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Valorization of side streams to enhance seafood sustainability

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The global seafood industry produces many byproducts, often called seafood side streams, encompassing fish heads, skins, bones, viscera, and shells. Traditionally viewed as waste, these byproducts possess considerable potential for valorization, supporting sustainability, circular economy principles, and fostering progress toward the Sustainable Development Goals (SDGs) of the United Nations. This review explores the composition, bioactive potential, and innovative valorization strategies for seafood side streams, focusing on green processing including enzymatic hydrolysis, fermentation, and recovery of bioactive compounds. Diverse applications of the recovered compounds in food, pharmaceuticals, cosmetics, packaging, and other fields highlight economic and environmental advantages of using seafood side streams. Nonetheless, technical limitations, financial feasibility, regulatory hurdles, and consumer acceptance remain significant obstacles. Policy recommendations, advancements in bioprocessing research, and integration of emerging technologies such as AI and blockchain for traceability are crucial for addressing these challenges. Emphasizing the value of cross-disciplinary collaboration, this review advocates the potential of zero-waste conversion of seafood side streams into valuable ingredients for a healthy blue economy and sustainable seafood industry.

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Sustainability spotlight

The global food system faces growing challenges, resource depletion, climate change, and food insecurity, making sustainable transformation urgent. Industries' intensive exploitation of marine resources contributes significantly to overfishing, habitat damage, and emissions. A shift toward ecosystem-based fisheries, sustainable aquaculture, and circular strategies like seafood byproduct valorization is essential. Valorizing byproducts like shells, skins, and bones reduces waste and pollution while producing high-value compounds like collagen, omega-3s, and chitin. These materials have diverse applications in the food, pharma, and cosmetic industries, boosting local economies and reducing environmental burdens. Integrating such approaches fosters circular bioeconomy practices and supports Sustainable Development Goals, particularly SDG 12 (responsible consumption) and SDG 13 (climate action).

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1. Introduction

Seafood industries generate a wide range of byproducts during processing and post-harvest handling, commonly including heads, shells, skins, scales, bones, fins, viscera, roe, and frames, which account for 30–70% of the total biomass, depending on species and processing methods.[1] Although traditionally discarded, these off-cuts are abundant in valuable bioactive compounds and can be repurposed into nutraceuticals, animal feed, and eco-friendly packaging materials.[2] The proper utilization of seafood side streams integrates with the principles of the circular economy, enhancing sustainability by reducing

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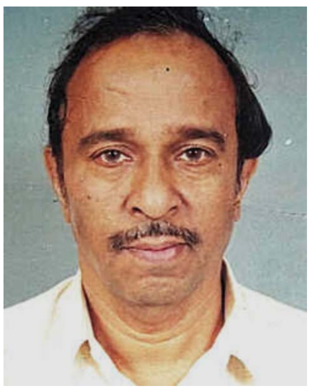

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waste and increasing resource efficiency. As world food demand is projected to increase by 50–60% by 2050, existing food production systems face mounting pressures due to resource depletion, climate change, pollution, and biodiversity loss.[3,4] Additionally, food waste contributes to inefficiencies by placing undue strain by imposing excessive demands on land, water, and energy.[5] Greenhouse gas emissions from food systems have increased by approximately 25% since 2010, cropland use has increased by about 6% since 2000, and blue water consumption continues to increase due to intensified agricultural and aquaculture practices (FAO, 2023; IPCC, 2021).[6]

Sustainable food systems are progressively recognized as essential for ensuring worldwide food security. Production systems must evolve to achieve sustainability by incorporating decarbonization strategies that mitigate climate change while enhancing resilience.[4] The seafood industry presents significant opportunities for reducing environmental impact by adopting sustainable aquaculture and fisheries management practices. Investments in green technologies and diverse aquaculture systems can significantly reduce the sector's carbon footprint. Moreover, green innovation has enhanced sustainable performance, bridging environmentally friendly human resource initiatives and improved sustainability outcomes for small and medium enterprises.[7] The marine food sector's role in food security, economic stability, and sustainable fisheries management is crucial to prevent overexploitation and ensure the long-term availability of seafood.[8] Unsustainable fishing methods threaten marine ecosystems, but implementing responsible fishing practices can help maintain biodiversity and ecosystem health. Certification programs such as the Marine Stewardship Council (MSC) provide critical oversight to promote environmentally accountable fishing.[9] Beyond environmental concerns, sustainability in seafood also involves social and economic aspects, including fair labor practices, equitable distribution of resources, and the well-being of fishing communities. A socio-ecological framework is integral for promoting sustainable seafood practices worldwide, accounting for cultural and regional differences.[10] Recent developments have significantly advanced the creation of regional and national ocean accounts. Collaborations like the Global Ocean Accounts Partnership play a crucial role by offering technical expertise and facilitating the sharing of knowledge across nations. Ocean accounts are built upon internationally recognized frameworks such as the System of National Accounts (SNA) and the System of Environmental-Economic Accounting (SEEA). These accounts provide a way to move "beyond GDP" by capturing the state and value of natural capital essential to the global economy. By integrating diverse data streams, these accounts support the creation of key indicators that help monitor progress towards a sustainable blue economy and fulfill global commitments like the SDGs.[11]

The seafood industry produces significant byproducts that, when managed sustainably, can be repurposed into valuable products like animal feed, biodegradable packaging, *etc.* Consumer engagement is a critical driver of sustainable seafood demand. Enhancing labelling transparency enables consumers to make informed choices, thereby fostering market incentives for responsible fisheries and aquaculture operations.[12] However, the global seafood trade remains complex, often disconnecting consumers and the sustainability of fishing and aquaculture practices behind their seafood choices. Establishing stringent traceability mechanisms and international sustainability standards ensures that seafood products meet environmental and ethical criteria.[8]

The UN SDGs introduced in 2015 serve as a guiding framework for fostering sustainability in various sectors, including seafood. Among these, SDG 12 (Responsible Consumption and Production, Circular Economy and Waste Reduction) and SDG 14 (Life Below Water-Sustainable Fisheries and Ecosystem Preservation) are related to seafood production and marine conservation.[4] SDG Target 12.3 aims to halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains by 2030.[13] The SDG is also oriented to promote efficient resource utilization in seafood production by advocating for sustainable fishing techniques, bycatch reduction, and waste minimization. Environmentally responsible aquaculture practices further support this objective.[14] SDG 14 calls for improved regulatory frameworks and sustainable fisheries management in order to preserve marine habitats and biodiversity and mitigate overfishing.[15] To achieve these goals, policy reforms, ecosystem-based management strategies, and innovative governance mechanisms must be prioritized.[16]

Wild-capture fisheries have plateaued in the past 30 years, putting pressure on sustainable seafood production. At the same time, conventional processing operations result in discards as high as 50% of the processed finfish and shellfish, which include heads, skins, bones, viscera, and shells. If not properly utilized, these discards not only deny valuable nutrients to consumers, but are also responsible for environmental pollution and global warming due to putrefaction and release of GHG emissions. Strategies are therefore essential for climate-smart seafood production, food waste reduction, dietary adaptations to combat the current dual emergencies of climate change, together with associated setbacks, and sustainable fisheries. Therefore, a radical transformation of food systems is imperative to reach the UN SDGs and to fulfil the Paris Climate Agreement to limit global warming to well below 2 °C and make efforts to limit it to 1.5 °C. This is urgent for global food security and environmental sustainability.[17] Sustainable seafood production, encompassing fish, shellfish, and seaweed, must be managed to enable species regeneration, habitat restoration, and ecosystem resilience.[18] Since agriculture and food sectors significantly contribute to greenhouse gas emissions, minimizing food loss and optimizing byproduct utilization are essential.[19] According to the FAO's 2024 report, world fisheries and aquaculture production reached a record of 223.2 million tonnes in 2022, comprising 185.4 million tonnes of aquatic animals and 37.8 million tonnes of algae. However, approximately 27% of landed fish is lost or wasted between landing and consumption, highlighting significant inefficiencies in the seafood supply chain.[20] This substantial loss underscores the need for improved handling, processing, and distribution practices to enhance sustainability and food security in the

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global seafood sector. Currently, seafood accounts for only 17% of total edible meat production, but projections indicate that by 2050, the sector could expand by 21–44 million tonnes, fulfilling 12–25% of the anticipated global meat demand.[18] However, the issue of food waste remains substantial, with nearly 1/3 of all food produced, approximately 1.6 billion tonnes annually, being lost, including 35% of fish and marine products. Addressing this inefficiency is crucial for strengthening global food security.[21]

This review explores the potential of seafood side streams as sources of nutrients and their usefulness, focusing on sustainable utilization strategies such as enzymatic hydrolysis, fermentation, and extraction of bioactive compounds. The valorization of these byproducts presents opportunities for different applications in the food processing, healthcare, and personal care industries, contributing to food security, health, and environmental sustainability. However, several challenges hinder widespread adoption, including technical limitations, cost constraints, regulatory barriers, and consumer scepticism. This review also attempts to address these challenges and provide future research directions, emphasizing advancements in bioprocessing, policy interventions, and the application of innovative technologies such as AI and blockchain to improve traceability and proficiency. By addressing these aspects, this review highlights the role of seafood side-stream valorization in promoting a circular bioeconomy and improving sustainability in the seafood sector.

2. Valorisation strategies for seafood side streams

A resilient food system cannot be achieved without minimizing losses of valuable resources; hence, it is imperative to adopt integrated approaches that reduce food loss and waste.[22] Maximizing food utilization requires coordinated efforts worldwide and within local communities. Using seafood byproducts is essential for enhancing sustainability and economic viability in fisheries and aquaculture sectors. The key to transformative change lies in adopting new technologies and innovative solutions, including e-commerce for marketing and mobile food processing, improved workflows, and effective practices for managing food quality and minimizing waste. Through implementing circular economy principles, the sector may convert low-value waste into high-value products, thereby enhancing food security and promoting environmental conservation.[23] Recent advancements in process optimization, green extraction methods, and enzyme-assisted technologies have improved the efficiency and sustainability of recovering well-established compounds such as collagen, gelatin, omega-3 fatty acids, and chitin from seafood by-products.[24] Moreover, hydrothermal and enzymatic procedures have surfaced as effective techniques for transforming seafood waste into biofuels, bioplastics, and useful components.[25] Fermentation and microbial processing augment the extraction of bioactive substances, facilitating sustainable resource utilization.[26] Considering the increasing apprehensions regarding environmental sustainability and food security, incorporating innovative valorization technologies for seafood side streams offers a feasible approach to minimize waste while producing economic and ecological advantages.[27]

2.1. Seafood side streams: composition and bioactive potential

Fishery byproducts refer to the side-streams generated during the processing of seafood. These include off-cuts of aquatic food that are not typically consumed directly, such as head, skin, tail, viscera, shells, and other cut-offs. These side streams are rich in components such as enzymes, proteins, healthy fatty acids (MUFA & PUFA), gelatin, and collagen.[25] Seafood side streams can be classified according to the type of seafood and the particular parts of the organism and are presented in Table 1. Seafood offcuts are high in nutritional and bioactive components, offering opportunities to develop valuable products with various uses in the food processing, healthcare, and personal care industries. The concentration and composition of these components are determined through various analytical methods, and their bioactive potential presents promising avenues for creating functional and health-promoting products. Seafood side streams, such as fish processing byproducts, contain moderate to high protein and lipid levels. For instance, sprat trimmings, marinated herring, and mackerel in tomato sauce had protein levels ranging from 28% to 32% of dry matter and lipid levels ranging from 34% to 43%. Additionally, sprat trimmings have approximately 29% ash and 1.5% phosphorus, indicating the presence of essential minerals that add value to these side streams.[28] Seafood byproducts such as fish viscera, skin, and heads contain notable levels of lipids, particularly MUFAs (*e.g.*, oleic acid) and PUFAs (*e.g.*, EPA and DHA). The fatty acid profile varies by species and tissue type, with oily fish waste (*e.g.*, from mackerel and sardines) being especially rich in omega-3 PUFAs, while lean fish may yield lower lipid fractions.[1] Seafood offcuts are rich in bioactive ingredients and fractions contain proteins, peptides, collagen, fish oils, gelatin, enzymes, chitin, and minerals. These bioactive components have been shown to possess various health-promoting properties such as antimicrobial, antioxidative, antihypertensive, and anti-hyperglycemic activities. Furthermore, bioactive components from seafood side streams have potential applications in nutrient-rich foods, special feeds, nutraceuticals, drugs, and cosmetic products.[29] The concentration and composition of seafood side stream components are determined through various analytical methods, including the assessment of protein, lipid, ash, and phosphorous levels in the side streams.[28] The proteins found in marine food byproducts are rich in nutritional value and possess functional properties. These proteins contain bioactive peptides that offer various health benefits, such as anti-inflammatory, anti-coagulant, anti-cancer, and hypo-cholesterolemic effects.[24] Fish fats are also an exceptional source of omega-3 PUFAs, with valuable therapeutic properties. The bioactive potential of seafood side stream components is evident in their diverse benefits on health, including cardioprotective, neuroprotective, antioxidant, anti-

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Table 1 Classification and composition of seafood off-cuts

Source/species group	Residue type	Protein (%)	Lipid (%)	Carbohydrate (%)	Ash (%)	Moisture (%)	Reference
Shrimp (crustacean)	Shell	25–40	2–5	20–30 (chitin)	15–25	8–15	33
Tuna (teleost)	Head	18–25	10–15	<1	5–10	50–55	34
Salmon (teleost)	Skin	20–30	15–25	<1	5–7	40–50	35
Skate (cartilaginous)	Cartilage/bone	15–22	2–5	1–2	25–35	35–40	36
Fish (mixed species)	Mixed waste	57.9 ± 5.3	19.1 ± 6.1	1.2 ± 1.2	21.8 ± 3.5	70–75	37
Shrimp	Waste	94.6 ± 0.2	4.1 ± 0.1	8.6 ± 0.1	1.3 ± 0.02	65–75	33
Lobster	Waste	28.6 ± 0.5	2.2 ± 0.2	22.8 ± 1.5	33.7 ± 2.2	65–72	38
Mackerel	Head	12.3	17.2	1.17	3.74	55–60	39
	Frame	14.2	10.4	0.31	3.48	50–55	
	Fins/skin/gut mix	12.2	20.8	0.00	1.36	55–60	
Salmon (viscera meal)	Meal	63.6	11.8	3.32	12.0	10.45	40
Anchovy (whole meal)	Meal	73.6	10.3	1.52	12.0	6.53	40
Sprat (whole meal)	Meal	70.1	9.9	3.77	12.0	7.15	40
Cod/hake (bone powder)	Bone	~13.2	~7.0	~1.8	49.9	28.2	41

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inflammatory, anti-cancer, antiobesity, anticoagulant, antimicrobial, and immunomodulatory activities.[30] Furthermore, bioactive components from seafood side streams have the potential to be developed into functional ingredients for use in functional foods and nutraceuticals, contributing to the maintenance of health and wellness.[31] Bioactive components from seafood side streams are incorporated into foods to enhance their nutritional value and health benefits. Many bioactives are used for their therapeutic properties in drug formulations and skincare products. In addition to proteins and lipids, seafood byproducts particularly shells and exoskeletons of crustaceans like shrimp and crabs are rich in minerals. Calcium is a major component, often present as calcium carbonate, accounting for up to 20–40% of dry shell weight. These mineral-rich residues have potential applications in nutraceuticals and bone tissue scaffolding and as natural calcium supplements. Other essential minerals such as magnesium, phosphorus, and trace metals (*e.g.*, zinc and copper) are also found, although their concentrations vary by species and processing methods.[32]

2.2. Extraction methods and technological approaches for byproduct valorization

The role of seafood side streams in circular food systems is paramount, with their utilization and waste management practices being more critical than those of other food sources. Seafood offcuts are indispensable in worldwide food security and human nutrition, yet substantial waste generation occurs throughout the seafood supply chain. The seafood industry discards millions of waste each year, predominantly consisting of crab, shrimp, and lobster shells, which contribute to environmental problems linked to COD and BOD.[42] Fish waste, which is animal-derived non-lignocellulosic biomass, lacks lignin, cellulose, and hemicellulose, distinguishing it from traditional lignocellulosic feedstocks. Instead, it is composed of carbohydrates, proteins, and fats. The biochemical composition of various seafood wastes has been documented; however, comprehensive characterization across different fish species remains limited. Studies suggest that the carbohydrate content in fish waste varies between 8% and 15%, whereas the protein content ranges from 30–50%, depending on the type of waste. Comparatively, meat and shrimp waste contains 20–25% and 30–45% protein, respectively. Furthermore, the fatty acid composition of fish waste can range from 10% to 60%.[33] Unlike lignocellulosic biomass, seafood waste is rich in proteins and fats, making it a valuable substrate for protein hydrolysates, bioactive compounds, and bioenergy applications.[43] Table 2 presents valorization of seafood by-products, their sources, composition, and bioactivities, and Fig. 1 represents various technologies used for the extraction of bioactive compounds from seafood by-products.

A thermochemical process called Hydrothermal carbonization (HTC), particularly suited for wet biomass (>50% moisture content), offers an efficient approach for converting fish waste into hydrochar and bio-oil.[43] Unlike pyrolysis, which requires an energy-intensive drying step, HTC directly utilizes wet biomass, thereby reducing energy demands.[44] This process involves submerging the biomass under subcritical water conditions, facilitating the conversion of organic components into bio-oil and carbonaceous solids (hydrochar), while producing minimal gaseous byproducts.[43] However, the application of HTC to seafood waste is limited due to its poor carbohydrate profile, as seafood residues are predominantly protein-rich (*e.g.*, fish oils, proteins, peptides, collagen, gelatin, enzymes, chitin, and minerals). Recent research has explored optimizing HTC for such feedstocks, with studies on microwave-assisted hydrothermal carbonization (MHTC) showing promise in producing hydrochar comparable to that from municipal and sewage waste.[44] Innovations in reactor design and process optimization have further enhanced the efficiency of HTC for fish waste treatment.[45] This approach provides a sustainable waste management solution and generates valuable carbonaceous materials and energy resources.[44] Traditional disposal techniques like landfills and ocean dumping have been hugely criticized due to environmental risks, and their industrial-scale adoption remains limited.[46] Scientific findings reveal that fish side-streams harbor essential bioactive ingredients, including fish oils, proteins, peptides, collagen, gelatin, enzymes, chitin,

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Table 2 Valorization of seafood by-products: sources, composition, and bioactivities

Component	Concentration/composition	Bioactive potential	Sources	References
Protein	Rich in fish protein hydrolysates (FPHs), bioactive peptides, collagen, and gelatin Shellfish-65% Muscles-17–22% Body parts 8–35%	Antioxidant, antihypertensive, anticoagulant, immunomodulatory, and antimicrobial	Fish muscle, skin, viscera, and shellfish	25 and 26
Fatty acids	Present in fish oils and other lipid fractions Shellfish-7–19% EPA – 24.7 DHA-28.3% PUFA-7–19% Omega-3-10.95%	Cardioprotective, anti-inflammatory, neuroprotective, and anticancer	Fish heads, viscera, and shellfish	29
Minerals/ash	Contains phosphorus, magnesium, sodium, calcium and other minerals Inorganic compounds-60–70% Fishbone-70% Shellfish – 21% Crab-28.5%	Bone health and mineral supplements	Fish bones, shellfish, and crab shells	24 and 30
Carotenoids	Present in fish skin and other pigmented tissues Astaxanthin, canthaxanthin, and zeaxanthin at 32%	Antioxidant, anti-inflammatory, and anticancer	Crustacean shells (primary), fish skin (secondary), shrimp shells, and fish skin	24 and 30
Enzymes	Chitinase, alkaline phosphatase, proteases, transglutaminase, lipases, hyaluronidase, and acetyl glycosaminidase	Used in food processing and pharmaceuticals	Fish viscera and shellfish	24
Polysaccharides (chitin, chitosan and glycosaminoglycans (GAGs))	Proteoglycans, glycolipids, and glycoconjugates Glycosaminoglycans (GAGs and sGAGs), hyaluronic acid (HA), chondroitin sulfate (CS), heparan sulfate, dermatan sulfate, and keratan sulfate Extracted from shells and other crustacean by-products 15–20% Lobster shell-70% Dry crab shell-67–72% Squid skeletal pen-41%	Anti-inflammatory, joint health, skin health, anticoagulant, antiallergic, antidiabetic, antihypertensive, and anti-obesity properties. Antimicrobial, antioxidant, anti-inflammatory, and wound healing	Fish cartilage and shrimp shells	29
Vitamins	Vitamin D (cholecalciferol), B12, and A	General health and antioxidant properties	Fish liver and fish skin	24

and minerals, offering significant potential for use in functional foods, high-performance feeds, nutraceuticals, pharmaceuticals, and cosmetic formulation. Some of the waste is converted into low-value products like animal feed for animals and aquaculture.[29] Given the high protein content of seafood residues, which contrasts with the carbohydrate-rich feedstocks typically suited for HTC, industrial-scale application of this technique for seafood waste is not yet widespread. Instead, valorization methods such as enzymatic hydrolysis and extraction are more commonly employed to leverage the protein-rich nature of these byproducts for higher-value applications.[45]

Several strategies and innovative technologies can be employed to improve the efficiency of seafood side-stream valorization. pH-shift technology uses acid or base solubilization and isoelectric precipitation to recover proteins from fish side streams. Compared to conventional methods, it has shown significant reductions in environmental impacts such as the carbon footprint, acidification, and water use. Its key benefits include a substantial reduction in environmental impacts and the potential for further enhancement with renewable energy integration.[47] Conventional protein recovery methods such as thermal coagulation and mechanical pressing often suffer from lower yields and higher environmental footprints. The term

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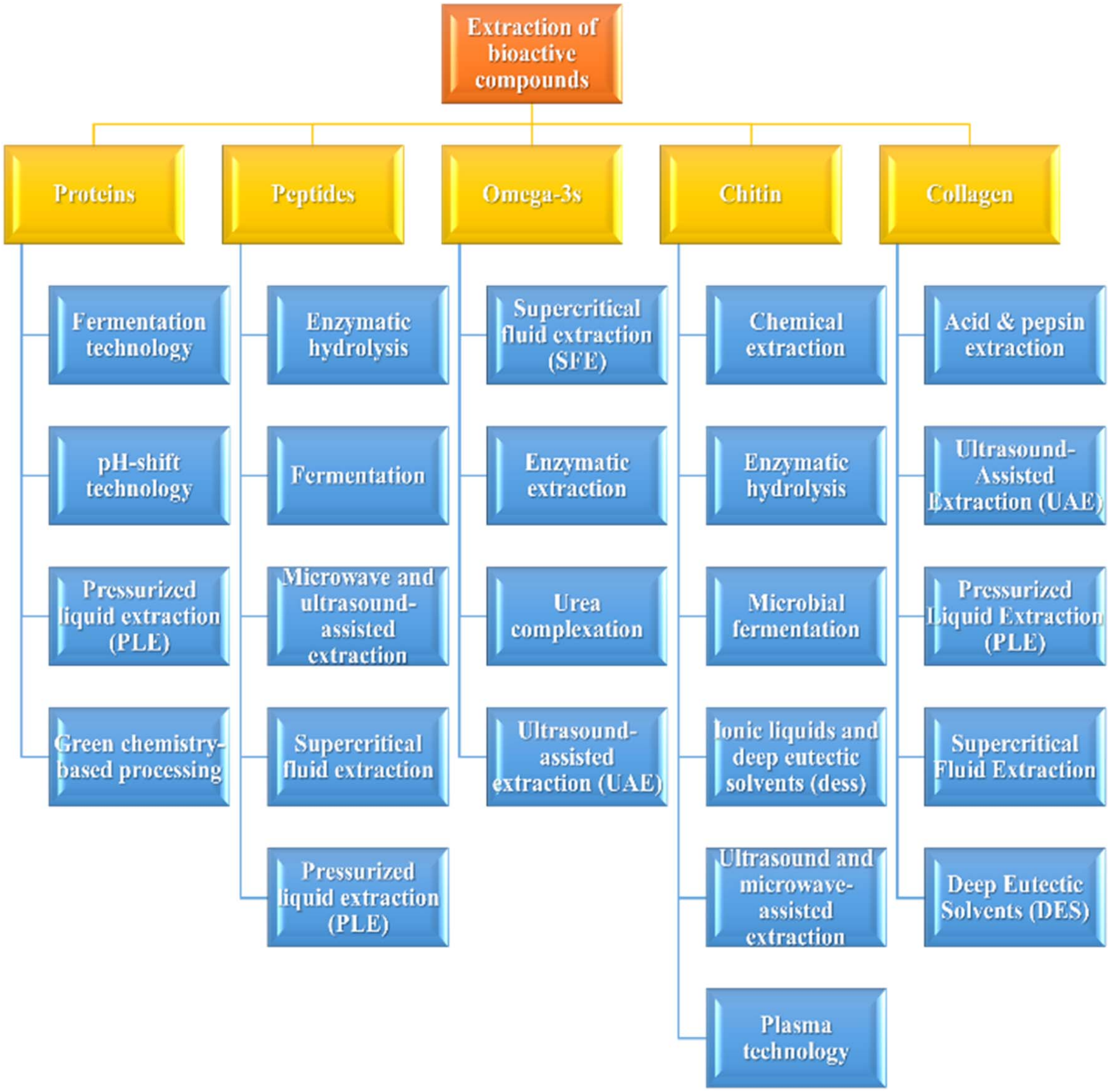

Fig. 1 Bioactive compound extraction from seafood by-products.

'acidification' in this context refers to environmental acidification from disposal of untreated seafood waste, not from the pH-shift processing itself.[48] Membrane concentration helps recover molecules from side streams, while flocculation aids in recovering proteins and phosphates, minimizing the organic load of effluents. Green extraction techniques such as microwave- and ultrasound-assisted extraction, supercritical fluid extraction, and subcritical water extraction are effective for extracting bioactive compounds from seafood by-products.[49] Implementing circular economy principles to reduce waste and enhance resource reuse can result in greater production efficiency and reduced demand for natural resources, improving sustainability and economic viability, thereby contributing to global food security and environmental conservation.[50] Several studies have explored the techno-economic feasibility of zero-waste processing of seafood side streams. Zero-waste biorefinery concepts are based on the full valorization of seafood side streams. Their proper utilization aligns with circular economy principles by reducing waste and increasing sustainability.[2] Utilization of seafood and side streams in accordance with circular economy principles enhances sustainability through reduced waste and increased resource efficiency. By integrating these innovative technologies, optimization strategies, and circular economy principles, the efficiency of seafood side-stream valorization can be significantly improved, leading to enhanced sustainability and economic benefits.

Seafood processing side streams through green chemistry present a transformative and eco-sustainable solution to the seafood industry's environmental challenges. Traditionally, these discards, which can constitute up to 70% of the raw material, are disposed of through methods such as landfilling, ocean dumping, or incineration, all of which contribute significantly to environmental degradation. Landfilling releases potent greenhouse gases like methane (CH_4), nitrous oxide (N_2O), ammonia (NH_3), and hydrogen sulfide (H_2S), which not only accelerate global warming but also contaminate soil and water systems. On the other hand, incineration emits CO_2, sulfur dioxide (SO_2), and nitrogen oxides, further polluting the atmosphere and harming biodiversity. Ocean dumping leads to the depletion of oxygen levels in marine environments, disrupting aquatic ecosystems.[51]

Techniques such as enzymatic hydrolysis, microbial fermentation, anaerobic digestion, and green solvents allow for efficient biotransformation of seafood waste under low-energy conditions. These processes minimize hazardous emissions and reduce reliance on fossil fuel-intensive practices. Integrating these green valorization methods into biorefinery platforms enhances environmental stewardship by achieving near-total utilization of waste biomass, thus embracing a circular economy model. This approach ensures that materials are continually recycled into the production chain, eliminating the "take-make-dispose" model and contributing to resource conservation. According to life cycle analysis (LCA) studies referenced in the paper, products recovered from seafood discards through green bioprocesses exhibit 88–94% lower greenhouse gas emissions than conventional products. For instance, managing protein-rich waste *via* valorization can prevent the release of up to 750 kg of CO_2-equivalents per kilogram of wasted protein.[52] Moreover, implementing cleaner production strategies and decarbonization pathways can reduce up to 35% of total GHG emissions in seafood supply chains, as observed in practical examples from Western Australia. Valorization also contributes to the achievement of key Sustainable Development Goals (SDGs), particularly SDG 12 (responsible consumption and production), SDG 13 (climate action), and SDG 14 (life below water). Ultimately, adopting green chemistry for seafood waste valorization reduces the seafood industry's ecological footprint and promotes economic viability and social responsibility, facilitating the emergence of a resilient, low-carbon, and sustainable blue economy.[44]

Biotechnological approaches in enzymatic hydrolysis and fermentation play a crucial role in utilizing seafood side streams, offering the possibility of retrieving valuable nutrients, minimizing waste, and producing value-added products.[53] In the enzymatic hydrolysis process, enzymes break down proteins in seafood side streams into smaller peptides and amino acids. This eco-friendly and efficient method produces valuable products such as fish protein hydrolysates (FPHs), which have applications in food, nutraceuticals, and animal feed. Table 3 depicts the enzymatic hydrolysis of various seafood side-streams. Fermentation utilizes microbes to convert seafood offcuts into value-added products. This process can produce biofuels, enzymes, and animal feed and is particularly effective in recovering nutritional components such as chitin, chitosan, and fish protein hydrolysates.[26] Since conventional techniques rely on large quantities of organic solvents, consume high amounts of energy, and are time-intensive, they are expected to be gradually replaced by more sustainable extraction approaches. These eco-friendly approaches improve selectivity and offer broader application potential.[54] Fig. 2 shows various fermentation methods used for seafood side streams involving enzymes.

2.3. Purpose and applications of extracted compounds

Seafood side streams, often considered waste, are increasingly recognized for potential applications across different industries, including food, pharmaceuticals, and cosmetics.[42] These peptides also enhance food ingredient solubility, water holding capacity, and gel formation.[58] Proteins and hydrolysates derived from seafood byproducts are used to develop protein-enriched foods. These proteins have functional properties like emulsification, solubility, and gelling capacities, making them suitable for use in protein-enriched foods, emulsified meat products, and surimi-based formulations. Due to their intense umami profile, peptides derived from enzymatic hydrolysis also serve as flavor enhancers, such as fish solubles used in broths and soups.[59] Fish soluble from side streams can be used as broth and flavor enhancers due to their high flavor intensity.[60] PUFA-rich oils, particularly those containing EPA and DHA, are recovered from fish viscera and heads. These omega-3 fatty acids are essential for cardiovascular and cognitive health and are used in fortified food products, pharmaceutical formulations, and infant nutrition. For instance, Hofseth BioCare (Norway) produces ProGo™, a clinically validated fish protein hydrolysate from salmon backbones and trimmings, which is used in nutritional supplements. The Thai Union has commercialized functional tuna essence derived from side streams of tuna processing.[61] Collagen and gelatin, sourced from fish skin, bones and crustacean shells, have growing applications in biomedical engineering, such as scaffold materials for tissue repair and drug delivery systems. In cosmetics, they are integrated into anti-aging creams and serums for their ability to improve skin hydration, elasticity, and overall appearance.[62] Marine bioactive compounds are utilized for their health benefits, including anti-tumor, antimicrobial, and anti-inflammatory effects, making them valuable in pharmaceuticals.[63] Carotenoids such as astaxanthin and fucoxanthin, derived from crustacean shells and marine algae, possess potent antioxidant and anti-inflammatory properties. These pigments are applied in functional foods, dietary

Table 3 Enzymatic hydrolysis of various seafood side streams

Substrate	Enzyme(s) used	Hydrolysis conditions	Yield (%)	Bioactivity measured	Reference
Tuna waste	Alcalase	pH 8.0, 55 °C, 2 h	65	Antioxidant and ACE-inhibitory	51
Salmon skin	Papain and trypsin	pH 7.5, 50 °C, 4 h	60	Collagen peptides and anti-aging	55
Shrimp head	Protamex	pH 7.0, 50 °C, 2 h	58	Calcium-binding peptides	56
Cod frame	Flavourzyme	pH 6.5, 50 °C, 3 h	62	Antimicrobial activity	57
Mackerel viscera	Neutrase	pH 7.0, 50 °C,1.5 h	70	DPPH radical scavenging capacity	39

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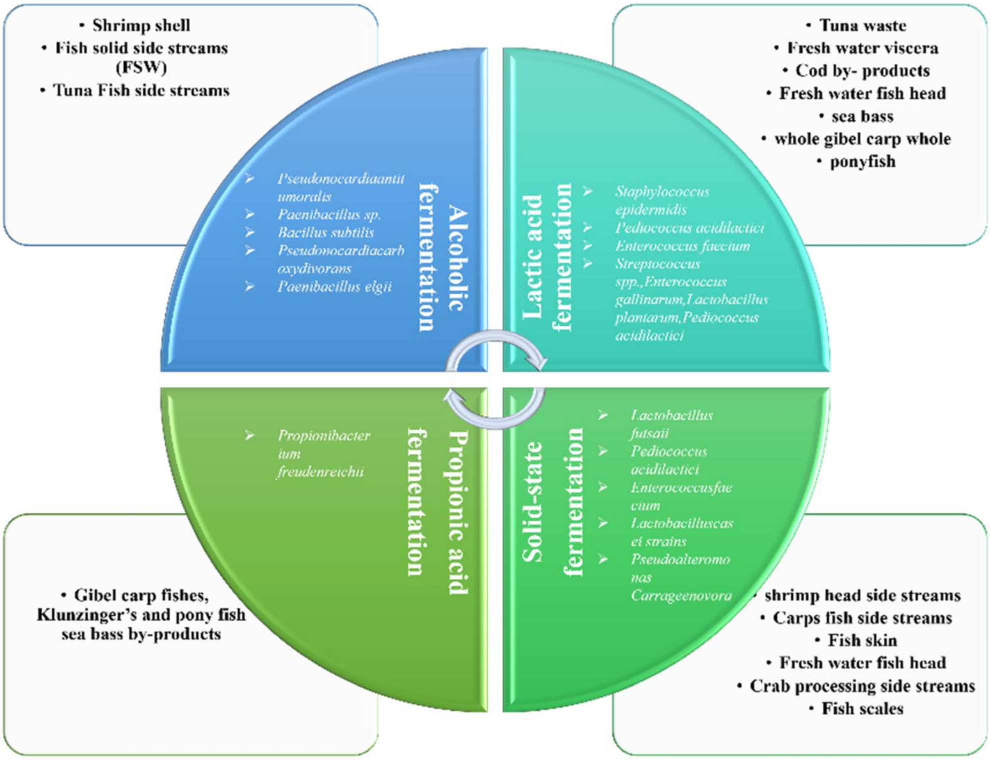

Fig. 2 Fermentation methods for different seafood side streams.

supplements, and cosmetic products, especially those targeting skin health and UV protection. Chitin and chitosan, extracted from shrimp and crab shells, are used in cosmetics for their moisturizing and film-forming properties.[64] Chitosan is used as a drug delivery vehicle and wound healing agent in pharmaceuticals due to its biocompatibility and ability to stimulate tissue regeneration. These compounds also have antimicrobial effects, making them suitable for skin care products.[65] Collagen and peptides from seafood byproducts are incorporated into anti-aging creams and lotions due to their ability to improve skin elasticity and hydration.[66] Table 4 demonstrates selected case studies of industrial seafood side stream valorization.

2.4. Economic feasibility and scale-up potential

Valorization of fish byproducts can lead to significant economic benefits by reducing waste management costs and

Table 4 Selected case studies of industrial seafood side stream valorization

Company name	Side stream used	Valorization method	Product developed	Application area	Country	References
Hofseth BioCare ASA	Salmon heads and bones	Enzymatic hydrolysis	ProGo™ (fish protein hydrolysate)	Clinical nutrition	Norway	61
Seagarden AS	Cod skin and heads	Collagen extraction	Marine collagen powder	Cosmetics and nutraceuticals	Norway	67
Thai Union Group	Tuna cooking water	Filtration and concentration	SEALECT Tuna Essence	Functional beverages	Thailand	68
Ocean Harvest Tech	Seaweed and fish waste	Fermentation	Functional animal feed	Aquaculture	Ireland	69
Primex Iceland	Shrimp shells	Chitosan extraction	High-purity chitosan	Pharmaceuticals, cosmetics, and agriculture	Iceland	70
BlueBioChain Project	Various marine by-products	Multiple (R&D initiative)	Enzymes, bioactive peptides, and omega-3 oils	R&D and biotechnology	EU-wide	71
Biomega Group	Salmon side streams	Enzymatic hydrolysis	Bioactive peptides and marine oils	Functional foods and pet nutrition	Norway	72
Sofina Foods	Fish skins and bones	Collagen and gelatin recovery	Collagen and gelatin	Food and pharmaceuticals	Canada	73

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generating additional revenue from high-value products such as fishmeal, oil, gelatin, collagen, and fish protein hydrolysates.[74] The global market for marine collagen was valued at approximately USD 700 million in 2022 and is projected to reach USD 1.2 billion by 2030, growing at a compound annual growth rate (CAGR) of 7.3%. Similarly, the global chitosan market, largely derived from crustacean shells, is expected to exceed USD 3.3 billion by 2027, driven by demand in pharmaceuticals, cosmetics, and biodegradable packaging. The fish protein hydrolysate market is also growing steadily due to increased demand in clinical nutrition and functional food sectors, particularly in Europe and Southeast Asia, which are leading the pace.[60] Establishing valorization processes often requires significant capital investment in infrastructure and technology, which can deter many businesses.[75] Ensuring that the valorization processes are economically viable at an industrial scale is a major challenge. Variability in feedstock can lead to fluctuations in product yield and quality, affecting the overall cost-effectiveness.[76] Valorized products must compete with conventional products that are often cheaper due to established production processes and economies of scale.[77] European nations and the United States are actively exploring the circular economy to advance sustainable valorization, aiming to generate valuable products from waste while maintaining environmental balance.[78] Consumers' preferences for sustainability influence firms' incentives to coordinate the introduction of sustainable product variants, which can lead to multiple equilibria and the idea of sustainable practice "first-mover disadvantage" as an explanation for an agreement between competitors.[79] Embracing an international sustainability standard (ISS) can improve firms' sustainability performance and market value, but beyond a certain point, firms' markets decline, creating a "penalty zone" that acts as an important barrier to further sustainability agendas through additional ISS adoption.[80] Challenges in integrating management tools and the vital role of collaboration between academia and industry call for enhanced support in technology commercialization and methods that promote industrial sustainability.[81] Developing integrated value chains that connect various stakeholders can improve the efficiency and economic viability of the valorization process.[82] Fig. 3 depicts current market distribution of key bioactive compounds recovered from seafood side streams.

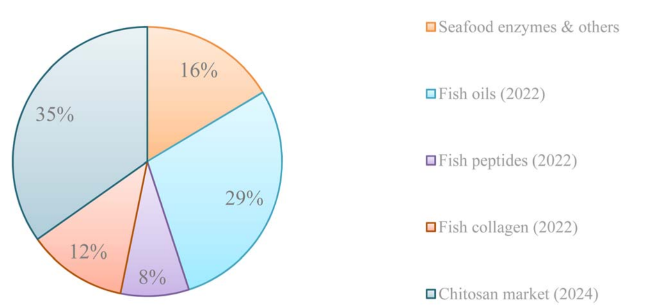

Fig. 3 Current market distribution of key bioactive compounds recovered from seafood side streams.[56,83–85]

3. Integration with sustainable development goals (SDGs)

3.1. SDG 2: zero hunger – contribution to food security and nutrition

By 2030, SDG 2 seeks to purge hunger, strengthen sustainable food access, improve nutrition, and encourage sustainable agricultural practices. This goal is interconnected with the other SDGs, requiring a holistic framework to discuss the complex challenges of food security and nutrition.[86] Various agricultural interventions, such as extension services, input subsidies, and value chain enhancements, have been implemented to improve food security. These interventions often include pro-poor features and community engagement. Approximately 67% of evaluated interventions positively impacted food security, 23% showed no measurable impact, and 10% had negative outcomes. The success of these interventions often depends on their design and implementation.[87] Effective pathways to achieve food security include agroecosystem diversification, ecological management, and place-based adaptive solutions. These practices ensure sustainability and resilience in food systems.[88] PUFA-rich oils, particularly those containing EPA and DHA, are vital for cognitive development and cardiovascular health. The inclusion of omega-3 fatty acids in therapeutic foods or nutritional supplements can address micronutrient deficiencies in vulnerable populations, especially among pregnant women and children. Gelatin and collagen, recovered from fish skin and crustacean shells, offer additional amino acid sources and may be incorporated into dietary supplements to support joint health and skin integrity, especially among the elderly and malnourished individuals. Policies promoting healthy and sustainable diets are essential for achieving nutrition security, including undernutrition and overnutrition, as seen in the European Union's efforts to combat childhood obesity.[89] Achieving zero hunger must be balanced with climate change goals. Pivotal changes in agricultural practices, gender equality, and education are necessary to minimize trade-offs.[90] Addressing these issues through social protection programs and economic development is crucial for long-term success.[91]

3.2. SDG 3: good health and wellness – bioactive compounds and health benefits

Enforcing good health and wellness for all ages is the core of SDG 3, which focuses on maternal and child health, combating diseases, and providing access to essential healthcare services. The goal is interconnected with the other SDGs, emphasizing the need for a holistic approach to health and well-being.[92] Bioactive peptides obtained from the enzymatic hydrolysis of fish proteins have shown promising effects in reducing blood pressure, inhibiting free radical activity, and modulating immune responses. They can be incorporated into functional foods, nutraceuticals, and clinical nutrition products targeting cardiovascular diseases, inflammation, and immune disorders.[96] These compounds offer numerous health benefits, such as anti-inflammatory, antioxidant, anticancer, antidiabetic, and antibacterial properties. They are essential in mitigating and

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controlling chronic diseases like cardiovascular diseases, diabetes, cancer, and neurodegenerative disorders.[93] Fish oils are routinely formulated into omega-3 capsules, fortified foods, and infant formulas, contributing to the prevention of heart disease, Alzheimer's, and cognitive decline. The positive impact of bioactive compounds ensures healthy lives and overall well-being. Developing functional foods and nutraceuticals from these compounds can enhance public health and provide therapeutic advantages.[94] Collagen and gelatin, extracted from marine sources like fish skin and crustacean shells, are widely used in joint and bone health supplements, tissue engineering, and wound healing applications. Collagen peptides have also demonstrated roles in improving skin elasticity, muscle recovery, and gut barrier function. Chitin and chitosan, derived from shrimp and crab shells, possess antimicrobial, anti-obesity, and cholesterol-lowering effects. Due to their biocompatibility and bioactivity, these compounds are employed in dietary supplements, drug delivery systems, and wound dressings. Marine carotenoids like astaxanthin and fucoxanthin exhibit strong antioxidant and anti-inflammatory activities. These are associated with reduced risk of oxidative stress-related diseases, such as cancer and metabolic disorders, and are formulated into nutraceuticals and health beverages. Opportunities for addressing health-related aspects of SDG 3 through bioactive compounds include developing novel delivery systems, such as nano-formulations, to overcome physiological barriers and improve effectiveness in treating cardiovascular diseases.[95]

3.3. SDG 6: clean water and sanitation – reduction of seafood processing waste impact

SDG 6 aims to promote the sustainable harnessing and management of water resources while ensuring sanitation for all. A significant aspect of this goal involves addressing the impact of seafood valorization on water quality and sanitation. The industry is a major consumer of water and energy used in various processes such as cleaning, freezing, and refrigeration. This high consumption results in significant wastewater generation, which poses a challenge for sustainable management.[96] Effluents from marine processing plants can lead to water quality degradation in nearby water bodies, which includes increased biochemical oxygen demand (BOD) levels, chemical oxygen demand (COD), and nutrients like nitrogen and phosphorus.[97] In regions like the Southwest coast of India, seafood processing waste has been linked to hydrogeochemical alterations in shallow aquifers, making the water unsuitable for drinking and posing risks to agricultural use.[96] Implementing advanced wastewater treatment technologies, including biological, chemical, and physical methods, can significantly reduce the environmental footprint of seafood processing plants.[96] Techniques such as bioremediation and absorbing materials can help treat effluent waters and recover valuable nutrients.

3.4. SDG 9: industry, innovation, and infrastructure – advancements in valorization technologies

SDG 9 works toward developing resilient infrastructure, ensuring inclusive industrial growth, and fostering a culture of innovation. Advancements in valorization technologies contribute significantly to achieving these objectives by reforming waste and byproducts into valuable resources, thus supporting sustainable industrial practices. Technologies like gasification and anaerobic digestion are being adapted for seafood waste valorization due to their ability to process high-moisture organic residues. Integrated frameworks, supported by AI and sensor-based controls, can optimize feedstock utilization and energy recovery from seafood processing side streams. The development of frameworks like DPSIR (Driver, Pressure, State, Impact, and Response) and the use of interval-valued intuitionistic fuzzy number-based methods can help address the uncertainties and optimize the valorization process.[98] The WaSeaBi project focuses on valorizing seafood byproducts into sellable products like protein-based food ingredients and bioactive peptides. Technologies such as pH shift, enzymatic hydrolysis, and membrane concentration are employed to extract valuable components.[23] The project NEPTUNUS aims to support the sustainability of the seafood sector by defining eco-innovation approaches and methodologies for eco-labeling products, aligning with the UN SDGs.[99] The use of digital transformation, including Information and Communication Technology (ICT), Internet of Things (IoT), AI, and blockchain, can support the expansion needs of the fisheries industry, contributing to SDG 9.[100] Using new technologies, such as Industry 4.0 innovations, offers a pioneering strategy to improve the blue economy and food sustainability globally.[27] Artificial Intelligence (AI) can significantly enhance seafood valorization by optimizing enzyme loading, fermentation time, and yield prediction using machine learning models trained on historical process data. Blockchain technology ensures transparent traceability of valorized products, documenting each stage from raw material origin to end-use application. Coupled with IoT sensors, these tools can monitor pH, temperature, or contamination in real-time, ensuring consistent quality in hydrolysates, peptides, and oils derived from seafood residues. AI-enabled image recognition can also aid in real-time sorting and segregation of seafood waste streams, improving efficiency and reducing cross-contamination.[101]

3.5. SDG 12: responsible consumption and production – circular economy and waste reduction

The circular economy framework is integral to achieving SDG 12, which focuses on responsible consumption and production. A circular economy aims at practices such as recycling, reusing, and reducing waste generation. For instance, fish gelatin and chitosan extracted from seafood waste can be used to create biodegradable food packaging materials, reducing reliance on synthetic plastics.[102] Biological methods, such as microbial fermentation and algal biotechnology, offer sustainable ways to convert seafood waste into valuable products while maintaining their bioactivity. These processes

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Table 5 Key actions to restore the seafood system[a]

Key actions	Suggestions
Increase product efficiency	Innovations and growth
Increase biodiversity	Provide technical and financial support for regenerative practices with added environmental benefits
Explore new food sources	Close collaboration with business partners and consumers within specific regions guarantees natural ingredient volumes and quality
Reduce waste	Re-cycle waste and up-cycle byproducts
Reduced energy system	Encourage net-zero emissions and allow carbon sequestration and efficient water usage

[a] Source: adapted from Knorr and Augustine.[110]

can produce biofuels and other high-value chemical feedstocks, promoting a circular bioeconomy within the seafood sector[103] The Fish Waste-based Eco-Industrial Park (FWEIP) model aims to convert linear waste management into a circular system, favoring biofuel production and other sustainable practices.[104] Circular economy practices in seafood processing can mitigate environmental pollution, reduce emissions of greenhouse gases, and support the sustainability of aquatic resources.[105]

3.6. SDG 14: life under water – sustainable fisheries and ecosystem preservation

Sustainable fisheries face several setbacks, including overfishing, forbidden, unreported, and unregulated (IUU) fishing and the readiness of stakeholders to adopt sustainable practices. Valorizing seafood byproducts into bioactive compounds, nutraceuticals, cosmetics, and feed ingredients reduces environmental impact, promotes a circular bioeconomy, minimizes overharvesting, and supports biodiversity conservation.[102] Moreover, it alleviates the pressure on marine habitats and ecosystems by preventing the illegal dumping of discards and limiting eutrophication and habitat degradation. Effective governance and stakeholder engagement are crucial for achieving sustainable fisheries.[106] Regional fisheries management organizations play a significant role in managing international fisheries and can contribute to ending overfishing and protecting marine areas. However, there is a need for better cooperation with other maritime organizations and more comprehensive management measures.[27] Establishing Marine Protected Areas (MPAs) can protect critical habitats and biodiversity. Fully and partially protected areas contribute significantly to achieving SDG 14 targets.[107] Achieving SDG 14 can bring significant economic benefits, particularly for small-scale fisheries and developing countries that depend on marine resources for revenue and sustainable economic growth.[108] Using marine resources through sustainability can contribute to economic growth, livelihoods, and community sustainability, aligning with the broader economic goals outlined in the SDGs.[109] Implementing Ecosystem-Based Fisheries Management (EBFM) can help balance the needs of fisheries with the health of marine ecosystems, ensuring long-term sustainability. Table 5 points out key actions to restore the seafood system.

4. Future perspectives and research directions

The future of seafood side stream valorization lies in developing and integrating innovative technologies, addressing environmental and economic challenges, and overcoming technological and market barriers. Future research should focus on scaling up the pH-shift method technology, membrane concentration, and flocculation technologies and integrating renewable energy sources to enhance sustainability.[47] Biorefineries integrate various technologies such as enzymatic treatments, microbial fermentation, and extraction using green solvents like ionic liquids and deep eutectic solvents, among others.[111] Studies have highlighted the importance of reducing chemical consumption and improving energy efficiency to optimize the environmental performance of valorization technologies.[23] A five-tier model suggests applications for seafood side-streams in medicine, food manufacturing, animal feed, fertilizers, and energy fuel, maximizing their potential and reducing waste.[42] Incorporating renewable energy sources can further enhance the sustainability of valorization processes.[23] Combining different treatment methods based on the composition and properties of side-streams can improve environmental performance.[112] Increasing awareness and acceptance among stakeholders is essential for successfully implementing valorization strategies.[50] Continued research and development, along with stakeholder engagement, are key to achieving a sustainable and circular seafood industry.

4.1. Technical and processing limitations to sustainable valorisation

Sustainable valorization, the technique of converting waste into value-added products, faces several technical and processing challenges that hinder its widespread adoption and efficiency. The inconsistency in the composition of waste materials, such as waste generated from food, affects the efficiency and yield of valorization processes. This variability can lead to fluctuations in product quality and process performance.[75] Effective valorization requires precise separation and classification of waste materials, which is technically challenging, especially for mixed waste streams like plastic films and food waste.[113] Hydrothermal carbonization and microbial electrosynthesis are

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Table 6 Challenges in sustainable valorization

Category	Changes	Reference
Regulatory	Lack of clear regulations and over-regulation	118
Technological	Path-dependence lock-ins and infrastructure requirements	119
Economic	Financial constraints and high operational costs	120
Social	Stakeholder involvement and market acceptance	121

promising novel technologies, but they are still in the developmental stage and face scalability issues.[114] While pyrolysis may require significant energy inputs, anaerobic digestion is a net energy-producing process due to the generation of biogas, offering a sustainable solution for seafood waste management.[115] The regeneration of green sorbents used in pollutant mitigation from marine-derived waste presents technical challenges, particularly in maintaining their sorption capacity and surface functionality over multiple cycles.[57] Significant investment in infrastructure and equipment is necessary to implement valorization technologies at an industrial scale, which includes the need for specialized facilities and machinery, which can be a major financial barrier.[116] The complexity of supply chains for sustainable chemical technologies adds another layer of difficulty, requiring coordination among various stakeholders to ensure smooth operation and integration.[117] Table 6 presents category-wise challenges in sustainable valorization.

Table 7 Policy recommendations for sustainable valorization

Policy recommendations for sustainable valorization	Actions to be taken	References
Implement sustainable fishing practices	Enforce the Common Fisheries Policy (CFP) to ensure sustainable fishing through conservation measures, fleet management, and by-catch strategies. Adopt individual quota systems based on total allowable catch and maximum sustainable yield	124
Enhance traceability and transparency	Implement policies to minimize illegal, unreported, and unregulated (IUU) fishing. Improve catch documentation and supply chain transparency	125
Promote certification and eco-labeling	Encourage the use of third-party certifications and eco-labels like the Marine Stewardship Council (MSC) and Seafood Watch. Develop government-operated certification programs based on established principles	124
Foster consumer awareness and education	Launch media campaigns and partnerships with advocacy groups to raise consumer awareness about sustainable seafood. Develop school meal programs and hospitality menus featuring sustainable seafood	125
Support sustainable aquaculture	Promote sustainable aquaculture practices, including the use of eco-friendly feed and minimizing environmental impacts. Expand sustainable coastal mariculture to enhance food security and economic resilience	124
Valorize seafood processing waste	Implement bioconversion and biorefinery processes to convert seafood waste into products like biofuels, omega-3 fatty acids, and nutraceuticals. Develop circular bioeconomies within the seafood processing sector	103
Integration with food security goals	Apply Marine Spatial Planning (MSP) and EBM to protect marine ecosystems and biodiversity. Mainstream aquatic biodiversity in sectoral policies and planning	126
Develop sustainable supply chains	Transform supply chains to ensure sustainability from production to consumption. Support policies and regulations that facilitate sustainable commoditization of seafood	127
Minimize discards and optimize by-catch utilization	Implement guidelines to minimize discards and valorize unavoidable by-catch through efficient management networks. Develop protocols for the optimal valorization of discarded species	128
Address social sustainability	Ensure fair wages and working conditions in the seafood industry. Endorse local seafood as a fresh, sustainable, and ethical choice	129
Provide economic incentives	Introduce tax rebates and green loans for companies investing in seafood valorization infrastructure	126
Strengthen certification systems	Expand adoption of MSC (Marine Stewardship Council) and eco-labeling schemes for valorized products	127
Harmonize waste utilization standards	Align national seafood waste reuse standards with international FAO and EU circular economy frameworks	128

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Table 8 Protocols to protect the oceans and marine life[a]

Protocols	Advantages
Preventing overfishing, catch restrictions, seasonal restrictions, and bycatch reductions	Ensure that the fisheries population remains at a sustainable level
Establishing marine reserves	Provide havens for marine life, allowing the ecosystem to thrive without human interference. Helps preserve biodiversity and supports fish stock recovery and the resilience of marine habitats
Promoting aquaculture	Allows a sustainable source of alternate seafood with eco-friendly practices, disease management, and feed sustainability
Educating fishermen	Provides awareness of the benefits of sustainable practices and provides training on alternative livelihoods
Educating consumers	It provides awareness of the importance of choosing sustainably sourced seafood. Can drive demand for responsible fishing practices and foster sustainability in the seafood industry
Supporting policy and regulation	Essential for enforcing sustainable fishing practices and protecting marine ecosystems
Research and innovation	Developments in innovative practices for sustainable protocols are highly beneficial

[a] Source: adapted from Sustainable Fisheries: 6 powerful ways to protect our oceans and marine life, https://ecochatters.com/sustainable-fisheries-ways-to-protect-marine-life/

4.2. Regulatory and policy constraints

Table 7 depicts policy recommendations for sustainable valorization. The seafood industry yearly generates metric tons of offsets, overwhelmingly from shrimp, crab, and lobster shells, leading to environmental impacts due to COD and BOD issues.[42] Implementing stringent traceability regulations like those in the EU and the US can create conflicts between extraterritorial fisheries management and local market access. These regulations require detailed information on when, where, what, who, and how seafood is produced, which can complicate the valorization process.[122] The EU's Common Fisheries Policy reform mandates that fishers land all catches, including unwanted ones, instead of discarding them at sea. It can create a need for efficient management of low-value marine biomass, which can be challenging due to the lack of infrastructure and economic incentives.[123] The Marine Stewardship Council (MSC) certification has been shown to have implications for companies' value creation processes, with a disparity in economic outcomes of MSC-certified businesses over those that were not, indicating the economic benefits of sustainable fishing practices.[9] Table 8 suggests protocols to protect the oceans and marine life.

4.3. Consumer perception and acceptance

Research indicates that taste, freshness, and source attributes often influence seafood-related behavior. To shift consumer tendency toward green alternatives, coastal communities promote manufacturing and source attributes of local seafood, such as being wild-caught, ecologically sustainable, and harvested locally. However, consumers may lack confidence in distinguishing these attributes when purchasing seafood, indicating a gap between the importance and confidence in seafood attributes.[130] Customer impressions and retail choices are highly situational and vary significantly across different cultures and countries. To address consumer scepticism, transparent labeling with traceable QR codes, displaying the origin and transformation journey of seafood side streams into value-added products, can enhance consumer confidence. Public awareness campaigns featuring nutritionists, sustainability influencers, and testimonials have proven effective in shifting public perceptions. Additionally, integrating byproducts derived from seafood side-streams into recognizable formats such as soups, bars, or dietary supplements can improve acceptance, lower psychological resistance, and improve market adoption.[131] This variability makes it challenging to develop universally accepted sustainable seafood byproducts. The limited availability of clear and comprehensible data on the sustainability and benefits of seafood byproducts is a major barrier to social acceptance.[132] Effective communication strategies are essential to overcome this barrier. Adding new production attributes, such as "farmed in marine waters," increases the difficulty of consumer choices, which can further hinder acceptance.[130] Improving marketing and consumer education about the benefits and safety of sustainable seafood products can serve as a link between importance and confidence. Developing targeted communication strategies that consider cultural and contextual differences can help improve consumer perceptions and acceptance of sustainable seafood products.[132]

4.4. Industry-academia collaborations for innovation

Industry-academia collaborations contribute greatly to the innovation and valorization of seafood side streams, transforming what was once considered waste into valuable products. Projects like WaSeaBi, funded by the EU, focus on developing innovative technologies to efficiently valorize seafood off-cuts into market-based products such as high-protein food ingredients, bioactive peptides, and mineral supplements.[23] Effective communication, trust, and adequate funding are essential for successful university-maritime industry

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collaborations (UMICs). These elements help build strong partnerships and support the development of new technologies and solutions. Collaborations can lead to significant environmental benefits by reducing waste and improving sustainability. For example, the WaSeaBi project demonstrated that minimizing chemical consumption and enhancing energy efficiency are key to evaluating valorization technologies' ecological proficiency. Economically, these collaborations can enhance gear efficiency, create new fishery opportunities, and sustain fishing operations.[42] Decision-making tools developed within these collaborations help industry stakeholders select appropriate valorization strategies by considering technical, legal, economic, and environmental aspects. Successful collaborations, such as the development of the CTD (Conductivity, Temperature, Depth) tag by the SMRU (Sea Mammal Research Unit) and Valeport, highlight the mutual benefits for academia and industry. These partnerships can lead to rapid technological advancements and improved product performance.[133] Despite the benefits, collaborations often face challenges, such as differing agendas and goals. Addressing these challenges requires clear communication, mutual respect, and trust. Guidelines and best practices have been developed to promote sustainable and respectful collaborative research.

4.5. Prospects of integrating digital technologies

Artificial Intelligence (AI) can significantly enhance the efficiency and scalability of seafood byproduct valorization. AI can optimize extraction parameters for bioactive compounds from seafood byproducts, such as the enzyme/substrate ratio, pH, time, temperature, and performance of extraction instruments. This optimization can lead to higher yields of valuable compounds like polyunsaturated fatty acids, amino acids, peptides, and collagen.[134] Machine learning algorithms can streamline these processes by predicting optimal conditions and adjusting parameters in real-time. AI technologies, including machine learning and computer vision, can monitor the quality of extracted bioactive compounds. These systems can analyze large volumes of data to ensure consistent product quality and detect anomalies or deviations from optimal conditions. AI-driven monitoring systems can provide real-time alerts, allowing for timely interventions to maintain high standards.[135] Predictive analytics powered by AI can forecast the yield of bioactive compounds based on historical data and current process conditions. This capability helps in planning and optimizing production schedules, ensuring efficient resource utilization and minimizing waste.[136] AI models can achieve high accuracy in predicting yields, as demonstrated in bioethanol production optimization. AI can classify and manage waste streams effectively, identifying valuable components within seafood byproducts and directing them towards appropriate valorization processes. This classification can reduce environmental impact and enhance the sustainability of seafood processing. AI-driven systems can also optimize waste management practices, ensuring that valuable bioactive compounds are not lost.[49]

Blockchain's immutable ledger allows for real-time data sharing, which enhances traceability and transparency in the seafood supply chain. This capability helps verify the origins of seafood products, which ensures compliance with sustainability standards, and combat illegal, unreported, and unregulated (IUU) fishing. By reducing the need for intermediaries, blockchain can lower transaction costs and increase profit margins for fishermen and other stakeholders in the supply chain.[137] The integration of blockchain with other technologies like AI and IoT can improve sustainability practices by enabling better resource allocation, ecosystem modeling, and intelligent monitoring systems.[138] Regulatory uncertainty and the need for reforms in regulatory compliance are major factors affecting the adoption of blockchain technology in the seafood industry.[139] Incorporating De-Fi solutions can provide fishermen with better access to capital and global markets, enhancing the economic viability of blockchain projects in the seafood industry. Using automation and IoT in data collection can improve the quality and trust in data, further enhancing the benefits of blockchain technology. Blockchain can support sustainable practices by enabling better waste management techniques, innovative packaging solutions, and energy-efficient methods.[140]

5. Conclusion

This review highlights the promising aspects of seafood side streams in promoting sustainability through valorization strategies that convert waste into high-value-added products. Bioactive compounds derived from aquatic food side streams offer diverse applications in the food, pharmaceutical, nutraceutical, and cosmetic industries. Emerging technologies such as enzymatic hydrolysis and microbial fermentation have demonstrated promising results in extracting valuable compounds while minimizing environmental impact. However, technological limitations, regulatory hurdles, and market acceptance challenges should be addressed to meet the requirements of sustainable development goals, particularly SDG 12.

Policies should support circular economy principles, green processing technologies, and transparent supply chains to enhance sustainable seafood byproduct utilization. Strengthening anti-IUU (Illegal, Unreported, and Unregulated) fishing policies, promoting certification programs, and encouraging sustainable aquaculture practices are crucial. Industry stakeholders, including seafood processors and biotechnology firms, must collaborate to invest in research, infrastructure, and innovation for effective seafood side-stream valorization. Government incentives and funding for sustainable initiatives will further drive adoption.

Achieving sustainable seafood valorization requires a multidisciplinary effort involving biotechnologists, policymakers, environmental scientists, and industry leaders. Further research should emphasize developing cost-effective, scalable, and energy-efficient technologies. Artificial intelligence and blockchain integration can improve traceability and market transparency. Additionally, consumer awareness and education are pivotal in fostering demand for sustainable seafood-derived products. By embracing an interdisciplinary and collaborative

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approach, the seafood industry can transform towards a circular bioeconomy, aligning with SDGs and ensuring long-term environmental and economic benefits.

Author contributions

Sreedharan Advaitha – design of the methodology, acquisition of data, analysis, interpretation, and writing the original draft, Kappat Valiyapeediyekkal Sunooj – design of the methodology, acquisition of data, review, editing of the draft, supervision and project administration, Sathish kumar vellaisamy – review, Sahil Negi – review, Muahmmed Navaf – review and editing of the draft, Sarasan Sabu: review and editing of draft, Abhilash Sasidharan – review and editing of the draft, and Vazhiyil Venugopal – idea conceptualization, review and editing of the draft.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software, or code have been included, and no new data were generated or analysed as part of this review.

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