per capita, and is projected to keep increasing (FAO, 2024). To meet this demand, production peaked to 223.2 million tonnes in 2021, primarily from marine environments (FAO, 2024). However, substantial share of this biomass does not reach the food supply chain: 11.79% is lost during harvest, and an additional 21.55% of food-grade biomass is lost during subsequent processing (World Economic Forum, 2024). Even technologically advanced industries such as Norway's demersal fish sector only manages to reach 56% raw material utilization, considerably lower than Asian counterparts such as tilapia processing, which reaches 75% edible yield since only viscera are removed (Chary et al., 2025; Strand et al., 2024). These inefficiencies generate large volumes of biological by-products.

A deeper analysis of white fish side-streams in Norway shows significant potential for valorization (Fig. 1). Out of a total annual catch of 310,000 ton, approximately 136,4000 ton are not utilized (Strand et al., 2024). These side-streams contain valuable proteins and, if fully recovered, could yield up to 47,802 ton of protein (Kandyliari et al., 2020). The portion currently utilized is processed into products intended for human consumption. However, losses may still occur in the supply chain. Ultimately, only 36% of the weight of white fish catch ends up as edible product since processing fish for human consumption inevitably generates side-streams (World Economic Forum, 2024). Proportions of processing side-streams could still be edible but not consumed by the market due to various reasons (World Economic Forum, 2024). With the current data, it is still challenging to identify where the losses occur in the supply chain, whether they can be recovered for further processing, and how these side-streams are currently treated or managed.

According to Directive 2008/98/EC, by-products are objects or

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https://doi.org/10.1016/j.fufo.2026.101084
Received 7 November 2025; Received in revised form 24 February 2026; Accepted 8 June 2026

substances which are not the primary aim of a production processes. In aquatic food, by-products include heads, cheeks, fins, tails, scales, guts, blood, frames (backbone) from finfish, and shell, viscera, and legs from shellfish when the primary aim of production are fish fillet or shellfish and crustacean meat (Archer and Jacklin, 2022; World Economic Forum, 2024). Processing residues, such as wastewater from aquaculture and food processing facilities (e.g. mussel processing water), may also qualify as by-products when they meet the criteria for end-of-waste status (Directive 2008/98/EC). End-of-waste status is achieved when there is a market demand for a specific material which can be used for a specific purpose, and the material's use meet the legislations and standards applicable without causing harm to human health or the environment (Directive 2008/98/EC, 2008). In this paper, by-products and processing residues are collectively referred to as side-streams.

These side-streams are increasingly recognized for their nutritional and functional potential. They are rich sources of protein hydrolysates, omega-3 fatty acids, vitamins, minerals, enzymes, and bioactive compounds such as gelatin, collagen, and carotenoids (Gill et al., 2025a). Beyond nutritional value, compounds such as marine collagen have demonstrated functional properties like antioxidant and antimicrobial activity and potential applications as active packaging and scaffolding that promotes cell regeneration (Coppola et al., 2021).

Valorizing aquatic food side-streams is therefore an opportunity to reduce food waste, and a critical step toward circularity and resource efficiency in the blue economy (Gill et al., 2025a). Valorization is the process of extracting valuable components from food processing side-streams to harvest a high value product to address both disposal cost and environmental impact (Gill et al., 2025a). Within the food waste management hierarchy, valorization is considered a preferred strategy in the recovery stage, as it enables both waste minimization and resource optimization stage (Garcia-Garcia et al., 2017). In the context of aquatic food processing, this involves converting side-streams into compounds with applications in food, feed, pharmaceuticals, cosmetics, and agriculture (Gill et al., 2025b).

A wide range of technologies are being developed to recover compounds from aquatic food side-streams, including chemical, biological, and physical extraction methods. Conventional techniques often rely on solvents or chemicals which can create environmental concerns. Consequently, research has increasingly focused on non-thermal, environmentally friendly technologies with reduced energy consumption and solvent use (Hassoun et al., 2023; Smaoui et al., 2024). Examples include ultrasound-assisted extraction, pressurized liquid extraction (PLE), supercritical CO_2 extraction ($SCCO_2$), microwave-assisted extraction, and pulsed electric fields (Duppeti et al., 2023; Naghdi et al., 2023; Rodrigues et al., 2021; Semenoglou et al., 2021; Wang et al., 2023).

While aquatic food side-stream valorization holds great promise for reducing waste and enhancing resource efficiency, it is essential to critically assess whether these processes deliver genuine sustainability benefits. Valorization inherently involves additional inputs, such as energy, water, and chemical reagents, and thus may not always result in a net environmental gain. Without proper evaluation, there is a risk that valorization strategies could shift rather than solve environmental burdens and the economic feasibility of these technologies is important for industrial adoption (Wei et al., 2024). The least investigated, but equally important factor, is how these processing technologies affect society (Wei et al., 2024).

Several reviews have examined specific aspects of aquatic food side-stream valorization. For instance, Coppola et al. (2021) and Ganjeh et al. (2023) discussed technological developments and valorized products, while Yusoff et al. (2024) assessed environmental impacts of biorefinery applications using Life Cycle Assessment (LCA). However, that review excluded other environmental assessment methodologies (e.g. emergy, eco-efficiency, ecological footprint assessments), as well as the economic and social dimensions. Furthermore, studies on processing residues meeting the end-of-waste criteria and assessment of valorized product applications were not considered. This highlights the need for a comprehensive and integrative review that addresses all three pillars of sustainability.

In response, the present review provides an up-to-date overview of valorization technologies for aquatic food-side streams and their sustainability assessment across environmental, economic, and social dimensions. Specifically, it aims to: i) identify the most commonly targeted aquatic food biomass and side-streams; ii) map applied valorization technologies, processing steps, valorized products, and industry applications; and iii) examine the sustainability assessment methodologies, including indicators, frameworks, and reporting practices. Ultimately, the review proposes guidelines to harmonize sustainability

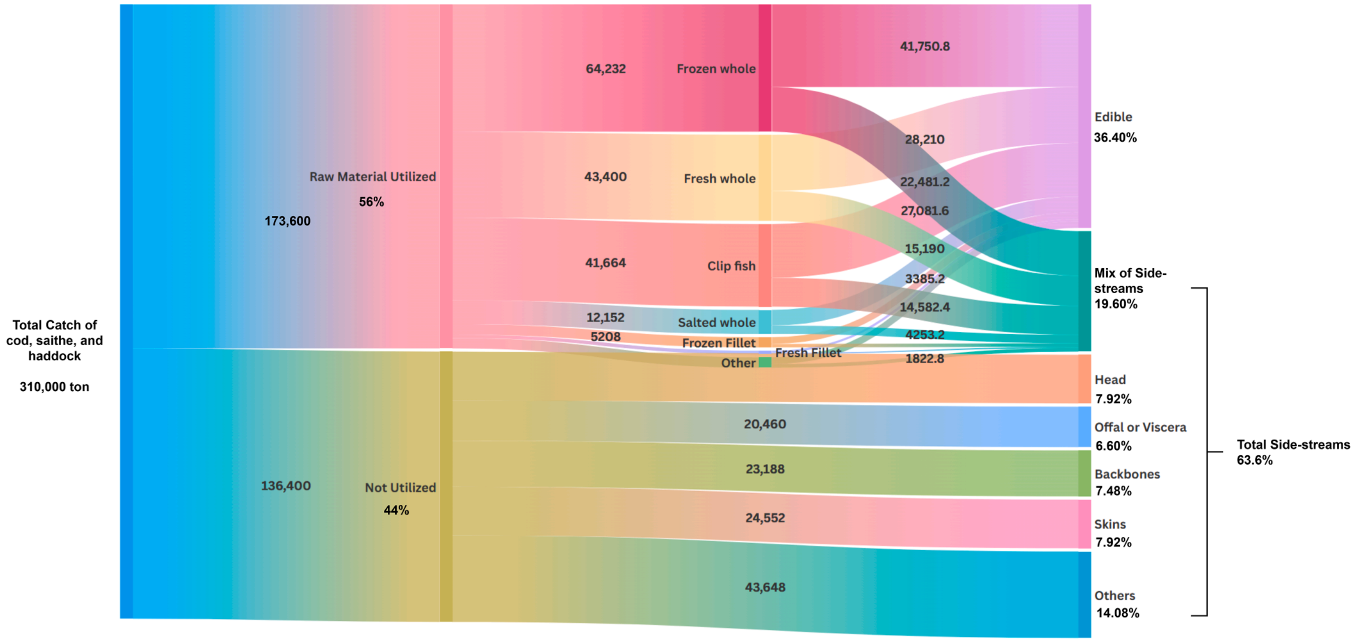

Fig. 1. Total side-streams generated from white-fish catch in Norway (Strand et al., 2024) using cod as a representative species for calculating the edible parts (World Economic Forum, 2024) and side-streams (Winther et al., 2020).

assessment and reporting in aquatic food side-stream valorization, supporting greater transparency, comparability, ad uptake in policy, industry, and research within the blue economy.

2. Methodology

A systematic review was conducted to identify and analyze studies that assess the sustainability of aquatic food side-stream valorization technologies. The review focused on literature addressing all three sustainability pillars, environmental, economic, and social, in the context of valorizing marine and freshwater side-streams.

The literature search was performed primarily using SCOPUS and Web of Science (WoS), which yielded the most relevant and comprehensive results. CORE UK and Google scholar search results were consulted, but the search results were mostly overlapping with SCOPUS and WoS outputs. To ensure comprehensive coverage, a snowballing technique was also applied: key references known to the authors but not retrieved via database searches were manually included, and their bibliographies were screened iteratively until no new, relevant studies were identified.

Search strings were constructed by combining terms related to aquatic food side-streams with keywords aligned with each sustainability pillar (Table 1). Boolean operators were used to link terms systematically across three thematic components: marine species, type of side-stream, and sustainability assessment methodology. The search focused only on peer-reviewed scientific articles published from 2000 to August 2025.

The overall screening and selection process is summarized in Fig. 2. After initial retrieval, duplicates were removed using Rayyan.AI (Ouzzani et al., 2016). Manual screening was then applied to refine the dataset, focusing on papers that explicitly addressed aquatic food side-streams and their valorization through processing technologies. A second screening phase excluded papers that discussed technical or efficiency aspects only without any sustainability assessment component. Ultimately, 40 studies met all inclusion criteria and were included in this review.

The selected papers were analyzed based on different metrics to assess the status of aquatic food valorization and novel technologies around it. The analysis included: i) the aquatic food biomass; ii) aquatic food side-streams derived from the biomass; iii) valorization processing technology; iv) valorized products, and; v) destination industry of the products assessed. In terms of valorization processing technology, the Technology Readiness Level (TRL) was determined using the modified TRL scale in Table S1 supplementary documents. This scale was developed to be appropriate for aquatic food valorization technologies using the TRLs in the chemical industry as basis (Buchner et al., 2019). Then, it was analyzed in relation to the species, side-streams, valorized products, and destination industry to get a picture of which ones already have a high TRL. The processing stages required to generate the valorized output were also mapped to understand the typical technological value chain. These results were processed using Python pandas library and visualized with Matplotlib and Plotly.

For each sustainability pillar addresses in the reviewed publications, the following methodological characteristics were extracted and compared: i) functional unit; ii) system boundaries; iii) allocation procedures; iv) assessment frameworks and tools (e.g., LCA, techno-economic analysis, S-LCA). The results of each study were further analyzed in terms of i) reported sustainability indicators; ii) key findings and trends; iii) transparency and reproducibility of reporting.

3. Results and discussion

3.1. Overview of selected publications

The sustainability pillar assessed by the publications selected were identified and the distribution of results is shown in Fig. 3. More details are summarized in Table S2. The environmental dimension is the most researched (32 papers), followed by the economic (16 papers). There is also more overlap between these two pillars (7 papers). Only one study was found to examine the intersection between three pillars, incorporating environmental, economic, and social scores in a multi-objective optimization model for Omega-3 production from fish oil (Monsiváis-Alonso et al., 2020). A more detailed analysis on the methodological choices for each of the dimension is provided in sections 3.3 Environmental Assessments, 3.4 Economic Assessments, and 3.5 Social Assessment. There is a clear gap in the literature concerning the assessment of social impacts. In terms of geographic distribution, a significant proportion of the publications modelled the processing in the context of Spain (11 publications) (Figure S1). Despite the high volume of aquatic food production in countries like China and other countries in Southeast Asia (FAO, 2024), publications on sustainability assessment from those countries remain very few.

3.2. Valorization pathways: aquatic food biomass, types of side-streams, processing steps, and applications

To assess the current state of research, the reviewed papers were analyzed in relation to the aquatic food side-stream valorization value chain (Fig. 4). Using World Customs Organization’s nomenclature of aquatic food commodities as basis, the aquatic food biomass were grouped into: i) fish (grouping together freshwater, demersal, pelagic, and marine); ii) crustaceans; iii) mollusks cephalopods, and; iv) “other aquatic animals” for those that do not fall within aforementioned categories such as sea cucumbers, sea urchins, and jellyfish (WCO, 2022). The papers were also grouped based on the side-streams derived from the aquatic biomass. Both information are summarized in Fig. 4a. It is evident that offal or viscera of fish being valorized is the most studied (35%), followed by exoskeleton of crustaceans (20%). Among the side-streams, by-catch is the least studied (5%) with a growing attention to valorizing liquid effluent or wastewater (18%) from aquaculture and aquatic food processing to aid in wastewater treatment. Among aquatic food biomass, there is a limited assessment among mollusks (13%) and other aquatic animals (3%). Although, some of these species show promising potential as source of high-value compounds, like marine

Table 1
List of keywords used to search for relevant papers in databases (SCOPUS and WOS) from year 2000 to August 2025.

Sustainability pillar	Marine species	Boolean	Specifying side-stream	Boolean	Assessment method
Environmental	"fish" OR "marine" OR "seafood" OR "aquaculture"	AND	"by-product" OR "side-stream" OR "valorization"	AND	"Environmental Impact Assessment" OR "Environmental Assessment" OR "Life Cycle Assessment" OR "Life Cycle Analysis" OR "Water Use" OR "Carbon Footprint" OR "Ecological Footprint" OR “LCA”
Economic	"fish" OR "marine" OR "seafood" OR "aquaculture"	AND	"by-product" OR "side-stream" OR "valorization"	AND	"Economic Assessment" OR "Techno Economic Analysis" OR "Total Cost of Ownership" OR “Life Cycle Costing” OR “LCC”
Social	"fish" OR "marine" OR "seafood" OR "aquaculture"	AND	"by-product" OR "side-stream" OR "valorization"	AND	"Social Impact" OR "Socio-Economic" OR "SLCA" OR "S-LCA" OR "Social Life Cycle Assessment"

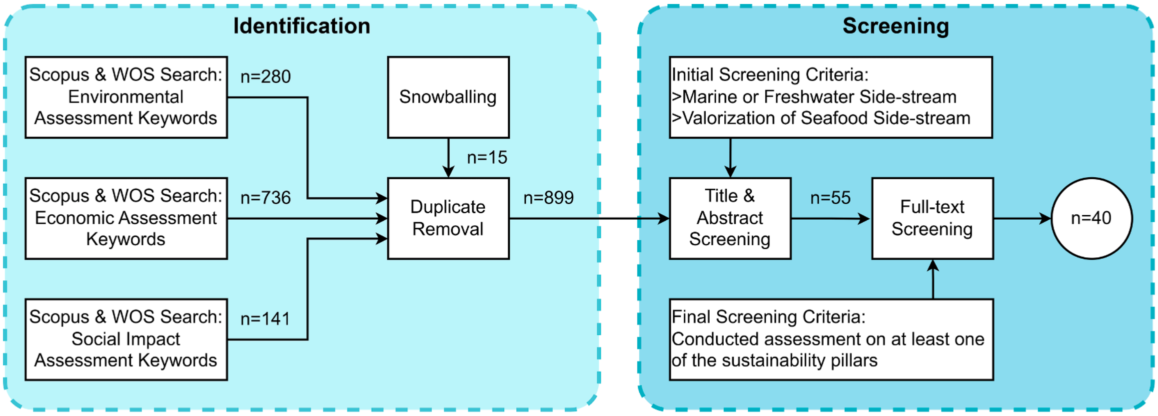

Fig. 2. Screening methodology applied for the selection of published papers included in this study. n=number of papers.

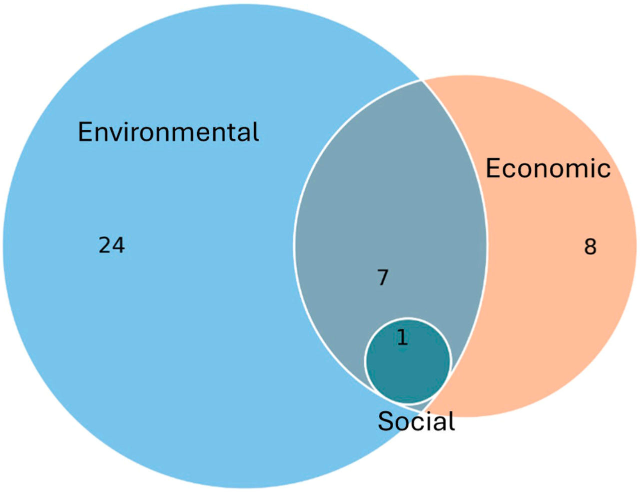

Fig. 3. Overview of selected papers categorized by the sustainability pillar analyzed.

collagen from eel-fish skin, jellyfish (ribbon and umbrella), squid, and sea cucumber (Pal and Suresh, 2016), as well as protein hydrolysates from scallops, sea squirt (tunicate), and cuttlefish (Smaoui et al., 2024), to name a few.

The TRL of the valorization processing technologies reported in the reviewed publications was determined according to Table S1 since only one paper explicitly reported on the technology's TRL. These TRLs were analyzed in relation to the aquatic food side-streams being valorized. In Fig. 4b, the count represents scenarios rather than papers. Scenario counts exceed paper counts because 88% of the papers assessed scenarios valorizing a single side-stream, 8% analyzed two side-streams, 3% analyzed three side streams, and another 3% did not specify from which side-stream the high value product came from. Valorization technologies at TRL 4 or laboratory scale validation comprise 43% of the papers followed by TRL 3 at 39%. Technologies with TRL levels 7 (5%) and 8 (9%) from the processing of fish offal and viscera, external fish parts (e.g. head and tails), liquid effluent, and fish by-catch were rarely assessed in terms of sustainability as shown by the low paper count (Fig. 4b).

Industry application in relation to TRL level of valorization technology is summarized in Fig. 4c. The counts represent the number of scenarios which exceeds the number of papers because 33% of the papers assessed multiple valorization products (20% of papers assessed two valorization products, 13% assessed three). Among intended industry applications, feed has the highest proportion of technologies at advanced TRL (3). There is also a high number of papers aggregated in fine chemical feedstock, which includes diverse products that are not intended exclusively for food or other industries mentioned, such as protein hydrolysate, chitin and chitosan, gelatin for packaging, omega 3 lipids, pigments (e.g. astaxanthin), and antimicrobials (e.g. pediocin). However, these technologies remain at TRL 3, 4, or 5. These findings suggest that sustainability and economic assessments are applied to valorization technologies still in their infancy. This highlights the need for more sustainability assessments of scaled-up technologies and a broader exploration of high-value industry applications.

Since there was a variety of valorization technologies, this information was drawn side by side with inputs and outputs and industry applications. The summary for the food sector is in Fig. 5. The flow diagram in Fig. 5 starts with the aquatic food species which are the source of side-streams, followed by the specific types of side-stream generated from that supply chain. It proceeds with the processing steps that is applied to the side-streams. This central section shows the complex network of major and intermediate processing steps. Then, the resulting valorized products are connected to their intended or recommended industry application. The thickness of each connecting line represents the number of papers reporting on the process (not based on mass of volume). Same was done for other industry applications such as energy and agricultural input (Figure S2), fine and bulk chemicals (Figure S3), and feed (Figure S4). The following discussion will go through each group in detail.

Energy recovery applications (Figure S2) make up 14% of the scenarios assessed across the selected publications. Valorized products are used as energy substrates (for cement factory and biogas production), biofuel or biodiesel, and fish oil. Using aquatic food side-streams as biogas substrates or bioenergy typically involved fewer processing steps than conversion to biofuel, but green technologies like supercritical fluid extraction for biofuel production are also assessed for environmental sustainability (Cristiano et al., 2022, 2023; Kratky and Zamazal, 2020).

Agricultural applications (Figure S2) account for 9% of the valorization scenarios. Valorized products included fertilizers and biochar from conventional solvent extraction and high energy pyrolysis processes, respectively. For this industry application, the side-streams come from fish guts, external parts, wastewater, and fish mortality.

Fine and bulk chemical applications (Fig. 4c) represent 31% and 7% of assessed scenarios, respectively, making fine chemicals the most represented industry application. Fine chemical products include pigments, chitin/chitosan, proteins, bacteriocins, omega-3 lipids, cartilage compounds, and gelatin while calcium compounds are typically produced for bulk chemical applications (Figure S3). Encapsulation emerged as a unique final processing step for omega-3 lipids (Monsiváis-Alonso et al., 2020). Drying as a final step was prominent, with specific application of freeze drying for bacteriocin production (Arias et al., 2022). The valorization processing technologies employed to produce these end products showed the most variety of extraction

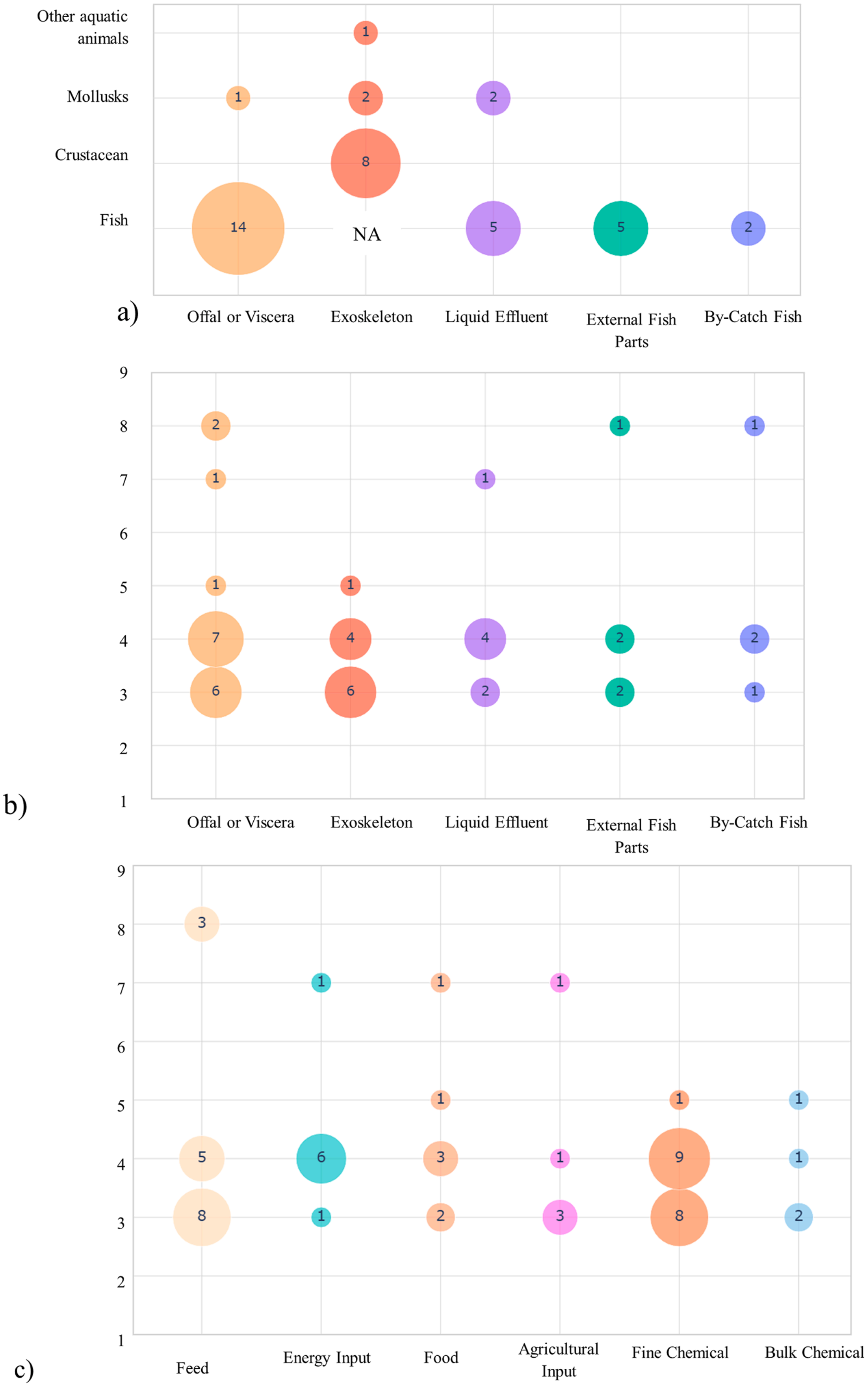

Fig. 4. (a) The count of papers based on the seafood species and the side-stream categories it analyzed. (b) Count of scenarios based on TRL of valorization technology in relation to side-stream category that was processed, and (c)count of scenarios based on TRL of valorization technology in relation to the application industry declared or intended in the paper.

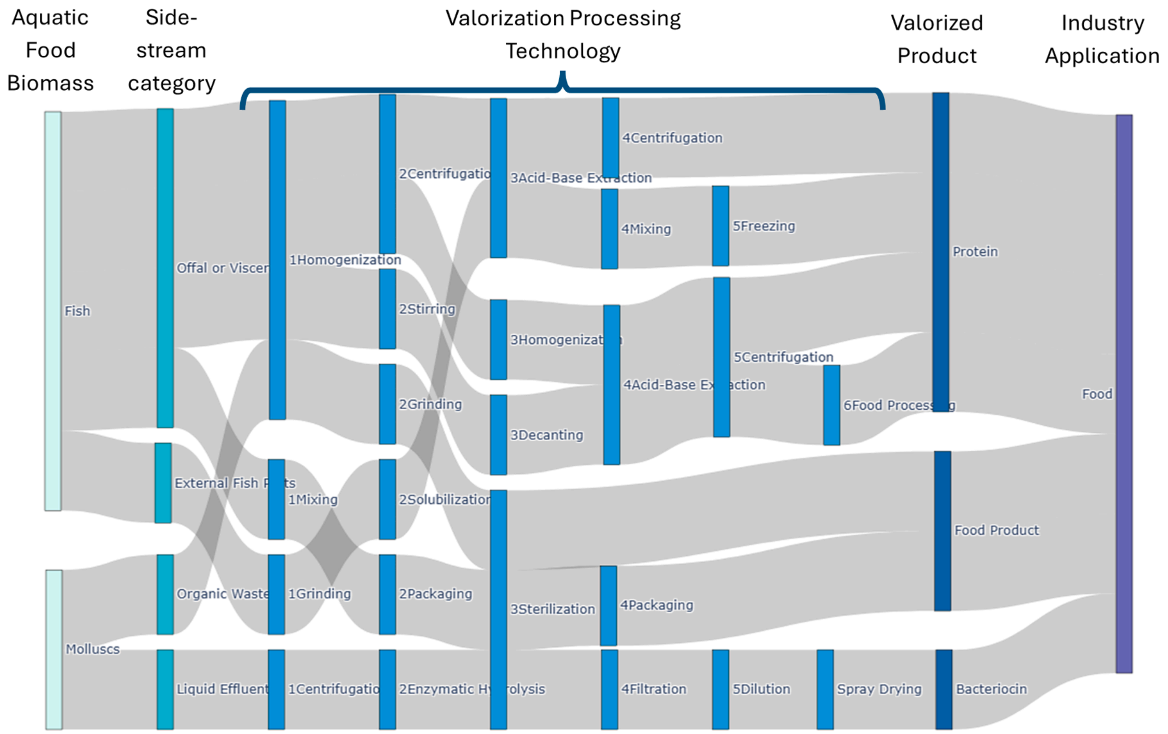

Fig. 5. Summary of the processing steps employed in the publications selected with products intended for food applications, along with the sources of side-streams, side-streams processed, and valorized products. Figure for other industry application such as energy input and agricultural input fine and bulk chemicals, feed are available in the supplementary documents.

methods, including solvent extraction, enzymatic hydrolysis, acid-base extraction, hot water extraction, deproteinization, and demineralization. Super critical fluid fractionation was also found to be applied for omega-3 lipids extraction (Hublin et al., 2024). This industry valorizes side-streams from all aquatic food sources except from the rarely studied "other aquatic animals", and utilizes all types of side-streams except external fish parts.

Feed applications emerges as the second most assessed industry application, accounting for 28% valorization scenarios reviewed (Fig. 4c). Valorized products are in the form of fish meal, fish oil, pet food, silage, protein, omega-3 lipids, and calcium compounds (Figure S4). Drying is again a prominent final step, with technologies ranging from conventional, freeze drying (Bashiri et al., 2024) and super-heated steam drying (Cristiano et al., 2022, 2023). Sustainability of feed as industry application was assessed using technologies with higher TRL since third party processing facilities were already accessible. The feed industry utilizes diverse side-stream including common fish processing wastes such as guts, external parts, wastewater, and by-catch, but also the less utilized side-streams such as squid gut (Kader et al., 2019) and sea urchin (Zilia et al., 2023) and shrimp (Yang et al., 2019) exoskeleton. It is the only industry where "other aquatic animals" have been assessed in terms of sustainability.

Food applications (Fig. 4b) account for 12% of the scenarios assessed in the selected publications. Valorized products are dominated by protein with the intention of using it as a food ingredient. Valorized products as ingredients for food products, most of the time as patê, employed less chemical extraction but has sterilization steps for food safety purposes (Cortés et al., 2021; Iribarren et al., 2010). Extracting protein for food application involved more acid-base extraction (Cadena, Kocak, et al., 2025; Coelho et al., 2022, 2023) while extraction of bacteriocin involved enzymatic hydrolysis (Arias et al., 2022). Drying is less observed as a final step. Instead, freezing (Cadena, Kocak, et al., 2025) and packaging (Iribarren et al., 2010) are identified as final steps. This industry destination mainly valorized side-streams from fish guts and external parts and mollusks organic waste and effluent.

Finally, an overall comparison across the destination industries reveals similarities and differences in processing complexity and common unit operations employed. Among the destination industries, fine and bulk chemical applications show the most elaborate processing steps, while food application showed more straight forward procedures. Drying emerged as the most common final unit process, reported in thirteen studies. Oven drying was the most predominant method, but other methods such as infrared drying (Cristiano et al., 2023), spray drying (Arias et al., 2022), freeze drying, and the novel method of superheated steam drying (Cristiano et al., 2022) were also evaluated.

The variety of aquatic food biomass, side-streams, and valorized product did not allow for an overall comparison of inventories across all papers. Also, only 8% of the papers have reported the yields of their process, all of them are economic assessments studies. The other 60% of papers gave sufficient information to calculate their process yields and the remaining 33% did not provide enough information for calculation. The process yields are summarized in Table S2. Process yields for protein extraction ranges from 6–53%, with the lowest yield coming from fish processing residue and the highest yield coming from fish frames. Fine chemicals like astaxanthin and chitin has lower yields of <1 to 3%. Process yields for fishmeal and oil, when calculated from fish raw material, ranges from 2–28% depending on the fish species, process applied, and side-stream processed.

3.3. Environmental impact assessments

Across the 40 reviewed publications, 80% employed environmental impact assessment methodologies. Life Cycle Assessment (LCA) was the method of choice in 91% of the papers. The rest used Eco-efficiency, Ecological Footprint (EcoF), and Emergy Assessment (EA). A detailed list of papers and methodological choices is available in the supplementary material (Table S3). Since more comparisons can be made among the studies that conducted LCA, it is discussed later, and the following subsection will start with the less applied methodologies.

3.3.1. *Emergy assessment*

EA aims to quantify the energy that was directly or indirectly used to produce products or services in one unit, usually as solar emjoule (sej) per unit (Cristiano et al., 2023). Cristiano et al. (2023) used EA to assess environmental performance of an innovative recirculating aquaculture system (RAS), where sludge and fish mortalities are valorized into pet food ingredients or energy sources. EA results for sludge valorization exhibit a negligible decrease. The significant contributions coming from fish feed and salmon eggs account for total emergy requirement of 17% and 18%, respectively. When these inputs and their corresponding labor and services emergy requirements are removed, the valorization scenario shows 98% decrease for emergy requirement coming for fuels used to transport by-products. However, this decrease is counterbalanced by increased emergy requirements due to inputs for machinery to perform the valorization (33%) and increase in net water use (20%). On a separate paper published a year earlier, the same authors conducted an LCA for the same system and valorization scenarios (Cristiano et al., 2022). Both EA and LCA showed the significant contributions of fish feed and water use and avoided impacts from fuel due to transporting by-products. EA was able to highlight additional contributors specifically the salmon eggs and the inputs necessary for the new machinery. This study recommends that future studies must investigate the impacts of the significantly contributing inputs as valorization technologies have very little effect.

3.3.2. *Eco-Efficiency assessment*

Eco-efficiency is a standardized sustainability assessment that employs LCA following the life cycle perspective, and additionally considers the product system's value through various costing methodologies (ISO, 2012). García-Santiago et al. (2021) applied this methodology to assess various biorefinery processes applied to cartilaginous fish discards to extract cartilage, gelatin, protein hydrolysates, and chondroitin sulfate with 90% purity. The eco-efficiency index (EI) was calculated using the ratio of the value of the product system (gross benefit) and the environmental impact in a specific category (climate change and normalized index [EcoPt]). The study found that higher utilization of fish biomass for extraction of more varied bio-compounds has higher eco-efficiency than simply producing fishmeal. However, if the valorization only yields a single product of fish protein hydrolysate and compared to fish meal, the gross benefit of the former is higher, but the environmental performance of the latter is better. A sensitivity analysis also showed that the eco-efficiency index is significantly influenced by the product sell price (García-Santiago et al., 2021).

3.3.3. *Ecological footprint*

EcoF is an indicator used to quantify the global hectares of biologically productive land and water required to generate the resources consumed and absorb the waste generated per unit of a certain product, service, or activity being assessed (Choudhury and Sahu, 2025). Three of the reviewed papers used EcoF to quantify the environmental impacts of different aquatic food side-stream valorization pathways.

Gaviria et al. (2021) evaluated the environmental impact of producing dry chemical silage from tilapia *(Oreochromis* spp.) viscera in comparison with shallow landfill disposal. They found that shallow landfill disposal has a higher environmental impact, amounting to −10.15 ha/ton, and the alternative scenario of generating dry chemical silage with −2.84 ha/ton. Valorization results in 30% less CO_2 emissions compared to landfill disposal. Despite these reductions, the study identified hot spots in the valorization process, which are disposal of organic waste and energy requirement for drying. The alternatives, specifically producing biogas from organic waste and substituting conventional drying with solar, further reduced the environmental impact of the valorization scenario by 86% (−8.79 ha/ton).

Lopes et al. (2018) compared chemical and enzymatic extraction methods of chitin from crustaceans' biomass. Chemical extraction was found to have a greater global impact (5.3 global ha/ton) compared to enzymatic extraction (2.8 global ha/ton). The study also highlighted EcoF's effectiveness in assessing energy and land use, while noting its limitations in capturing water-related impacts (Lopes et al., 2018). In another study, Lopes et al. (2015) used EcoF to compare environmental impacts of converting fish by-products into fishmeal and oil against other waste management techniques, such as composting, incineration, and landfilling. The results did not show significant difference from each other, but incineration showed a higher impact than landfilling (Lopes et al., 2015).

Using the EcoF method has limitations. There are variations in reporting as seen in Gaviria et al.'s (2021) choice to report the results with a negative value, which was not done in the two other papers. It also limited sensitivity to water-related impacts suggests that it should be complemented with other indicators for a more comprehensive sustainability assessment. While water is considered as an input and output in the calculations, its impact is ultimately translated into this land-based metric (Lopes et al., 2015). This conversion might not adequately capture the multifaceted environmental burdens specifically associated with water use and pollution.

3.3.4. *Life cycle analysis*

Among the 32 publications that assessed the environmental sustainability of valorization technologies, 29 papers)pplied LCA both solely or in combination with other environmental and economic assessments (Table S3). Only one paper conducted a Material Flow Analysis (MFA) which highlighted waste quantities from fish processing that then led to the conduct of LCA (Hublin et al., 2024). MFA tracks material flow and mass balance, which could be a useful foundation for LCA as it can extend to using MFA results to calculate emissions and extractions (Jolliet et al., 2015). Only two papers further used the LCA results into eco-efficiency assessment (García-Santiago et al., 2021) and EcoF (Lopes et al., 2015), respectively. This section will focus only on the findings of environmental analysis following the four steps of the LCA methodology.

3.3.4.1. Goal and scope definition. The majority of the papers' objectives can be summarized into three specifc goals: (i) identification of hotspots in processes (24%), (ii) comparative LCA between products (24%) and processes (41%), and (iii) prospective LCA (7%). Prospective LCA was conducted to compare the environmental impact depending on the projected changes in energy, transport, and resource consumption.

Since valorization is an alternative to waste management, the functional unit (FU) can either be from the product perspective or waste perspective, consistent with the distinction described by Sanabria Garcia et al. (2025) on modelling multifunctional systems (Table S4). More than half (59%) of the papers chose the product perspective. The FU were defined either as valorized products (e.g. 1 kg of fish protein hydrolysate, 1 t of omega-3 fatty acids), or as applied products (e.g. 100 g of protein (Coelho et al., 2023), mass of valorized alternative required to formulate 100 g of SPF 20 sunscreen (Righi et al., 2023)). For the papers that used the waste perspective (28%), the FU referred to the mass of aquatic food side-stream requiring treatment or valorization (e.g. 100 kg of shrimp shell, 1 ton of fish by-products). A small subset of papers (10%) used the mass of aquatic food entering the process as the FU (e.g. 1 ton of raw tuna, 1 ton of farmed fish, 1 kg of whole cartilaginous fish). Although this approach is uncommon in sustainability assessment, it may still provide useful insights when considered from the perspective of food processing facilities or aquaculture farms when the assessment aims to determine the efficiency of raw material utilization.

ISO 14,044 defines system boundary as the set of criteria specifying which unit processes are part of a product system (ISO, 2006). Out of the 29 publications, 62% explicitly stated the system boundary, while 34% did not mention them but allowed for reasonable assumptions based on the methodological process flows and inventory data. Only one study, Monsiváis-Alonso et al. (2020), integrated the LCA results into a multi-objective optimization model, but it did not provide sufficient information to determine the system boundaries. Fifty-nine percent of the studies assessed environmental impacts using Cradle-to-Gate system boundary, while 31% studies applied Cradle-to-Grave and 7% studies conducted assessment using Gate-to-Gate boundary.

3.3.4.2. Inventory analysis. Among the reviewed publications, 52% (16 papers) used primary data for the foreground inventory. The approaches varied from using laboratory scale data, pilot scale data, simulated industry scale data using modelling software, and industry scale data gathered through company interviews. When primary data were not sufficient, 37% (10 papers) supplemented the inventory with secondary data from literature and databases (Table S4). Three papers did not declare the source of inventory information. For the background data, 83% of the papers used secondary data through various databases. Ecoinvent database was used by 72% of the papers, 7% used Ecoinvent and Agribalyse in combination, and 3% used GaBi. The remaining 17% did not specify the database used. Regarding software, SimaPro was used by 48% of the papers, OpenLCA by 14%, Gabi by 7%, and one prospective study used Premise as source of background data future scenarios and Activity Browser for the analysis. The remaining 28% did not explicitly mention the software used for LCA.

In aquatic food valorization, allocation may occur at two stages in the supply chain. The first is at production of aquatic food, requiring a decision on whether the environmental impacts of cultivation or fishing are also attributed to the side-streams. Ten percent of the LCA studies adopt the cut-off or zero-burden approach which assumes that biomass classified as waste carries no environmental burden. Under this assumption, upstream impacts from biomass production are excluded from the system boundary (Dominguez Aldama et al., 2023). Iribarren et al. (2010), for example, assessed the environmental impact of processing mussel by-products with and without applying the zero-burden assumption and reported that its application led to a threefold reduction in GWP. Similarly, studies by Fraterrigo Garofalo et al. (2023) and Gargalo et al. (2022) excluded the environmental impacts of aquatic food production from their system boundaries by adopting the zero-burden approach.

The second case where allocation becomes relevant is in valorization scenarios that generate multiple products with different economic values. Among the reviewed studies, 21% applied mass-based allocation, 3% employed economic allocation, and 7% combined both methods. Allocation was particularly critical when a high-value co-product was produced in relatively low quantities. In a valorization scenario yielding pediocin, lactic acid, and crude protein, mass allocation would give the highest environmental impact to lactic acid (66.84%) and the lowest to pediocin (0.29%) (Arias et al., 2022). However, since both products have high economic value, economic allocation would associate close environmental impacts of 43.71% and 45.57 to pediocin and lactic acid, respectively (Arias et al., 2022).

3.3.4.3. Impact assessment. The most frequently used environmental impact categories across the reviewed studies are presented in Figure S5. Midpoint impact categories were used by 93% of the papers. Global warming potential (GWP) was reported in all 27 papers. It was closely followed by terrestrial acidification (23 papers) representing soil pollution, then by freshwater eutrophication (19 papers) representing water pollution.

In earlier studies, impact reporting was less standardized. For instance, Leceta et al. (2014) used impact categories such as ozone layer depletion, ecotoxicity, acidification, and eutrophication without further specifications. Over time, reporting practices have been more standard and specific. Although ReCiPe 2016 includes only freshwater eutrophication, 41% of the papers reported marine eutrophication and 10% of that reported all three types of eutrophication: freshwater, terrestrial and marine. More information about the impact indicators used by the papers can be found on supplementary Table S5.

To generate collective relevant insights from the results of the reviewed studies, results were compared to each other using a common metric. GWP, being present in 93% of the papers, was used to compare the impact of aquatic food valorization scenarios. It is important to note that GWP alone does not represent the full environmental profile. For example, Righi et al. (2023) and Coelho et al. (2022) found that valorization scenarios had higher GWP than alternatives, but trade-offs in other categories altered the interpretation of overall sustainability.

Fig. 6a lays out the unit processes for pre-valorization and valorization technology, along with the inputs and outputs that were reported by the papers as contributors to environmental impact. Fig. 6b summarizes which unit processes, inputs, and outputs were reported. For Fig. 6c the unit processes were ranked based on their relative contributions to GWP (top, second or third highest, minor, or avoided impacts). The results were ranked because the values reported in the results were not always in kg CO_2 equivalence, and the magnitude varies depending on the functional unit. The rankings shown are results based on scenarios and since 55% of the papers evaluated multiple valorization scenarios, the number of observations exceeds the number of studies. More details are available in Table S6.

In the pre-valorization stage, aquatic food harvest is rarely included (reported in five papers) and when included, it was identified as the top contributor to GWP in 70% of cases. This was attributed to the impacts of fish feed, fish meal and fish oil production, aquaculture infrastructure, fishery operations with diesel consumption (Coelho et al., 2022; Cortés et al., 2021; Cristiano et al., 2022; Silva et al., 2018). As mentioned previously, some papers used the zero-burden approach, so the aquatic food harvest is excluded in the impact assessment (Fraterrigo Garofalo et al., 2023; Lopes et al., 2015).

Among input contributors, reagents production and electricity consumption were most frequently reported (48%). Reagents production was the top GWP contributor in 37% of scenarios. Commonly cited reagents included hexane (8.02 kg CO_2eq) (Kiehbadroudinezhad et al., 2023), NaOH (88–96% of total environmental impact)(Cadena, Kocak, et al., 2025), limonene (7.2×10^{-2} kg CO_2eq) (Arfelli et al., 2023), and isopropanol (~70% of environmental impact)(Monteiro et al., 2018). Other reagents include acetic, citric and myristic acids, xylitol and methanol. Electricity was the top contributor in 40% of the scenarios. To mention a few cases, electricity contributed to >80% of climate change impact for extraction of high-value protein from cartilaginous fish (García-Santiago et al., 2021), astaxanthin and chitin extraction from crustacean side-streams (Berroci et al., 2022; Vicente et al., 2022), and savory compounds from mussel processing water (Cadena, Dewulf, et al., 2025).

For processing stages, the core valorization process and waste treatment were the most reported contributors to GWP. The core valorization process was the top contributor in 29% of scenarios, the second highest in 41%, and minor contributor in 29%. Waste treatment showed avoided impacts in 13% of scenarios, particularly when the waste treatment generates energy (Righi et al., 2023) or agricultural input from composting (Leceta et al., 2014; Uranga et al., 2016).

For outputs, the valorized products and co-products exhibit avoided impact or are reported as minor contributors to GWP, as they often serve as alternative to "business as usual" scenarios. For example, calcium carbonate derived from sea urchin waste showed an avoided impact of −100% of relative contributions compared to the conventional sources (Zilia et al., 2023). Similarly, alternative nitrogen, phosphorus, and potassium (NPK) fertilizers derived from anchovy leftovers show an impact of −2.8 kg CO_2 eq (Arfelli et al., 2023). Recovered compounds from salmon waste such as hexane (−7.62 kg CO_2 eq), methanol (-6.25×10^{-2} kg CO_2 eq) and fish oil recovered (-1.4×10^{-1} kg CO_2 eq) also exhibited avoided emissions (Kiehbadroudinezhad et al., 2023).

Only 34% of the papers applied normalization. Methods included neutral global units, Environmental Footprint (EF) 3.0 factors, ReCiPe normalization, and internal scaling (e.g., relative to the highest

Fig. 6. Summary of contributors to Global Warming Potential (GWP) reported by papers in the results. (A) The bar graphs show the percentage of papers that reported the unit process, input, and output. It is also indicated where it will not be applicable. (B)The bar graphs shows the impact of the unit process, inputs, and outputs reported by papers for each valorization scenario analyzed. Only valorization scenarios where included in the analysis (B); business as usual scenarios were not included.

contributor). Four studies applied weighting using EF 3.0 factors, IMPACT World+, and ReCiPe weighing factor.

3.3.4.4. Interpretation. In the interpretation phase, results are evaluated depending on the objective of the assessment. Across the reviewed studies, 41% of valorization scenarios (reported in 11 papers) showed lower environmental impacts than reference systems. In contrast, 11% (3 papers) showed higher impacts for valorization scenarios than the business-as-usual cases. The remaining 44% (12 papers) were comparisons between valorization scenarios, and one study applied the results to a multi-objective optimization model without comparing business as usual or alternative valorization options.

Studies focused on comparison with waste management alternatives showed mixed results. Three studies found that valorization of by-products and side-streams have lower environmental impact than conventional treatments such as landfill, incineration, sludge treatment, ensilage, or municipal solid waste disposal (Cristiano et al., 2022; Lopes et al., 2015; Zilia et al., 2023). However, results are context dependent as Iribarren et al. (2010) found that valorizing mussel shells into calcium carbonate had impacts lower than incineration but still higher than landfilling.

For papers comparing food application to other destination industries, the results show a consistent trend in favor of food application. Developing food products (e.g. pâte) from side-streams has lower environmental impact than fishmeal production (Iribarren et al., 2010). The use of side-streams to deliver dietary protein has more environmental benefit than fish fillet and incorporating side-streams from other sources (e.g. apple pomace) further lowers the environmental impact of food product development (Coelho et al., 2022, 2023).

Six studies compared utilization of valorized product from aquatic food side-stream with other conventional or alternative bio-based materials. Both chitosan and omega-3 from side-streams were found to have lower environmental impact than other bio-based alternatives (e.g. algae) (Barr and Landis, 2018; Leceta et al., 2014). However, both still have higher environmental impact than conventional sources, specifically polypropylene and land based animal fat, respectively (Hublin et al., 2024; Leceta et al., 2014). Contrary to this, substituting conventional growing media for fermentation and cosmetic product development with products from valorization has shown better environmental results (Arias et al., 2022; Righi et al., 2023).

Valorization processing technologies significantly influenced environmental performance. Papers found that reducing the number of chemical reagents used in extraction process resulted in lower environmental impact (e.g. replacing water with glycol, using hot water and carbonic acid instead of reagents) (Cristiano et al., 2022; Yang et al., 2019). Relating these findings to Fig. 6, it shows that the environmental impact is not solely reliant on the complexity of the processing stages, but also on volume of chemical reagents used. In one case, a novel biological-chemical extraction method still had higher environmental impact compared to conventional extraction but combining it with high hydrostatic pressure (HHP) lowered the environmental impacts due to increased yields (Monteiro et al., 2018). The papers also demonstrated that laboratory-scale valorization was more impactful than scaled-up scenarios (Arfelli et al., 2023).

Three studies analyzed the environmental impact at different stages of the value chain. Cortés et al. (2021) and Silva et al. (2018) identified fisheries as the main impact contributor, and valorization processes were minimal in comparison. In contrast, García-Santiago et al. (2021) reported higher impacts from the valorization stage. But when integrating product value through EcoF, valorization was more eco-efficient than fishmeal production when the product value is considered.

The choice of input material also affected results. Cadena et al. (2025) demonstrated that using herring frames via pH-shift technology had higher impacts than valorizing salmon or cod by-products.

3.3.4.5. Sensitivity and uncertainty analysis. Only 10% of the papers conducted uncertainly analyses using Monte Carlo Simulation and 34% performed sensitivity analysis. Sensitivity analysis showed that there is no significant difference from using different impact assessment methodologies (Bashiri et al., 2024). Results of environmental impact assessment were found to be sensitive to fuel type, electricity source (e.g. renewable, non-renewable), efficiency of energy consumption, and region (Barr and Landis, 2018; Bashiri et al., 2024; Cadena, Kocak, et al., 2025; Righi et al., 2023). This highlights the importance of regional context in environmental assessment.

3.4. Economic assessments

Several of the reviewed publications assessed the economic feasibility of aquatic food side-stream valorization using a range of methodological approaches. Out of the 40 publications, 16 (40%) conducted an economic assessment. Among these, seven (18%) combined economic and environmental assessments, while one integrated all three sustainability dimensions, economic, environmental, and social. The applied methodologies evolved over time. Earlier studies used various economic indicators, while more recent publications adopted more advanced methods, including Techno-Economic Analysis (TEA, used in 3 papers) and Life Cycle Costing (LCC, used in 2 papers). In other studies, various economic indicators (e.g. cost of production, gross profit, operating cost) were calculated, as summarized in Table 2. Among the combined assessments, only one used ecological footprint as the environmental framework; the others were conducted in conjunction with LCA. However, the economic perspective did not always look at the entire life cycle for the ones combined with LCA. The highlighted results of these studies are summarized in Table 3.

3.4.1. Techno-economic assessment

TEA is a methodology used to evaluate both technical and financial viability of products or processes (Mousavi-Avval et al., 2023). TEA was performed in four of the reviewed publications to assess economic feasibility of aquatic food side-stream valorization. These included assessments of processing mollusks and fish residuals (Andreola et al., 2023), a shrimp by-product biorefinery (Zuorro et al., 2021), comparison between traditional and less intensive demineralization for chitin recovery (Yang et al., 2019), and production of biodiesel from tilapia processing waste (Igansi et al., 2023). In terms of reporting the economic performance indicator, Zuorro et al. (2021) and Igansi et al. (2023) conducted comprehensive TEA and reported indicators such as NPV and payback period (PP). Andreola et al. (2023) and Yang et al. (2019), although both claimed to have done a TEA, only reported PP and net profit, and total capital investment (TCI) and total operation cost (TOC), respectively.

The three studies showed valuable results for aquatic food side-stream valorization scenarios. Valorization scenarios that resulted in positive NPV were technologies with the highest processing capacity (e.g. 140,000 tonnes/year of tilapia waste processed (Igansi et al., 2023; Zuorro et al., 2021) across the scenarios analyzed. Technologies that produce high value products, like protein hydrolysate (2 EUR/kg) also generated significantly higher net profit (302.0 EUR/ton). In contrast, low-value products like calcium carbonate (0.03 EUR/kg) led to a lower net profit of 20.6 EUR/ton (Andreola et al., 2023). In terms of sensitivity, valorization technologies were found to be affected by changes in raw material or reagents cost and selling price (Yang et al., 2019; Zuorro et al., 2021). Technologies which aimed to reduce reagent cost were less affected by varying reagent prices (Yang et al., 2019).

Collectively, these studies were able to show potential economic feasibility of aquatic food side-stream valorization through TEA. They also presented the importance of including sensitivity analyses to evaluate economic robustness under varying market and operational conditions. TEA offers insights both for the project developers considering implementation and for investors evaluating profitability and financial

Table 2
Methodologies and indicators used by publications that assessed the economic dimension.

Authors	Economic Assessment	Economic Indicators
Diná Afonso et al., 2004	Economic Assessment	Net Present Worth, Interest Rate of Return, Payback Period
Kaliba et al., 2010	Capital budgeting and risk analysis tools	Economic Profitability Index, Net Present Value, Interest Rate of Return, Payback Period
Kader et al., 2019	Economic Assessment	Total Feed Input Cost, Gross Return, Net Profit, OpEx
Vázquez et al., 2020	Economic Assessment	Cost of production
Andreola et al., 2023	Techno-economic Assessment	Net Profits (Total revenue - OPEX), CapEx, OpEx, Payback Period
Lopes et al., 2018	Economic Criterion (Sales Price-Operation Cost)	Economic Benefit, Sales Price, Operation Cost
Monteiro et al., 2018	Economic Assessment	Cost of production
Yang et al., 2019	Techno-economic Assessment	Yearly Returns on Investment, Minimum Selling Price, CapEx, OpEx
Vicente et al., 2022	Economic Assessment	Cost of Production, Return
Bashiri et al., 2024	Life Cycle Costing	Operating Cost
Hublin et al., 2024	Life Cycle Costing	Total Net Value (yearly), Production Value (yearly), Total Investment Cost (design and permiting included), Production cost (yearly), Operating and Maintenance (yearly), Total Net Present Value (15 years)
García-Santiago et al., 2021	Gross Benefit	Total Cost/FU, Income/FU, Gross Benefit/ FU
Monsiváis-Alonso et al., 2020	Economic Assessment	Total Annual Profit, CapEx, OpEx
Zuorro et al., 2021	Techno-economic Assessment	Gross Profit (depreciation included/not included), Normalized Variable Operating Costs, Cumulative Cash Flow, Return of Investment, Net Present Value, Payback Period, Profit after Taxes
Kratky and Zamazal, 2020	Economic Assessment	Simple Payback Time, CapEx, OpEx
Igansi et al., 2023	Techno-economic Assessment	Earnings before interest and taxes, Return on Sales, Net Present Value, Internal Rate of Return, Payback Period, Profit after Taxes

risks.

3.4.2. *Life cycle costing*

LCC is a methodology employed within the framework of life cycle management. In this review, two studies conducted LCC. Bashiri et al. (2024) assessed the life cycle cost of enzymatic hydrolysis of fish protein and oil in parallel with an environmental LCA. However, the analysis focused primarily on operating costs and excluded initial investments, maintenance cost, and end-of-life cost, because the technology being evaluated was still at laboratory scale. Additionally, this study also did not compare multiple scenarios, but instead just focused on identifying the production cost for 1 g of fish protein hydrolysate which was 3.68 EUR (Bashiri et al., 2024). Hublin et al. (2024) compared a business-as-usual scenario with a biorefinery valorization pathway for fish waste using NPV as an indicator. Although the investment cost for valorization of fish by-products was high, resulting in a lower profitability index over a 15-year timeframe, the valorization scenario yielded a much higher NPV (Hublin et al., 2024). This implied that, despite the higher investment cost, the biorefinery pathway can generate higher profit over time because high-value pharmaceutical and food ingredients are produced (Hublin et al., 2024).

3.4.3. *Other economic indicators*

The remaining 11 studies did not report explicit methodologies but instead used economic indicators to assess the feasibility of the valorization technologies. Some studies used the same indicators as would have been used in the previous methodologies discussed (NPV, IRR, PP) while others used conventional metrics such as capital expenditures (CAPEX), operations expenditures (OPEX), and net profit. Three papers used these indicators, along with an LCA, but did not employe life cycle perspective for the economic dimension. Gross Benefit was used as a factor for EcoF analysis (García-Santiago et al., 2021).

Due to the diversity of metrics and reporting approaches, it is difficult to make a generalized conclusion about the economic feasibility of valorization technologies from the papers that used varied indicators. Nevertheless, most studies showed favorable economic outcomes. Positive NPV or net profit values were reported in the valorization of fish offal, crustacean shells, and other aquatic food residues (Diná Afonso et al., 2004; Kader et al., 2019; Kratky and Zamazal, 2020; Vázquez et al., 2020). Novel technologies with higher yields of valorized products were found to have higher gross profit (Lopes et al., 2018; Monteiro et al., 2018). Plant operation at higher capacities (23 to 18 t of side streams processed over 48 h) was also found to result into positive NPV (Kaliba et al., 2010). In cases where multiple products are valorized from one side-stream, lower yields still resulted in positive returns when at least one of the co-extracted products have high selling price (e.g. astaxanthin) (Vicente et al., 2022). Low value products (e.g. co-fermented fish waste and cow dung for methane production) were only found to be profitable if green subsidy is present (Kratky and Zamazal, 2020).

Overall, aquatic food side-stream valorization shows the potential to be profitable given the right conditions. However, profitability is not assured and is dependent on several factors. Studies have shown that larger-scale operations are more likely to achieve economic viability due to economies of scale. High product market value, efficient processing methods that improve yields, stable raw material prices, and lower transport cost due to proximity of processing facility also contribute positively to profitability. Conversely, valorization pathways involving low-value products or low TRLs were associated with long payback periods and limited economic return. Future research would benefit from the adoption of standardized economic methodologies and comprehensive reporting practices to enable cross-study comparisons and inform investment decisions in this emerging field.

3.5. *Social assessment: A missing pillar*

The underrepresentation of the social dimension in sustainability assessment of side-stream valorization is evident in this review. Among the 40 studies analyzed, only one paper incorporated the social aspect. Monsiváis-Alonso et al. (2020) developed an optimization model that was benchmarked to assess environmental, economic, and social impacts. While an LCA was conducted to assess the environmental impact, the social dimension was limited in scope. It included only two indicators: “satisfaction of social needs” and “shared revenues,” the latter referring to the provision of omega-3 supplements to local communities near the processing facility (Monsiváis-Alonso et al., 2020). These indicators did not encompass a comprehensive social impact assessment and fell short of capturing the full range of potential social impacts across the product’s life cycle.

3.6. *Life cycle sustainability assessment (LCSA)*

LCSA is a comprehensive methodology that aims to assess both the benefits and the negative impacts of the three dimensions of sustainability, specifically, environmental, economic, and social sustainability to drive the development of holistically sustainable products (Ciroth

Table 3
Overview of economic assumptions made to assess valorization scenarios and corresponding results.

Paper	Economic Assessment	Scenario	Assumptions	Results
Diná Afonso et al., 2004	Economic Assessment	Integrated process of MF pre-treatment and UF for 69% Protein Recovery, 544 ton/year of fish meal	Discounting interest rate: 12% Tax Rate: 15% Expected project life: 10 years	Net Present Value: 160,000 USD Interest Rate of Return: 17% Payback Period: 8 years
Kaliba et al., 2010	Capital budgeting and risk analysis tools	Highest capacity plant: 181 mt/48 h operation to produce Fishmeal and Fishoil from channel fish processing waste, 15% discount rate	Discount rate: 15%	Net Present Value: 3084,341 USD Interest Rate of Return: 33% Payback Period: 3 years
Kader et al., 2019	Economic Assessment	Cost of fish production after 70 days of feeding trial with squid by product feed replacement (13.2% squid by-product soybean blend) 1 usd = 80.00 Tk		Gross Production Value: 1978.20 Gross Return: 577.6 Net Profit: 64,176.7 Tk/ha
Vázquez et al., 2020	Economic Assessment			
Andreola et al., 2023	Techno-economic Assessment	Scenario A - 1 ton Mussel Waste Scenario B - 1 ton Fish Waste Scenario C - 1 ton MW and 1 ton FW Scenario D - combination of 1 ton MW and 1 ton FW		Payback Period; Net Profit A. 78 years; 11.7 EUR/ton B. 3.1 years; 255.5 EUR/ton C. 78 years; 133.6 EUR/ton D. 7.4 years; 228.8 EUR/ton
Lopes et al., 2018	Economic Criterion (Sales Price-Operation Cost)	Chitin extraction via: -Enzymatic hydrolysis (with water recovery) -Enzymatic hydrolysis (without water recovery) -Chemical hydrolysis		
Monteiro et al., 2018	Economic Assessment	Extraction of omega 3 lipids from fish canning liquid by-products 1: Conventional 2: HPP & Solvents 3: Bio-chemical methods		
Yang et al., 2019	Techno-economic Assessment	Traditional vs Hot Water Carbonic Acid Demineralization HOWCA process based on minimum selling price: 9.893 USD/kg of Chitin		CapEx: 5134,471.09 USD OpEx: 781,258.63 USD/year
Vicente et al., 2022	Economic Assessment	Shrimp shells to produce: Astaxanthin Proteins Chitin		Gross Production Value Production Cost Complete: 0.035 EUR/g Astaxanthin: 0.014 EUR/g Proteins: 0.022 EUR/kg Chitin: 0.008 EUR/kg Return Complete: 0.022 EUR/kg Astaxanthin: 0.031 EUR/kg Proteins: −0.021 EUR/kg Chitin: 0.001 EUR/kg
Bashiri et al., 2024	Life Cycle Costing	Extraction of protein compounds and oil from Atlantic mackerel processing residues using enzymatic hydrolysis		
Hublin et al., 2024	Life Cycle Costing	Business as usual - waste animal fat, meat, bone meal Circular Economy CE- omega 3 oil, oil extraction	`-Construction period: 1 year Production period: 15 years Discount rate: 7% per annum	Net Present Value BaU: 528,441 EURCE: 1498,229 EUR
García-Santiago et al., 2021	Gross Benefit	S1: Cartilage, FPH, gelatin S2: CS90, FPH, Gelatin S3: Cartilage, FPH S4: FPH		
Monsiváis-Alonso et al., 2020	Economic Assessment			
Zuorro et al., 2021	Techno-economic Assessment	Best Case: processing capacity of 4110.37ton/year	Discount rate: 8% Plant life: 15 years Construction time of plant: 1 year Tax rate: 39% Subsidies: 0USD/year	Net Present Value: 1.12 Million USD Payback Period: 4.62 years Cumulative Cash Flow: <1

(*continued on next page*)

Table 3 (*continued*)

Paper	Economic Assessment	Scenario	Assumptions	Results
			Depreciation method: Linear	
Kratky and Zamazal, 2020	Economic Assessment	Anaerobic fermentation of fish waste		CapEx: 5274,000 EUR Taxable Income: 959,000 EUR/year
Igansi et al., 2023	Economic Assessment	Production of biodiesel and fishmeal from tilapia processing waste -capacity: 140 thousand t/year	Depreciation method: Linear Equipment life: 10 years Buildings life: 25 years Local tax: 15% profit before tax Life-time project: 10 years Discounted payback year: 3.09	Net Present Value: 13.89 million USD Interest Rate of Return: 50% Taxable Income: 7.87 million USD/year

et al., 2011). LCA is recommended to assess the environmental aspect, as standardized in ISO 14,040 and 14,044, LCC for the economic dimension, and social LCA (S-LCA) for the social dimension, recently standardized in ISO 14,075:2024.

Despite the integrative intent, research shows that the social aspect has been underexplored and underrepresented (Zarauz et al., 2025). S-LCA evaluates the social impact or potential impact of a product or service throughout its life cycle (Ciroth et al., 2011; UNEP, 2020). It follows the same iterative phases of an environmental LCA, but it assesses impact across categories that affect relevant stakeholders (UNEP, 2020). Earlier guidelines were published in the UNEP guidelines for S-LCA of products and organizations, last updated in 2020.

Among the 40 studies on aquatic food side-stream valorization, none conducted a comprehensive S-LCA even though studies evaluated both economic and environmental impacts. The social aspect is equally as important as the environmental and economic aspects to ensure inclusive and just sustainable transition (Zarauz et al., 2025). Bioeconomy policies should encompass environmental aspects, but also incorporate social aspects such as equity, social justice, local development, and human rights (Kurki and Ahola-Launonen, 2021). The findings emphasize the need to incorporate the social dimension into sustainability assessments of aquatic food side-stream valorization. Moving forward, research must not only apply S-LCA more consistently but also advance its development to ensure that it addresses issues of social equity, inclusion, and long-term societal wellbeing.

3.7. Challenges and recommendations

This review of 40 sustainability assessments of aquatic food side-stream valorization reveals several methodological challenges and opportunities for improvement. The studies generally aimed to quantify environmental and economic impacts within a defined system boundary, but the integration of the social dimension was absent. Furthermore, differences in methodological choices, particularly regarding functional units, system boundaries, allocation methods, and result presentation, reduce the comparability and transparency of findings. These limitations hinder the development of a robust and harmonized knowledge base across the three sustainability pillars. The following section will summarize the challenges observed in this review and some recommendations for future research.

3.7.1. Challenge 1: limited use of MFA to support LCA

Among the reviewed studies, only one applied MFA to motivate or guide the LCA, despite its potential to highlight the significant amounts of waste generated in fish processing. Additionally, the data on side-streams generated by aquatic food processing and how they are currently being utilized are not readily available. On the global scale, the Technical Platform on the Measurement and Reduction of Food Loss and Waste (FAO, 2026) does not cover aquatic food losses. Even the global report on Investigating Global Aquatic Food Loss and Waste (World Economic Forum, 2024) only mapped out where the losses occur in the supply chain but does not provide information on how these losses are managed or treated. On the local scale, data are limited to raw material utilization rate without enumerating which parts are not utilized and how they are treated.

3.7.1.1. Recommendation. Future research should consider using MFA as a preliminary step to LCA to identify inefficiencies and prioritize side-streams with the highest valorization potential. MFA results can also support the quantification of food loss and waste along the supply chain, distinguish between edible and inedible side-streams, and map out how these side-streams are currently utilized and which industries they are directed to.

3.7.2. Challenge 2: lack of clear guidance on setting functional unit

As mentioned previously, three distinct perspectives were observed across the studies. The functional units often reflected the chosen comparative perspective, but in some cases, they were limited to the mass of input or output rather than the intended function of the valorized product. This can misrepresent the added value of valorization and reduce the relevance of comparisons.

3.7.2.1. Recommendation. Researchers should clearly define the comparative perspective adopted in their study and ensure that it aligns with the goal. A product-perspective functional unit is most appropriate when comparing the impacts of conventional versus emerging valorization technologies, or when comparing different valorization products derived from the same side-stream. In contrast, a waste-perspective functional unit is more suitable when comparing the impacts of valorizing a side-stream against conventional waste management practices. Future research should consider going beyond the mass as functional unit but also reflect the intended function of valorized products (e.g., nutritional value, material property, fertilizer content). Where possible, employ functionally equivalent units (e.g., 100 g protein, 1 MJ energy) to enable fairer comparisons with conventional products.

3.7.3. Challenge 3: lack of consistency and transparency in the choice of system boundaries across sustainability dimensions

The reviewed studies showed variation in system boundaries. Environmental assessments omitted important life cycle stages such as product storage, formulation, or equipment and infrastructure. These elements were consistently included in economic assessments. Such differences hinder integration of results across sustainability dimensions.

3.7.3.1. Recommendation. In parallel, system boundaries should consistently include relevant machinery, infrastructure, and processing stages across environmental, economic, and social assessments, with clear justification provided for any exclusions. This harmonization would enhance transparency, comparability, and integration across sustainability dimensions. Fig. 6a identifies the input, output, and processing stages that are present in a valorization technology. This could be a starting point in defining the system boundary of future research.

3.7.4. Challenge 4: limited availability of scaled-up data

Some studies relied on laboratory-scale data without scaling to pilot or industrial scale as reflected by the low TRL of technologies assessed (Fig. 4b and C). There is evidence that lab-scale processes tend to yield inflated environmental impacts due to inefficiencies (Arfelli et al., 2023).

3.7.4.1. Recommendation. Where feasible, technologies subjected for sustainability assessment must be at least TRL 5. When using laboratory data, researchers should apply upscaling factors or scenarios and transparently communicate limitations. The TRL framework adapted for aquatic food side-stream valorization (Table S1) may be used as a reference for reporting the TRL in future studies.

Primary data should be prioritized for foreground processes, while background processes can be modeled using recognized databases (e.g., ecoinvent, carbon minds, Agribalyse). In the case of S-LCA, primary data is recommended as the first option, since the specificity of the location is extremely important for obtaining a representative analysis. Regarding economic data, it is suggested to use updated market values and/or projections from analyses carried out in collaboration with experts in the field of study who are knowledgeable about macroeconomic trends, whenever possible.

3.7.5. Challenge 5: inconsistent allocation methods and zero-burden assumptions

Allocation approaches varied across studies, with some using mass-based allocation and others using economic allocation, particularly when high-value products were produced in small quantities. Additionally, the zero-burden approach was inconsistently applied.

3.7.5.1. Recommendation. Economic allocation should be used when dealing with high-value co-products, aligning with ISO 14,044 guidance. The current Marine Fish PEFCR also recommends the use of economic allocation when allocation cannot be avoided (Marine Fish PEFCR, 2025). However, this guidance is meant for fish produced for human consumption and assumes that side-streams have no economic value. Future works must also be done to extend the guidelines to scenarios where valorization is applicable, and side-streams possess economic value. If the zero-burden approach is applied, it should be justified with respect to the study objective and comparison perspective.

3.7.6. Challenge 6: variable selection and reporting of impact categories

Environmental impact categories were inconsistently applied. While Global Warming Potential was commonly reported, categories such as eutrophication, water use, and toxicity were variably included. The lack of granularity, such as distinguishing between freshwater and marine eutrophication, limits the relevance of the results to aquatic systems. For economic indicators, NPV, IRR, and Payback Period were the most frequently used. Social impact indicators will depend on the case, country, type of value chain, or the product.

3.7.6.1. Recommendation. Studies should include a core set of midpoint impact categories relevant to marine and aquatic systems, such as GWP, freshwater and marine eutrophication, water use, and toxicity. There are approved Product Environmental Footprint Category Rules (PEFCR) for unprocessed marine fish intended for human consumption (Marine Fish PEFCR, 2025). This framework applies to both wild caught and farmed fish, but does not include crustaceans, mollusks, and other aquatic invertebrates (Marine Fish PEFCR, 2025). It also does not cover valorized products from aquatic food value chain. While recommendations exist for land-based food side-streams in PEFCR v. 6.3 corresponding guidance for aquatic food side-streams is yet to be developed (European Commission, 2018). Future work is recommended to identify the most appropriate indicators for aquatic food side-stream valorization for the three sustainability pillars.

3.7.7. Challenge 7: inconsistent reporting of results

Half of the studies presented results in tables, and the other half used only graphical formats. This makes it difficult to extract and compare results, especially when supporting data is not available in supplementary materials.

3.7.7.1. Recommendation. Results should be reported both graphically and in tabular form. When only visualizations are included in the main text, numerical data should be made available in supplementary materials. Including the top-contributing processes and categories enhances transparency and supports meta-analyses.

3.7.8. Challenge 8: limited use of sensitivity and uncertainty analyses

Only a minority of studies applied sensitivity (10 papers) or uncertainty (3 papers) analyses, despite the variability in inputs and assumptions that affect the robustness of findings.

3.7.8.1. Recommendation. Sensitivity and uncertainty analyses should be standard practice in sustainability assessments (ISO, 2006). These tools help identify influential parameters, assess data reliability, and provide more robust evidence for decision-making, particularly when comparing multiple scenarios.

3.7.9. Challenge 9: lack of aggregation of results across sustainability dimensions

While environmental and economic assessments were frequently conducted, only one study included social aspects, and none performed a full S-LCA. This imbalance hinders holistic sustainability evaluations and limits the ability to identify social trade-offs or synergies.

3.7.9.1. Recommendation. Future studies should try to adopt the LCSA framework, integrating LCA, LCC and S-LCA. Where full integration is not yet feasible, practitioners should acknowledge the gaps and provide recommendations for addressing them. The use of ISO 14,040:2006, ISO 14,044:2006, and ISO 14,075:2024 standards can guide methodological alignment across the three pillars. Some recommendations on the execution of LCSA are laid out by Valdivia et al. (2021). Aggregation of results across sustainability dimensions, either through monetization or developing a multi criteria decision model, may help stakeholders better understand the overall sustainability performance of a valorization technology.

Addressing the methodological challenges outlined above will significantly enhance the quality, comparability, and comprehensiveness of sustainability assessments in aquatic food side-stream valorization. Improvements such as standardized comparison perspectives, function-based functional units, full system coverage, transparent data reporting, and multi-dimensional integration will support more robust and policy-relevant conclusions. As the field evolves, further work is needed to define social impact indicators, establish data scaling protocols, and expand applications of integrated LCSA. These efforts are essential for supporting a sustainable, inclusive, and circular bioeconomy based on marine resource recovery.

4. Conclusion

Valorizing aquatic food processing side-streams offers a compelling pathway toward a more circular and sustainable bioeconomy. By transforming what was traditionally considered waste into valuable materials, this approach aligns resource efficiency with economic opportunity.

Realizing this potential, however, requires robust and integrated sustainability assessments. Current research has made significant progress in applying life cycle thinking to environmental and, to a lesser extent, economic dimensions. Yet, efforts remain fragmented, and the social pillar is still largely absent from most assessments. A deeper integration of life cycle methodologies, encompassing environmental, economic, and social considerations, is necessary to support informed decision-making and guide sustainable innovation in the sector.

Looking ahead, future research must move beyond isolated case studies toward comparative, function-oriented assessments that explore trade-offs and synergies across different valorization pathways. Greater attention should also be given to underutilized aquatic resources, emerging high-value markets, and the socio-economic contexts in which these systems operate. Advancing methodological consistency and embracing interdisciplinary collaboration will be essential for establishing aquatic food side-stream valorization as a key part of the sustainable blue economy.

Ethical statement

This work has not involved experimentation on humans or animals and does not involve patients or volunteers.

This research presents an accurate account of the work performed, all data presented are accurate and methodologies detailed enough to permit others to replicate the work.

This manuscript represents entirely original works and or if work and/or words of others have been used, that this has been appropriately cited or quoted and permission has been obtained where necessary.

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All authors have been personally and actively involved in substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content.

CRediT authorship contribution statement

Iris Joy Villanueva Abrigo: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Erasmo Cadena:** Writing – review & editing, Validation, Supervision, Conceptualization. **Jo Dewulf:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Acknowledgements

The authors would like to thank The Research Foundation – Flanders (FWO) for funding the FOODIMAR project and making this research work possible. Additionally, the authors want to extend their gratitude to the partners of the FOODIMAR project and STEN research group, for providing valuable feedback to improve the paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2026.101084.

Data availability

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

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