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Sustainable valorisation of fish processing byproducts through integrated biorefinery approaches

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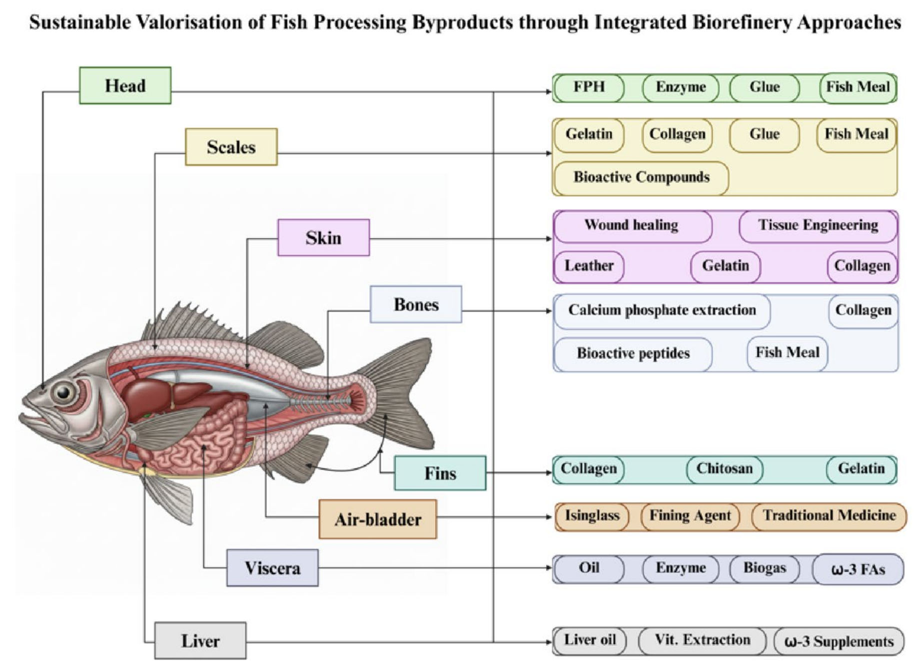
Abstract

Fish processing waste represents a significant, underutilized biomass resource, with global annual production typically estimated at 50–130 million tonnes. Current disposal methods, such as landfilling and ocean dumping, contribute to eutrophication, nutrient enrichment, and climate change. Additionally, food system assessments indicate that waste accounts for approximately 8% of greenhouse gas emissions. This review consolidates existing evidence on the zero-waste valorisation of fish byproducts within circular bioeconomy frameworks, analysing technological feasibility, environmental performance, and regulatory constraints. The analysis investigates significant side streams, including scales, skin, bones, viscera, heads, oils, swim bladders, crustacean exoskeletons, fins, and livers, focusing on compositional variability and its implications for process design. The evaluation of key extraction and conversion routes includes enzymatic hydrolysis, ultrasound-assisted processing, microwave-assisted processing, supercritical fluid extraction, and pulsed electric field treatment, with an emphasis on recovery yield, functional quality, and energy intensity. Integrated biorefinery configurations achieve over 70% resource recovery and reduce greenhouse gas emissions by 50–75% compared to disposal. However, outcomes depend on feedstock logistics, stabilization, and the integration of unit operations. Persistent barriers encompass sanitary compliance, cross-batch standardization, contaminant surveillance and removal, and substantial capital requirements, which disproportionately hinder operators in small-scale and developing countries. Research priorities encompass techno-economic assessment, life-cycle impact quantification, regulatory harmonization, and quality specifications, as well as policy implements that mitigate investment risks and expedite deployment.

Keywords Fish byproducts, Waste valorisation, Zero-waste, Sustainability, Circular bioeconomy, Food security

Graphical Abstract



1 Introduction

Global fisheries and aquaculture production reached 223.2 million tonnes in 2022, with aquaculture accounting for 130.9 million tonnes (58.6%) and capture fisheries for 92.3 million tonnes (41.4%) FAO, [62]. The estimated first-sale value of this production was USD 472 billion, with aquaculture contributing USD 312.8 billion, serving as a crucial foundation for global food security and economic development [62]. While processing is essential for food security, it produces significant byproducts (30–75% of the raw material), estimated at 50–130 million tonnes worldwide each year [49, 207]. These byproducts include muscle trimmings (15–20%), viscera (12–18%), bones (9–15%), heads (9–15%), skin and fins (1–5%), and scales (2–5%) [49]. Annual bycatch discards amount to 17.9–39.5 million tons [62]. Conventional disposal methods such as landfilling, ocean dumping, or incineration entail significant expenses and missed opportunities for resource recovery and value generation.

Improper disposal of fish waste results in various and substantial environmental consequences. The direct discharge of fish processing effluents into aquatic environments results in anoxic conditions, eutrophication, the initiation of harmful algal blooms, destruction of benthic habitats, and amplification of disease vectors [58]. Fish processing wastewater exhibits chemical oxygen demand values of 8,000 to 15,000 mg/L, total suspended solids of 3,000 to 6,000 mg/L, lipid concentrations of 3,000 to 6,500 mg/L, and protein levels of 1,500 to 2,500 mg/L [49]. The disposal of fish waste in landfills produces greenhouse gas emissions via anaerobic decomposition, with methane having a global warming potential 25–28 times that of carbon dioxide over a century [61]. Aquaculture operations in China contributed approximately 6.25 teragrams of CO_2-equivalent annually from 1980 to 2022, primarily due to methane emissions from pond decomposition and feed production [247]. Food loss and waste in fish value chains account for roughly

8% of global anthropogenic greenhouse gas emissions [61]. Aquaculture and fishing operations contribute 75–80% of nitrogen and 60–75% of phosphorus from feed inputs to surrounding waters via metabolic waste and uneaten feed, significantly impacting ecosystem nutrient cycles and productivity [51, 210].

Recent advancements in science and technology offer significant opportunities to fully valorize fish waste through advanced extraction and processing techniques. Enzymatic hydrolysis, ultrasound-assisted extraction, microwave-assisted processing, supercritical fluid extraction, and pulsed electric field treatment facilitate the selective recovery of collagen, gelatin, bioactive peptides, omega-3 polyunsaturated fatty acids, hydroxyapatite, chitosan, and other high-value compounds, achieving enhanced yield, purity, and environmental performance compared to traditional methods [80, 214]. Integrated biorefinery approaches facilitate the sequential or concurrent extraction of multiple value streams from a single feedstock, resulting in overall resource recovery rates exceeding 70%, compared with 30–40% for single-product extraction [30, 155]. Data from life cycle assessments indicate that the valorisation of fish waste leads to a reduction in greenhouse gas emissions by 50–75%, a decrease in eutrophication potential by 40–60%, and a reduction in overall disposal-related costs by 20–40% per tonne processed when compared to traditional landfilling [143]. Significant obstacles remain in achieving regulatory alignment, standardizing processes, integrating supply chains, reducing capital costs, and demonstrating commercial-scale viability, especially in developing countries where waste processing volumes are highest, and infrastructure investments are most constrained.

This review consolidates existing evidence on the zero-waste valorisation of fish byproducts within circular bioeconomy frameworks, highlighting significant gaps in technological innovation, economic feasibility, environmental sustainability, and regulatory implementation. We assess (i) the composition and functional potential of fish byproducts, (ii) conventional and emerging recovery technologies, (iii) key product pathways and techno-economic considerations, and (iv) environmental and regulatory aspects using available life cycle and policy evidence. This study integrates quantitative evidence from food science, biotechnology, process engineering, environmental science, and policy studies to establish an interdisciplinary foundation for advancing sustainable valorization of fish waste. This approach supports the development of a blue bioeconomy in alignment with the United Nations Sustainable Development Goals 12 and 14, as well as the FAO Code of Conduct for Responsible Fisheries.

2 Overview of different fish processing byproducts

The various components of the fish body that are usually not consumed are discarded; these are referred to as fish leftovers, byproducts, or waste. Not only the fish industry, but also retail markets, produce vast amounts of fishery byproducts (Fig. 1). Efficient management of these byproducts is crucial for mitigating environmental problems and enhancing the sustainability of aquaculture and fisheries [224]. Furthermore, fish processors often lack sufficient knowledge of the technologies required to process byproducts effectively [157]. Given the escalating issue of fish waste and the urgency of intervention, numerous global initiatives have been implemented to prevent food waste [172]. These byproducts, including scales, skin, fins, bones, and viscera, are increasingly recognised as sources of valuable biochemical compounds [118]. Table 1 presents different

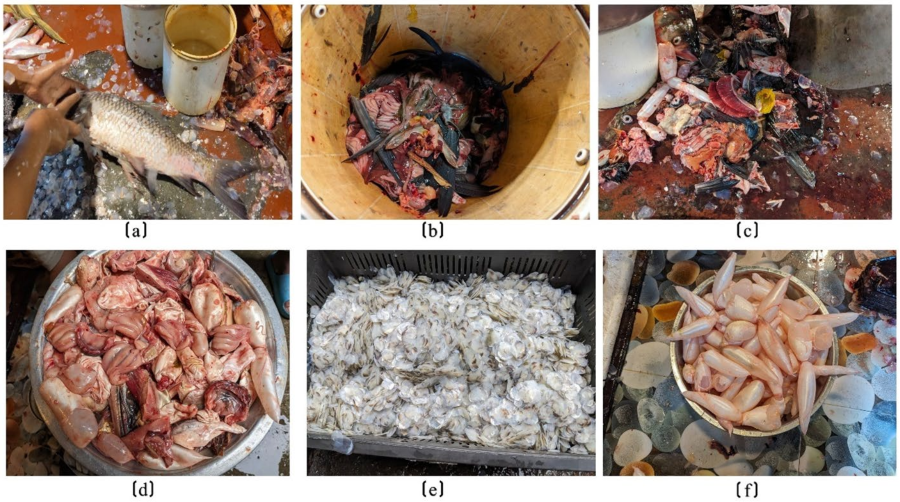


Fig. 1 Photos of different fish byproducts collected from retail markets, Bangladesh: **a** Whole Rohu fish; **b** Fins, viscera, liver, in the bin **c** Swim bladders, gills, scales, fins in the floor **d** Heads, skin, viscera parts **e** Washed scales **f** Washed Swim bladders

compounds and the principal utilization routes of fish processing byproducts, and Table 2 outlines extraction methods, reported yields, and optimal processing conditions for significant byproduct utilization.

2.1 Fish scales

Valorization of fish scales presents a sustainable method for transforming seafood processing waste into high-value biomaterials, thereby contributing to circular economy goals [176, 221]. Scales comprise collagen, hydroxyapatite, chitin, and various bioactive compounds, facilitating their use in biomedicine, nutraceuticals, environmental remediation, and advanced materials [85, 249]. Recent studies highlight the advantages of milder and intensified recovery methods, including microwave-assisted extraction, ultrasound-assisted extraction, supercritical fluid extraction, and enzymatic hydrolysis with hydrothermal pretreatment [126, 214, 249]. These methods enhance yield and minimize environmental impact compared with traditional acid or alkali treatments [126, 214, 249].

Quantitative assessments indicate that scales account for approximately 1 to 5% of total fish weight, comprising roughly 40 to 60% hydroxyapatite and 30 to 40% collagen on a dry weight basis [8, 81]. Yields reported differ by method and species: acid soluble collagen yields 8 to 18% on a wet weight basis [205, 220]; enzymatic hydrolysis following demineralization yields 12 to 22% [205]; hydrothermal pretreatment achieves protein recovery near 84.81% with significant ACE inhibitory activity; hydroxyapatite recovery via calcination yields 25 to 45% of dry mass [249]; chemical precipitation yields 30 to 50% with Ca to P ratios of approximately 1.60 to 1.67 [85]; and chitin yields range from 2 to 8% with degrees of deacetylation to chitosan between 70 and 85% [85, 117, 249]. Process intensification reduces processing time and energy consumption while maintaining product quality [238].

Technical and logistical challenges limit commercialization. Demineralisation and deproteinisation typically necessitate substantial energy inputs and potent chemicals, resulting in hazardous effluents and significant water consumption. While enzymatic

Table 1 Bioactive compounds and principal utilization routes of fish processing byproducts

Fish processing byproducts	Primary bioactive compounds	Principal utilization routes and applications	References
1. Fish scales	Collagen (type I and II), proteins, chitin/chitosan, hydroxyapatite, bioactive peptides, calcium phosphates	Extraction of collagen and gelatin for biomedical devices and functional foods; recovery of hydroxyapatite via thermal calcination or hydrothermal synthesis for bone tissue engineering and dental applications; production of chitosan-based biopolymers for pharmaceutical and environmental applications; development of bioactive peptides with antioxidant and antimicrobial properties; manufacture of mineral sorbents for heavy metal remediation in wastewater treatment systems	[3, 8, 76, 177, 220]
2. Fish skin	Type I collagen, gelatin, structural proteins, bioactive peptides, astaxanthin, lipid-soluble compounds	Industrial-scale collagen extraction via acid-alkali or enzymatic hydrolysis for pharmaceutical and cosmetic applications; gelatin production for food additives and biomedical encapsulation; development of collagen-based tissue engineering scaffolds and wound dressing materials; manufacture of edible films and coatings for food preservation; extraction of bioactive peptides with documented antihypertensive and anti-inflammatory properties; production of sustainable leather substitutes and biotextile materials	[33, 49, 69, 77, 177, 192, 223]
3. Fish bones (Endoskeletons)	Calcium phosphates (hydroxyapatite, β-tricalcium phosphate), collagen, mineral matrices, protein hydrolysates, bioactive peptides, essential trace elements	Production of nanostructured hydroxyapatite via thermal calcination or wet chemical synthesis for orthopedic implants and dental restorations; manufacture of calcium-fortified functional food ingredients; recovery of collagen and gelatin for industrial and biomedical applications; enzymatic hydrolysis for generation of bioactive peptides with antihypertensive and immunomodulatory properties; production of fishmeal and protein concentrates for animal feed; development of mineral-enriched organic fertilizers and soil amendments	[3, 35, 76, 85, 147, 220]
4. Swim bladders (Fish maws)	Collagen, elastin, bioactive peptides, polysaccharides, lipopolysaccharides	Production of isinglass (food-grade gelatin) for clarification of beverages; extraction of high-purity collagen for cosmeceutical and pharmaceutical formulations; development of bioactive peptide preparations with documented antioxidant and anti-inflammatory activity; manufacture of collagen-elastin composite biomaterials for tissue engineering applications; valorisation as luxury food ingredient and traditional Chinese medicine preparation	[15, 49, 55, 105]
5. Fish oil	Omega-3 long-chain polyunsaturated fatty acids (eicosapentaenoic acid, docosahexaenoic acid), omega-6 polyunsaturated fatty acids, vitamin A, vitamin D, squalene, phospholipids	Production of nutraceutical omega-3 supplements targeting cardiovascular protection and neuroprotection; formulation of infant formula and functional foods enriched with long-chain polyunsaturated fatty acids; development of pharmaceutical preparations for metabolic and inflammatory disorders; incorporation into aquaculture feeds and terrestrial animal feeds to enhance nutritional profiles; synthesis of biodiesel and other renewable biofuels via transesterification; utilisation in cosmetic formulations, dermatological products, and skincare preparations	[2, 16, 44, 93, 178, 189]

Table 1 (continued)

Fish processing byproducts	Primary bioactive compounds	Principal utilization routes and applications	References
6. Fish viscera	Digestive proteases (pepsin, trypsin), lipases, structural proteins, bioactive peptides, protein hydrolysates, omega-3 polyunsaturated fatty acids, minerals	Production of fish protein hydrolysates via enzymatic digestion with documented antihypertensive, antioxidant, and immunomodulatory activities; isolation and purification of digestive enzymes for use as industrial biocatalysts; extraction of omega-3-enriched oils for nutraceutical and pharmaceutical applications; fermentation-based production of fish silage as a cost-effective animal feed ingredient; anaerobic digestion for biogas production as renewable energy; development of bioactive peptides for functional food formulations	[6, 34, 49, 161, 202]
7. Fish heads	Proteins, collagen, lipids, omega-3 polyunsaturated fatty acids, minerals (calcium, phosphorus), bioactive peptides	Large-scale production of fishmeal and fish oil via thermal processing for aquafeeds and terrestrial animal feeds; generation of fish protein hydrolysates through enzymatic and microbial processes; extraction and characterisation of bioactive peptides with documented health-promoting properties; isolation of proteolytic and lipolytic enzymes for food processing industries; manufacture of fish glue and other adhesive products; production of mineral-enriched organic fertilizers for agricultural applications	[76, 94, 150, 161, 225]
8. Crustacean exoskeletons	Chitin, chitosan, carotenoids (astaxanthin, beta-carotene), calcium carbonate, proteins, lipids	Industrial synthesis of chitosan via deacetylation of chitin for pharmaceutical, nutraceutical, and biomedical applications; production of chitooligosaccharides with documented prebiotic and immunomodulatory properties; development of active food packaging materials and edible films with antimicrobial functionality; manufacture of sorbents for water treatment and heavy metal remediation; production of dietary supplements targeting joint health and metabolic function; development of biocompatible scaffolds for tissue engineering applications	[46, 81, 142, 224, 236, 242]
9. Fish fins	Collagen (type I and II), gelatin, mineralized collagen matrix enriched in calcium and phosphorus, trace elements (zinc, selenium, iron)	Extraction of high-quality collagen and gelatin via acid-alkali or enzymatic hydrolysis for food, cosmetic, and biomedical applications; development of collagen-based biomaterials and three-dimensional scaffolds for tissue engineering; potential recovery of calcium phosphate minerals for orthopedic and dental applications; production of value-added functional food ingredients with mineral fortification; development of bioactive peptides via proteolytic hydrolysis	[131, 132, 176, 239]
10. Fish livers	Omega-3 long-chain polyunsaturated fatty acids (eicosapentaenoic acid, docosahexaenoic acid), fat-soluble vitamins (retinol, calciferol), high-quality proteins, essential minerals (selenium, iodine, iron)	Industrial production of fish liver oil as a primary source of omega-3 polyunsaturated fatty acids for global nutraceutical markets; development of vitamin A and vitamin D concentrates for pharmaceutical and functional food applications; formulation of omega-3 supplements targeting cardiovascular and neurological health; incorporation into infant formulas and medical foods; utilisation in cosmetic and skincare formulations; application in aquaculture feeds to optimise growth performance and disease resistance in farmed fish	[98, 122, 141, 189, 218]

and green alternatives are more environmentally friendly, they also elevate capital and operational expenses and introduce uncertainties regarding scalability [8, 220]. The low unit mass and dispersed generation increase collection and logistics costs for artisanal and multi-species fisheries, while regulatory uncertainty and fluctuating consumer acceptance hinder adoption for food and biomedical applications [49, 81]. Addressing

Table 2 Fish processing byproducts valorization: Source, extraction methods, and yield (%)

Fish processing byproducts	Primary compounds	Optimal species/source	Extraction method	Typical yield (state basis)	Key quality parameter	References
1. Fish scales	Collagen	Tilapia, carp	Enzymatic + demineralisation	12–22%	ACE inhibition IC_{50} 0.15–0.35 mg/mL	[220, 249]
	Hydroxyapatite	Tilapia, tuna	Calcination 800–1000 °C	25–45% (dry wt)	Ca/P ratio 1.60–1.67	[71, 85]
	Chitin	Carp, tilapia	Acid-alkali extraction	2–8% (dry wt)	Degree of acetylation 70–85%	[59, 117]
2. Fish skin	Collagen	Tilapia, cod, tuna	Pepsin-aided enzymatic	5–30% (dry weight; species & method dependent)	Denaturation temp. 25–35 °C	[8, 226]
	Gelatin	Tilapia, cod	Thermal hydrolysis	15–18% (tilapia), 12–16% (cod)	Gel strength 150–300 g Bloom	[106]
	Bioactive peptides	Salmon, tuna	Enzymatic hydrolysis	10–25%	ACE inhibition IC_{50} 0.1–0.4 mg/mL	[192, 203]
3. Fish bones (Endoskeletons)	Hydroxyapatite	Tuna, swordfish, cod	Calcination 800–1000 °C	40–65% (dry wt)	Crystallinity 0.70–0.85	[35, 85, 208]
	Collagen	Cod, salmon	Acid + enzymatic	5–15%	Denaturation temp. 28–35 °C	[77, 99, 106]
	Biochar	Mixed species	Pyrolysis 350–500 °C	30–45% (dry wt)	Surface area 100–300 m^2/g	[38, 190]
4. Swim bladders (Fish maws)	Collagen	Yellow croaker, sturgeon, barramundi	Pepsin-aided enzymatic	15–30%	Gel strength 200–350 g Bloom	[55, 199, 232]
	Bioactive peptides	Yellow croaker	Enzymatic hydrolysis	12–25%	ABTS scavenging 65–85%	[47, 121, 127]
5. Fish oil	Omega-3 (EPA + DHA)	Mackerel, salmon, anchovy viscera/liver	Supercritical CO_2 extraction	10–16% (whole fish basis)	EPA + DHA 25–35%	[101, 180, 217]
	Concentrated EPA + DHA	Anchovy, mackerel oil	Molecular distillation	60–75% (lipid basis)	EPA + DHA 50–70%	[5, 56, 180]
6. Fish viscera	Protein hydrolysates	Salmon, cod	Alcalase enzymatic	15–30%	ACE inhibition IC_{50} 0.08–0.25 mg/mL	[82, 150]
	Oils (EPA + DHA)	Mackerel, herring	Enzymatic extraction	10–20%	EPA + DHA 18–28%	[10, 26, 181]
	Silage (fermented)	Mixed species	Lactic fermentation	80–90% digestibility	Crude protein 8–15% (dry matter)	[184]
7. Fish heads	Protein hydrolysates	Salmon, cod	Enzymatic or subcritical water	15–28%	DPPH scavenging 50–80%	[95, 150, 155, 169]
	Oils (EPA + DHA)	Salmon, tuna	Subcritical water co-extraction	5–12%	EPA + DHA 15–25%	[139, 155, 233]

Table 2 (continued)

Fish processing byproducts	Primary compounds	Optimal species/source	Extraction method	Typical yield (state basis)	Key quality parameter	References
8. Crustacean exoskeletons	Chitin	Shrimp shells	Acid-alkali extraction	15–35% (dry wt)	Degree of acetylation 85–95%	[242]
	Chitosan	Shrimp, crab shells	Deacetylation (40–50% NaOH)	Based on chitin	Degree of deacetylation 70–95%	[242]
	N-acetylglucosamine	Shrimp chitin	Enzymatic (chitinase)	60–85% (chitin basis)	Purity > 95%	[21, 237]
	Astaxanthin	Shrimp, crab shells	Supercritical CO_2 + ethanol	0.8–2.5 mg/g (dry shell)	Purity 85–95%	[146]
	Calcium carbonate	Crab shells	Precipitation from demineralisation	15–30% (dry wt)	Particle size 1–10 µm	[81]
9. Fish fins	Collagen	Clown featherback fin	Pepsin-aided enzymatic	8–18%	Denaturation temp. 32–35 °C	[114, 125, 167]
	Protein hydrolysates	Tilapia fin collagen	Subcritical water	10–20%	DPPH scavenging 45–70%	[7, 211]
10. Fish livers	Fish oil (EPA + DHA)	Cod, shark, halibut	Enzymatic or supercritical CO_2	25–50% (liver wt)	EPA + DHA 15–25%; Vit A 10,000–30,000 IU/g	[180, 217, 218]
	Protein hydrolysates	Cod, tuna	Enzymatic hydrolysis	8–15%	Degree of hydrolysis 20–35%	[92, 201]

these constraints is crucial for realizing the complete sustainability and economic potential of materials derived from scale.

2.2 Fish skin

Fish skin, a prevalent byproduct of global fish processing, serves as a concentrated source of type I collagen and gelatin. Its valorization transforms low-value waste into high-value biomaterials, yielding significant economic and environmental advantages [176]. Fish-derived collagen, as a non-mammalian source, addresses religious and public health concerns associated with terrestrial gelatin and mitigates risks of bovine spongiform encephalopathy [99, 149]. Fish skin produces bioactive peptides that exhibit antioxidant, antimicrobial, and antihypertensive properties, facilitating their use in pharmaceuticals, cosmetics, food, and tissue engineering [129, 192, 248].

Species and extraction method influence yield and material properties. Fish skin generally accounts for 2 to 10% of the total fish biomass, with collagen constituting approximately 60 to 70% of the dry weight of the skin [8, 154, 226]. Yields for acid-soluble collagen are reported between 12 and 35%, while pepsin-assisted enzymatic extraction yields range from 15 to 40%, enhancing molecular weight control and raising the denaturation temperature by approximately 3 to 8 degrees Celsius. Thermal gelatin yields vary from 8 to 20%, influenced by species: Tilapia (*Oreochromis niloticus*) yields 15–18%, Atlantic cod (*Gadus morhua*) yields 12–16%, and Yellowfin tuna (*Thunnus albacares*) yields 10–14% [106, 167, 205]. Ultrasound-assisted extraction, a form of process intensification, decreases processing time and energy consumption while enhancing yield [220]. Reported functional metrics indicate an increase in gel strength from 150 to 300 Bloom and viscosity from 2.5 to 4.5 millipascal seconds at a concentration of 6.67% and a temperature of 60 degrees Celsius [106, 167, 220].

Commercialization is constrained by perishability, variability, and environmental impact. Maintaining skin moisture levels between 70 and 80%, along with elevated endogenous protease activity and microbial loads, necessitates prompt stabilization and effective cold chain management to ensure extractability [49]. Variability among species and environmental factors complicates the standardization of pharmaceutical-grade materials [226]. Conventional acid and base processing produce corrosive effluents and incurs substantial wastewater treatment costs. In contrast, enzymatic and other green technologies mitigate environmental impact but entail higher capital and operational costs, limiting their adoption to premium markets. Additionally, varied consumer acceptance and stringent regulatory pathways further hinder large-scale implementation [8, 49, 106].

2.3 Fish bones (Endoskeletons)

Valorization of fish bones represents a sustainable approach to transforming seafood processing waste into high-value products applicable in biomedical, nutritional, agricultural, and environmental fields [176]. Fish bones contain significant amounts of calcium phosphate, calcium carbonate, and magnesium phosphate, which can be used as feedstock for the production of hydroxyapatite, protein hydrolysates, and bioactive peptides [85]. Each of these components plays a specific functional role in applications such as bone tissue engineering, dental materials, drug delivery, and food fortification sectors [85, 165, 176]. Optimized recovery methods, such as thermal calcination, hydrothermal synthesis, and controlled chemical precipitation, yield nanoscale hydroxyapatite with appropriate crystallinity and biocompatibility for medical applications [60, 182, 235].

The reported compositional and yield metrics demonstrate technical viability and emphasize the dependence on methodology. Fish bones generally account for 10 to 20% of fish biomass, comprising approximately 50 to 70% calcium phosphate, 20 to 30% collagen, and 5 to 10% water on a dry basis [153, 165, 219]. Calcination at temperatures ranging from 800 to 1000 degrees Celsius produces hydroxyapatite with yields of 40 to 65%, characterized by Ca: P molar ratios between 1.63 and 1.68 [35]. Hydrothermal synthesis at 150 to 250 degrees Celsius yields 35 to 55% nanostructured material, with particle sizes of approximately 20 to 80 nanometers and an enhanced surface area [60]. Additionally, collagen extraction from bone yields 5 to 15% by wet weight and exhibits thermal stability comparable to collagen derived from skin [35, 77, 85, 99]. Low temperature pyrolysis yields biochar at rates of 30 to 45%, with surface areas suitable for soil amendment and wastewater remediation [38, 174].

Essential constraints must be addressed to facilitate scaling and market translation. The significant thermal energy requirements for calcination and hydrothermal processes may negate environmental advantages unless they are coupled with renewable energy sources or waste heat recovery [35, 85]. Additionally, bones have the potential to bioaccumulate heavy metals and persistent pollutants, necessitating thorough screening and purification to comply with regulatory standards [35]. Logistical challenges stem from the dispersed and heterogeneous nature of species supply, resulting in higher collection and processing costs for artisanal fisheries. Additionally, competition from synthetic hydroxyapatite and established supply chains constrain commercial adoption. Advancing green processing methods, harmonizing quality control, and clarifying regulatory pathways are essential for realizing the circular bioeconomy potential of fish bone-derived materials [38, 85].

2.4 Swim bladders (Fish Maws)

The valorisation of fish swim bladders offers a sustainable method for transforming processing byproducts into high-value biomaterials [121, 176]. Swim bladders contain high levels of collagen, elastin, and glycosaminoglycans and have historically been utilized as fish maw, which is believed to possess therapeutic benefits [54, 121]. Recent research validates the biomedical potential, indicating antioxidant, anti-inflammatory, and anticancer properties, and endorsing uses in food, pharmaceuticals, cosmetics, biodegradable films, and tissue scaffolds [75, 121, 176, 196]. Species with nutritional and functional potential, such as bighead carp, enhance the impetus for the development of nutraceuticals and dietary supplements derived from swim bladder peptides [55, 127].

Metrics of composition and performance exhibit dependence on both method and species. Swim bladders generally account for 0.5 to 3% of the wet weight of fish, with collagen constituting 50 to 70% of the dry mass, elastin 10 to 20%, and glycosaminoglycans 5 to 10% [106, 121, 127]. Yields for acid-soluble collagen range from 10 to 25%, while pepsin-aided extraction yields range from 15 to 30%. Denaturation temperatures are reported as 28–36 °C for warm-water species and 18–25 °C for cold-water species [121, 127]. Gelatin derived from air bladders exhibits gel strengths between 200 and 350 g Bloom and viscosities of 3.0 to 5.5 mPa·s [42, 75]. Bioactive peptides exhibit ABTS radical scavenging activity ranging from 65 to 85% and cyclooxygenase-2 inhibition between 50 and 70% [55, 121]. Process intensification techniques, such as microwave-assisted extraction, decrease processing time by 60 to 75% while enhancing collagen yield by 10 to 20% [121]. Controlled oven drying at 50 to 60 degrees Celsius for 8 to 12 h produces translucent, stable products with a moisture content below 12% [48, 95, 214].

Limited feedstock availability, high technical costs, and regulatory uncertainties hinder industrial-scale-up. Commercially viable swim bladders are primarily found in large physoclistous teleosts, which limit supply and concentrate markets. The luxury demand for these products has led to overexploitation in certain regions, prompting conservation responses [50, 54, 121, 176]. The high costs associated with enzymatic and chemical extraction, the labor-intensive nature of manual processing, the sensitivity of product quality to sanitization and drying, and the environmental impacts of conventional chemical methods hinder wider adoption unless addressed through green technologies and energy integration [172, 187, 221]. To achieve scalable and sustainable valorisation, priorities encompass responsible sourcing and aquaculture, validation of bioactivity and safety, implementation of intensified green extraction methods, and establishment of harmonised processing and regulatory standards [221, 243].

2.5 Fish oil

Recent advancements in fish oil valorisation emphasize the adoption of milder extraction methods and the incorporation of renewable energy to enhance yield and quality, while reducing environmental impact and promoting circular economy objectives [11, 16, 67, 141, 143]. The primary focus is on long-chain omega-3 polyunsaturated fatty acids, specifically eicosapentaenoic acid and docosahexaenoic acid, due to their cardioprotective, neuroprotective, and anti-inflammatory effects [16, 135, 143]. Process intensification and green technologies, including enzymatic hydrolysis, supercritical carbon dioxide extraction, real-time near-infrared monitoring, and microencapsulation with biopolymers, improve PUFA retention, stabilize products for nutraceutical applications, and support adherence to quality standards [52, 138, 221, 241].

Yield measurements and quality metrics highlight the dependence on both method and species. Common feedstocks consist of viscera, heads, frames, and liver, with lipid contents differing by tissue and season: viscera contain 15 to 40% lipids, heads 5 to 20%, and liver 40 to 80% [5, 171]. Wet rendering generally produces 8 to 18% oil from the whole fish, whereas enzymatic hydrolysis yields 12 to 22% oil, with reduced thermal damage to polyunsaturated fatty acids [138]. Supercritical carbon dioxide extraction conducted at pressures of 300 to 400 bar and temperatures of 40 to 60 degrees Celsius yields oil content ranging from 10 to 16%, characterized by low peroxide and anisidine values, and enhanced EPA plus DHA fractions of approximately 25 to 35%, compared to 18 to 28% obtained through conventional rendering [101, 138, 180]. Molecular distillation effectively concentrates EPA and DHA to levels of 50–70%, achieving lipid yields of 60–75% [56, 241]. Additionally, microencapsulation efficiencies ranging from 80 to 95% significantly enhance shelf life [52, 107, 164]. Life cycle assessment studies indicate greenhouse gas reductions of approximately 1.5 to 2.2 kg CO_2-eq per kilogram of oil, alongside energy savings of about 8 to 15 MJ per kilogram compared to disposal scenarios [104]. Additionally, near infrared spectroscopy demonstrates predictive accuracy adequate for process control ($R^2 > 0.95$) [104, 143, 221].

Significant obstacles to scaling persist in the technological, environmental, and economic domains. The elevated polyunsaturated fatty acid (PUFA) content in oils predisposes them to autoxidation and enzyme-catalyzed peroxidation, necessitating stringent control of time, temperature, and oxygen, as well as the implementation of antioxidant strategies, which adds complexity and cost [180, 217]. Viscera and liver oils accumulate fat-soluble contaminants, including polychlorinated biphenyls, dioxins, and brominated flame retardants, necessitating advanced purification methods such as molecular distillation or supercritical fractionation [180]. Variability in fatty acid composition due to seasonal, geographic, and dietary factors, along with emerging microplastic contamination and limited supply chain integration, complicates standardization for nutraceutical markets. Additionally, economic competition from algal omega-3 and the capital intensity of green extraction pose challenges to commercial adoption [151, 218]. To fully realise the sustainability and public health potential of fish oil valorisation, further optimisation of green extraction protocols, robust contaminant control, integrated supply chains, and supportive regulatory and market incentives are necessary [100, 168, 176].

2.6 Fish viscera

Fish viscera comprise a significant portion of fish processing waste and serve as concentrated sources of proteins, lipids, enzymes, and polysaccharides. The valorisation of viscera supports circular economy goals by transforming a waste stream into bioactive ingredients that exhibit antioxidant, anti-inflammatory, and antihypertensive properties, applicable in food, pharmaceutical, and feed sectors [72, 92, 104, 176]. Implementing milder, integrated recovery strategies enhances resource efficiency and reduces environmental impact and disposal costs [11, 34, 238].

Enzymatic hydrolysis is the primary method for peptide recovery, yielding protein hydrolysates at 15–30% wet weight and degrees of hydrolysis of 15–40%, contingent on factors such as enzyme type, temperature, and duration. Commonly utilised proteases include endogenous and industrial options such as Alcalase, Flavourzyme, and Protamex, while tuna viscera provide enzymes of industrial significance, including trypsin and pepsin [82, 162, 163, 230]. Viscera oils can be extracted enzymatically at yields of 10–20%, providing sources of EPA and DHA comparable to those of whole fish oil [104]. In contrast, fermentation-based silage offers a cost-effective feed alternative, achieving protein digestibility rates of approximately 80–90% [181, 183]. Emerging technologies such as solar-assisted pretreatment, microwave-assisted extraction, subcritical water hydrolysis, and supercritical fluid extraction facilitate the concurrent recovery of peptides, lipids, and minerals, thereby enhancing biorefinery concepts and improving process economics [11, 104, 155, 215].

The scaling process is constrained by factors such as rapid autolysis, microbial spoilage, compositional variability among species and seasons, and contamination risks from bile, heavy metals, and pathogens. These challenges necessitate rigorous handling, purification, and regulatory measures [6, 72, 157]. Addressing these challenges necessitates the implementation of short supply chains or onboard stabilization, standardized quality control, integrated biorefinery designs that co-extract multiple fractions, and focused policy and infrastructure support to mitigate investment risks and facilitate market entry [34, 92, 181, 238].

2.7 Fish heads

Fish head valorisation transforms a nutrient-rich byproduct into a feedstock for food, pharmaceutical, cosmetic, and bioenergy applications by recovering proteins, omega-3 polyunsaturated fatty acids, minerals, collagen, and bioactive peptides [94, 181, 221]. Fish heads, previously underutilised, now provide functional ingredients for nutraceuticals, cosmetics, and biomedical applications due to their demonstrated antioxidant, anti-inflammatory, and antimicrobial properties [121, 137, 150, 169, 192]. Recent process innovations, such as enzymatic hydrolysis, fermentation, subcritical water extraction, and pulsed electric field pretreatment, enhance recovery efficiency and product quality while minimizing environmental impacts [128, 137, 155].

Quantitative metrics and process outcomes are highly contingent upon the chosen methodology. Fish heads represent approximately 9 to 15% of the total weight of fish and generally consist of 12 to 20% protein, 3 to 15% lipids, and 2 to 6% collagen [94, 223]. Enzymatic hydrolysis produces protein hydrolysates at 15 to 28% wet weight, achieving DPPH scavenging rates of 50 to 80% and ABTS scavenging rates of 60 to 85% [36, 169]. In contrast, subcritical water treatment at temperatures ranging from 160 to 200 degrees Celsius co-recovers proteins (18 to 30%), oils (5 to 12%, with EPA and DHA at 15 to 25%), and soluble minerals [150, 155, 169]. Salmon head hydrolysates containing peptides under 3 kDa exhibit ACE inhibitory activity, with IC50 values ranging from 0.12 to 0.35 mg per mL [41, 68, 113]. Additionally, collagen recovery from head skin ranges from 3 to 8%, highlighting the need for rapid stabilisation to mitigate collagenase activity [94, 150]. Pulsed electric field pretreatment at 2 to 5 kV/cm and 10 to 50 pulses enhances extraction yields by 12 to 25% and reduces hydrolysis time by 30 to 50% [137]. The techno-economic analysis of cod head biorefining demonstrates favourable returns when protein hydrolysates, oils, and bone meal are co-produced [104, 155].

Significant constraints persist and require attention for scaling up. Heads exhibit high perishability due to elevated moisture content, enzyme activity, and microbial loads, necessitating prompt processing or cold chain logistics, which escalates operational costs [94, 157]. Variability in composition among species and the complexity of anatomy hinder standardization and selective separation. Additionally, gill tissues can accumulate contaminants and biofilms, necessitating thorough screening [94, 150]. The energy-intensive extraction processes and the potential accumulation of heavy metals increase purification costs and regulatory challenges [157, 181]. The realisation of commercial viability relies on integrated biorefinery designs, on-site or near-source concentration, harmonised quality protocols, and supportive policies and infrastructure to mitigate investment risks and facilitate sustainable valorisation pathways [34, 155].

2.8 Crustacean exoskeletons

Crustacean shells from shrimp, crab, and lobster comprise significant amounts of chitin, protein, calcium carbonate, and carotenoids, particularly astaxanthin, which support various applications in pharmaceuticals, water treatment, agriculture, cosmetics, and food preservation [22, 91, 146, 185, 212]. Recent developments in catalytic and biochemical conversion methods broaden the range of products to include platform chemicals like levulinic acid and gamma valerolactone, thereby enhancing the economic viability of integrated shell biorefineries [20, 45, 89, 91, 111]. Optimised depigmentation and streamlined processing steps have improved exergy efficiency and production metrics in chitosan manufacturing [140].

Enhanced, environmentally friendly extraction methods improve yields while maintaining the functional integrity of the recovered fractions. Ultrasound-assisted deproteinization reduces alkali use and shortens processing time, while simultaneously enhancing chitin purity [13, 24, 222]. Supercritical carbon dioxide extraction, utilizing ethanol as a co-solvent, effectively produces astaxanthin and other lipophilic pigments at significant concentrations, thereby enhancing revenue generation in biorefinery models [146, 197]. Chemical methods are effective for demineralisation, deproteinisation, and deacetylation to chitosan, yielding chitin at approximately 15–35% and chitosan with degrees of deacetylation ranging from 70 to 95%, contingent on specific conditions [21, 81, 242]. In contrast, enzymatic chitin hydrolysis yields N-acetylglucosamine with high purity and market value, though at a higher cost [21, 81, 142, 242].

Widespread deployment faces limitations due to environmental, technical, and market barriers, necessitating integrated responses [81, 242]. Conventional chemical processing produces substantial effluent volumes, excessive water consumption, and neutralization emissions. Additionally, shells can accumulate contaminants such as heavy metals and microplastics, which require stringent purification and quality assurance measures [81, 242, 244]. Variability in species, seasonality, and geography complicates the standardization of chitin and chitosan specifications for pharmaceutical and biomedical applications [242]. To achieve scalable and sustainable valorisation, key actions involve the adoption of green extraction technologies in modular biorefinery designs, integration of life cycle and techno-economic assessments in process selection, establishment of harmonised quality standards, and implementation of targeted policy incentives to mitigate investment risks and enhance market competitiveness compared to synthetic alternatives [20, 89, 111, 140, 238, 244].

2.9 Fish fins

Fins represent an underutilized byproduct with established value for collagen, gelatin, protein hydrolysates, and bioactive peptides in circular bioeconomic frameworks [12, 99, 172, 200]. Reported biomass fractions differ by definition and species; however, fins generally constitute a minor portion of total fish mass, typically ranging from 1 to 10%, contingent upon the inclusion of paired fins and fin rays [12, 152, 172]. Fin-derived biomolecules exhibit functional properties pertinent to food, cosmetic, and biomedical applications, characterized by advantageous amino acid profiles and proven antioxidant activity [27, 152, 154, 211].

Recovery metrics and process performance are significantly reliant on the chosen methodology. Acid-soluble collagen yields vary from 5 to 12% of wet weight, while pepsin-assisted extraction yields range from 8 to 18%. Fin collagens demonstrate denaturation temperatures of 32–35 °C, gel strengths of 180–250 Bloom, and a high-water-holding capacity [69, 99]. Subcritical water hydrolysis at temperatures ranging from 150 to 180 degrees Celsius yields protein hydrolysates with 10–20% wet weight yields and DPPH scavenging activities of 45–70% [152]. In contrast, enzymatic digestion yields gelatin at 6 to 14%, while fin oils contain 10 to 18% EPA and DHA, which are suitable for nutraceutical concentration via molecular distillation [88, 211].

Commercialization is limited by restricted feedstock mass, composite fin morphology, and species-dependent variability, which collectively hinder economies of scale and complicate selective extraction and standardization [40, 115, 172, 229]. Reputational and regulatory risks associated with shark fins, along with the irregular morphology of fin rays and their co-mingling with other byproducts, further limit market access. Consequently, viable pathways involve integrated multi-stream biorefineries aimed at high-value biomedical and cosmetic niches [65, 220]. Priority actions include adopting green, intensified extraction; onsite or near-source concentration; comprehensive cross-species characterisation; and techno-economic assessment to validate scalable, sustainable valorisation routes [19, 65, 172, 214].

2.10 Fish livers

Fish liver valorisation provides a high-value route for converting seafood waste into nutraceutical, pharmaceutical, and functional food ingredients owing to its rich composition of long-chain omega-3 polyunsaturated fatty acids, fat-soluble vitamins, proteins, enzymes, and bioactive lipids [98, 229]. Livers from cod, halibut, and tuna are notable for elevated EPA and DHA and substantial vitamin A and D content, underpinning anti-inflammatory, antioxidant, and immunomodulatory applications while also raising safety considerations for hypervitaminosis A and contaminant bioaccumulation [37, 98, 188, 229, 231].

Recent process innovations improve yield and product quality. Conventional wet rendering of cod liver yields approximately 30 to 50% oil of liver wet weight with EPA and DHA comprising roughly 15 to 25% of the oil, whereas enzymatic extraction with Alcalase or Protamex increases yield by about 10 to 20% while operating at lower temperatures and reducing oxidation [37, 98, 138]. Supercritical carbon dioxide extraction preserves vitamins and reduces contaminants at pressures of 350–450 bar and temperatures of 40–50 °C, yielding oil yields of 25–40% [180]. Complementary methods such as ultrasound-assisted extraction, microwave processing, and hyperspectral imaging for line-level quality control support integrated valorisation and circular economy models [138, 158, 214].

Key barriers to scalable deployment include contaminant concentrations in liver tissue, seasonal and species variability in lipid content, rapid autolysis and oxidative instability of polyunsaturated lipids, and regulatory constraints on vitamin-rich products [98, 100]. Addressing these challenges requires rigorous contaminant monitoring and purification, standardised batch characterisation, rapid near-source processing or stabilisation, adoption of low-temperature green extraction, and harmonised regulatory pathways to ensure safe, consistent, and commercially viable liver-derived products [108, 188, 229].

3 Zero-waste utilisation

3.1 Biofuel production

The use of biofuels has been regarded as one of the most efficient alternatives to nonrenewable energy sources, primarily due to their renewable nature, ecological sustainability, biodegradability, and nontoxicity [53]. These biofuels can be produced from various organic wastes streams, including vegetable waste [204], fish waste [18, 100, 110, 170], and animal waste [4, 124]; microalgae [29, 216]; seaweed [32, 86]; and plants such as *Jatropha* sp. Kywe and Oo, [119]. Waste biorefineries are attracting considerable global interest due to their ability to address energy demands and waste management issues within the framework of a circular economy [9, 245]. The fish industry is among the fastest-growing sectors globally, generating substantial waste, and improper disposal can pose significant health and environmental risks [74]. The fish processing industry generates waste from various parts of the fish, including the head (21.5%), liver (5.1%), skin (3.3%), gut (7.7%), fillet/skinned (36%), backbone (15.3%), fins (6.1%), and roe (4.2%) [214]. Fish waste, particularly fish oil, holds considerable potential as a biofuel source due to its elevated levels of long-chain fatty acids, which are suitable for biodiesel production [74]. Fish waste can be utilised in various applications, including the production of biofuels that enhance socioeconomic stability, increase energy security, and improve resilience to climate change-related environmental challenges by reducing greenhouse gas emissions [18]. The elevated lipid content of waste fish oil renders it a more appropriate source for biofuel production [240].

3.2 Collagen extraction

Collagen extraction from fish waste has emerged as a critical research domain, driven by the imperatives of environmental sustainability and the increasing demand for biocompatible materials. Compared with mammalian sources, fish-derived collagen offers distinct advantages, including a reduced risk of disease transmission, increased bioavailability, and the absence of religious constraints [120, 172]. Traditional extraction methods, particularly acid-soluble collagen (ASC) and pepsin-soluble collagen (PSC) techniques, are favoured for their ability to maintain the native triple-helical structure of type I collagen, which is essential for retaining bioactivity [69, 79]. Conventional approaches, however, exhibit limitations, including prolonged processing times and restricted yields. Advanced techniques have addressed these constraints. Ultrasound-assisted extraction (UAE) has demonstrated improved efficiency and reduced processing time while maintaining collagen quality [83]. In contrast, enzyme-based methods utilising pepsin and Lactobacillus fermentation achieve high yields with preserved structural integrity [112]. Green extraction technologies represent the most significant advancement, with deep eutectic solvent (DES) systems and supercritical fluid extraction (SFE) offering rapid, cost-effective, and environmentally sustainable alternatives [80, 89]. These methodologies demonstrate exceptional efficiency, achieving extraction yields of up to 90% from cod skins and producing high-quality type I collagen with superior biocompatibility [172]. The combination of natural deep eutectic solvents with ultrasonication exemplifies the optimal integration of green chemistry principles, resulting in enhanced extraction performance. Precise control of critical optimisation parameters, such as extraction time, temperature, solvent concentration, and solid-to-liquid ratio, is essential for maximising yield and quality [69, 133]. Collagen extracted from fish waste has broad cross-sector applicability. Biomedical utilisation capitalises on biocompatibility, biodegradability, and bioactivity for wound healing, tissue-engineering scaffolds, and drug-delivery systems [69, 120]. The food and nutraceutical industries leverage the high bioavailability and functional properties of ingredients for applications in joint health, skin elasticity, and bone strength [103]. Cosmetic applications utilise hypoallergenic properties and anti-ageing benefits to enhance skin hydration, firmness, and elasticity [120, 172]. Integration into sustainable packaging materials aligns with environmental sustainability objectives.

The valorisation of fish waste for collagen extraction represents a significant shift toward sustainable resource management, addressing waste reduction, resource efficiency, and the development of sustainable alternatives [69, 80]. Green extraction technologies enhance sustainability profiles by minimising solvent usage, reducing energy consumption, and eliminating harmful chemicals, thereby supporting environmentally friendly manufacturing practices [63]. Current challenges necessitate continued research focus. To ensure collagen quality and yield, standardisation of extraction protocols across species and geographic regions remains crucial, given the inherent variability in raw materials [14].

3.3 Chitosan extraction

Chitosan extraction from fish and seafood waste has evolved from traditional chemical methods to sustainable green technologies, a shift prompted by environmental considerations and the need to valorise byproducts in the fisheries industry. This biopolymer has garnered significant attention due to its biocompatibility, biodegradability, and diverse industrial applications [57]. Conventional chitosan extraction involves three sequential steps: demineralisation with HCl, deproteinization with NaOH, and deacetylation using concentrated alkali at elevated temperatures [90, 206]. Despite their effectiveness, these methods are not environmentally friendly because of the use of strong chemicals, high water consumption, and the generation of hazardous waste [177, 209].

Recent developments have focused on eco-friendly biotechnological approaches, including enzymatic deproteinization via fish viscera proteases and lactic acid fermentation, which minimise chemical consumption while preserving polymer quality and increasing yield [136, 166, 213]. Microbial fermentation and enzymatic hydrolysis enable selective processing of chitosan under milder conditions, yielding higher-quality chitosan with improved molecular weight and functional properties [70, 96]. Additionally, ultrasound-assisted and microwave-assisted extractions increase efficiency, reduce solvent use, and expedite processing timelines [43]. Nevertheless, challenges remain for large-scale applications regarding processing duration and industrial scalability.

Chitosan demonstrates diverse applications across multiple sectors. In the food industry, it serves as a natural preservative and a biodegradable packaging material with bactericidal effects [177]. Biomedical applications include wound dressings, drug delivery systems, and tissue engineering scaffolds, owing to their biocompatibility and hemostatic properties [87, 96]. In agricultural contexts, bio-stimulants and biopesticides function as agents that facilitate plant growth and improve resistance to biotic stressors and diseases [70, 109]. Environmental applications focus on water treatment and heavy metal removal [96, 186], whereas the cosmetic and biotechnology sectors utilise its antimicrobial and film-forming capabilities [173].

3.4 Fishmeal production

The protein content of fish byproducts typically falls within the range of 49.22% to 57.92% on a dry weight basis, with ash content varying between 21.79% and 30.16%, and fat content ranging from 7.16% to 19.10% [1, 148]. Fish meal is a protein-rich feed component characterised by its superior amino acid profile, high digestibility, exceptional palatability, and absence of antinutritional effects [97, 102]. Fish meal is preferred in aquaculture diets due to the lack of nutritional inhibitors or antinutritional factors [179]. Owing to its protein content, fish meal is considered the most valuable byproduct of the marine sector [78]. Fishmeal's high biological value stems from its rich content of essential amino acids, particularly lysine and sulfur-containing amino acids, which are not synthesised by the animal body, establishing it as a superior feed component [6]. Fishmeal serves as a significant source of unsaturated fatty acids, including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). In both humans and animals, these fatty acids have beneficial effects on autoimmune diseases, heart diseases, and inflammatory conditions [198]. Fish waste and byproducts have demonstrated potential for utilisation in the production of fish meals, serving as a valorisation strategy for this waste. The production of fish meals from fish waste has gained popularity due to its nutritional value and superior performance compared to other feed ingredients globally.

3.5 Limitations and trade-offs of valorization pathways

Although technical feasibility has been established across various valorisation pathways, each method presents unique technical, economic, and environmental trade-offs that require thorough evaluation within geographical and institutional contexts to guarantee sustainable implementation.

3.5.1 Process-specific constraints and economic realities

The production of biodiesel and biogas from fish oil-rich byproducts provides opportunities for renewable energy generation and greenhouse gas reduction. However, economic viability is heavily influenced by factors such as feedstock availability and consistency, energy requirements for lipid extraction and transesterification, and supportive policy mechanisms such as blending mandates [30, 225]. Life cycle assessments indicate that environmental benefits may be minimal or even detrimental when processes depend on fossil-derived energy inputs or employ energy-intensive drying operations [30].

Biomedical-grade collagen, pharmaceutical-grade chitosan, and purified bioactive peptides require rigorous quality control, comprehensive purification, regulatory documentation, and adherence to Good Manufacturing Practices [49, 81, 195]. The outlined requirements increase capital intensity, demand specialized technical expertise, and confine production to facilities equipped with advanced analytical capabilities, thereby restricting access for small and medium enterprises and producers in developing countries [49, 242].

The production of conventional fishmeal and fish oil, although technologically advanced and economically viable, is susceptible to fluctuations in raw material supply, volatility in commodity markets, increasing energy and labor costs, and sustainability issues related to dependence on capture fisheries [157, 218]. The accumulation of contaminants, such as dioxins and polychlorinated biphenyls, in lipid-rich fractions requires decontamination measures or limitations on their use in animal feed, especially for sensitive species [180, 217].

Organic fertilisers derived from fish processing residues offer opportunities for nutrient cycle closure and local agricultural development. However, their adoption is limited by odour emissions, inconsistent nutrient composition compared to synthetic fertilisers, regulatory constraints on pathogen and heavy metal levels, and logistical challenges associated with bulky, low-value products [84].

3.5.2 Systems-level considerations

The selection of valorization pathways is influenced by a variety of technical, economic, and contextual factors, requiring a context-specific assessment that integrates technical performance (yield, purity, functionality), economic indicators (capital costs, revenue potential, payback period), environmental impacts (climate change, eutrophication, resource depletion), and alignment with local capacities and regulatory frameworks [30, 39, 84]. Integrated biorefinery concepts that facilitate the sequential or parallel recovery of multiple value streams are promising for enhancing resource efficiency and economic returns. However, they necessitate advanced process design, meticulous management of quality trade-offs among co-products, and coordination across various end-use sectors [49, 223].

4 Impact of zero-waste utilization

4.1 Environmental impacts

Landfill disposal of solid fish waste contributes to methane and other harmful gas emissions, exacerbating greenhouse gas emissions and contributing to climate change [31, 49]. A crucial aspect is the environmental impact of fish waste on aquatic ecosystems, as the discharge of organic waste can significantly alter the richness, diversity, and community structure of benthic assemblages [229]. Instead of disposing of fish waste, secondary processing and valorisation transform it into high-value goods, including fish meal, fish oil, collagen, enzymes, bioactive peptides, and biopolymers. This methodology supports a circular bioeconomy by recovering resources, minimising environmental degradation, and generating economic benefits [160]. Fish are rich in nitrogen, phosphate, calcium, and micronutrients that plants need for development. Through fermentation or composting, fish waste can be transformed into organic hydrolysate fertilisers that enhance soil health, increase nutrient availability, promote robust crop development, and boost yields. The practice of repurposing materials helps reduce landfill waste and associated adverse environmental effects [247]. An efficient and enhanced approach to waste utilisation is needed to mitigate the environmental impact of fish processing [130].

4.2 Economic impacts

Inadequate fish waste management not only causes pollution but also represents a lost economic opportunity [17]. Numerous studies suggest that the valorisation process can be economically viable, contingent upon achieving specific technical benchmarks. For instance, anaerobic digestion for biogas production is financially feasible only if the methane output surpasses 0.34 L per kg of volatile solids and the methane price exceeds 0.17 EUR/kWh [116]. These benchmarks highlight the need to enhance processing technology to ensure economic viability. Moreover, advancements in biorefinery and integrated waste management have allowed the upcycling of fish waste into biodiesel, a sustainable energy alternative, hence broadening the product line and augmenting profitability [100].

4.3 Industrial impacts

A zero-waste strategy for fish byproducts offers substantial economic and industrial benefits through optimised resource allocation and creation of new revenue streams [39]. Industries can generate high-value products, including fishmeal, collagen, omega-3 supplements, and bioactive peptides, by utilising fish heads, bones, skins, and offal, which are commonly regarded as waste. This approach reduces disposal expenses while generating supplementary revenue from formerly regarded as waste [175]. Furthermore, transforming byproducts into fertilisers, animal feed, or biodegradable materials promotes circular economic principles, reducing environmental impact and lowering raw material costs. Implementing zero-waste principles in fish processing enhances profitability, alleviates waste management challenges, and fosters sustained industrial development [144].

4.4 Social and health impacts

A waste-minimising approach to utilising fish byproducts offers significant social and health benefits. This approach utilises fish skins, bones, and offal for culinary, supplementary, or industrial purposes, thereby minimising waste and promoting sustainable resource utilisation. Fish byproducts are rich in protein, omega-3 fatty acids, and collagen, which can enhance food security and improve public health when incorporated into the diet [156]. It socially benefits fishing communities by generating additional revenue streams and job opportunities in the byproduct processing sectors. Furthermore, reducing fish waste mitigates environmental contamination, resulting in healthier ecosystems and reduced health hazards from contaminated water or soil. A zero-waste approach for fish byproducts enhances economic stability, improves nutritional outcomes, and promotes environmental sustainability, ultimately increasing both societal and individual welfare [145].

4.5 Sanitary and regulatory constraints

The extensive valorisation of fish processing byproducts is significantly constrained by interconnected sanitary regulations and diverse regulatory frameworks that differ markedly across jurisdictions, thereby posing considerable obstacles to industrial-scale up and commercialisation.

4.5.1 Microbiological and chemical safety barriers

The characteristics of fish processing byproducts, such as high moisture content (65–80%), elevated pH, abundant amino acids and lipids, and active endogenous enzyme systems, foster an environment that promotes rapid microbial growth, including spoilage organisms and potential pathogens like *Salmonella*, *Listeria monocytogenes*, *Vibrio* species, and parasites [6, 191, 205, 234]. In the absence of prompt processing or adequate preservation methods (such as refrigeration, freezing, acidification, or enzymatic stabilization), microbiological degradation makes materials unfit for high-value uses and presents food safety hazards when employed in animal feed or organic fertilizers [73, 94, 150]. The implementation of comprehensive Hazard Analysis and Critical Control Points systems, the maintenance of unbroken cold chains, the design of hygienic equipment, and the establishment of robust traceability systems are essential prerequisites for safe valorisation. However, these measures impose significant technical and financial burdens, particularly for small-scale operations [28, 39, 157].

The bioaccumulation of persistent environmental contaminants in fish tissues, such as heavy metals (mercury, cadmium, lead, arsenic), persistent organic pollutants (dioxins, polychlorinated biphenyls, polybrominated diphenyl ethers), and emerging contaminants (microplastics, pharmaceutical residues), raises significant safety concerns that necessitate thorough monitoring, risk assessment, and potentially expensive purification processes [16, 81, 231]. Contaminant concentrations differ significantly across species, trophic level, age, habitat characteristics, and geographical location, requiring the implementation of raw material segregation strategies and analytical screening protocols to maintain regulatory compliance [231].

4.5.2 Regulatory heterogeneity and market access barriers

The legal and regulatory frameworks governing fish processing byproducts vary significantly across jurisdictions, leading to uncertainty and transaction costs that hinder the scaling up and commercialization of valorisation efforts. Definitional inconsistencies fundamentally differentiate "waste," which is subject to disposal regulations and restricted use, from "byproduct" which is eligible for value-added applications. Classification criteria for these terms vary across countries and agencies [40]. The European Union Animal By-Products Regulation (EC 1069/2009) delineates hierarchical categories (Category 1, 2, and 3 materials) that specify distinct processing requirements and allowable uses, in contrast to other regions that utilize varying classification systems or lack clear regulatory frameworks [40, 134].

Maximum residue limits for contaminants, microbiological criteria, processing validation requirements (time-temperature profiles for pathogen reduction), and labelling regulations differ significantly among markets. This variation leads to expensive analytical testing, extensive documentation, and the possibility of product reformulation to achieve compliance across multiple markets [49, 123, 192]. Regulations on novel foods and feeds introduce significant administrative and financial challenges for ingredients without established use histories. These requirements include comprehensive safety dossiers, toxicological studies, and pre-market authorisation processes that can span several years, incurring costs ranging from hundreds of thousands to millions of dollars [49, 159].

International harmonisation initiatives that adhere to Codex Alimentarius principles, along with bilateral and multilateral mutual recognition agreements and regional regulatory convergence efforts such as the European Union single-market frameworks, have the potential to reduce compliance costs and enhance trade in fish-derived ingredients significantly [40, 159]. Creating transparent, science-based, risk-proportionate guidance documents for byproduct handling, processing, and acceptable uses would mitigate regulatory uncertainty and promote investment in valorisation technologies [40, 223].

5 Technological and scientific advancements

The zero-waste strategy for fish byproducts utilises technological and scientific innovations to optimise resource efficiency and minimise environmental impact. Current methodologies, such as the use of specialised enzymes and biorefinery systems, enable the conversion of fish waste into valuable products, including protein, collagen, omega-3 fatty acids, and fertilisers. Advanced extraction techniques, such as supercritical fluid extraction and ultrasound-assisted extraction, increase yield and purity while minimising energy consumption. Biotechnology plays a crucial role in microbial fermentation, transforming waste into biofuels, biodegradable polymers, and bioactive substances. Automation and artificial intelligence enhance sorting and processing, increasing efficiency and minimising waste [25]. Moreover, life cycle assessment (LCA) tools facilitate sustainability evaluation, ensuring environmentally responsible operations. These developments promote a circular economy and generate new revenue streams, thereby enhancing the sustainability and economic viability of the fishing industry [227].

6 Policy and regulatory relevance

Implementing a zero-waste strategy for fish byproducts is crucial for effective policy and regulation, as it promotes sustainable resource use, mitigates environmental degradation, and reinforces the principles of a circular economy. Governmental bodies and regulatory agencies can promote waste valorisation by offering subsidies and tax incentives, as well as by enforcing strict waste-disposal regulations, to reduce landfill use and marine contamination [66]. Policies that require converting byproducts into high-value products (e.g., fishmeal, collagen, or biofuels) can increase food security, mitigate overfishing, and reduce carbon emissions. International frameworks, such as the FAO's Code of Conduct for Responsible Fisheries, can incorporate zero-waste methods to match global sustainability objectives, including the UN SDGs [64]. Enhancing compliance through monitoring and certification programs ensures industry responsibility while fostering innovation in waste-to-wealth technology. These regulatory measures not only reduce ecological damage but also improve economic resilience in the fishing sector.

7 Future perspectives

The sustainable valorisation of fish processing byproducts within circular bioeconomy frameworks is a crucial intersection of environmental stewardship, economic innovation, and food security. Despite considerable advancements in extraction technologies and the conceptualization of biorefineries, notable knowledge gaps and implementation challenges persist across technical, economic, regulatory, and socio-institutional domains [40, 80, 157].

7.1 Research gaps and priority development pathways

Current valorisation methods are limited by a lack of standardised processing protocols, especially given the variability in composition across heterogeneous raw material sources, seasonal changes in biochemical profiles, and differing handling practices across supply chains [8, 94, 203]. The establishment of harmonised methodologies for byproduct classification, quality assessment, and functional characterisation is crucial to ensuring product consistency, facilitating regulatory approval pathways, and enabling market development for high-value applications in the pharmaceutical, nutraceutical, and biomedical sectors [49].

Advanced green extraction technologies, such as ultrasound-assisted extraction, microwave-assisted processing, enzymatic hydrolysis, supercritical fluid extraction, and pulsed electric field treatment, exhibit superior recovery efficiencies, improved product functionality, and diminished environmental impacts relative to traditional chemical-intensive methods [106, 182]. Nonetheless, their industrial application is constrained by substantial capital investment needs, increased operational complexity, uncertainties in scaling, and a lack of comprehensive techno-economic evaluations across various geographical and institutional settings [157, 193, 223]. Future research should focus on comprehensive life-cycle assessments and techno-economic analyses that combine environmental impact quantification with economic viability metrics across scales ranging from artisanal community-based facilities to industrial biorefinery complexes [30, 223].

7.2 Technological innovation requirements

The advancement of cost-effective, rapid analytical techniques for real-time quality monitoring and traceability systems is essential for adequate byproduct segregation and value chain optimisation [40, 150]. Emerging technologies, including near-infrared spectroscopy, hyperspectral imaging, electronic nose sensors, and blockchain-enabled traceability platforms, require systematic evaluation regarding their applicability in resource-constrained environments typical of small-scale fisheries and developing economies [180, 217].

Digital transformation via artificial intelligence-driven process control, machine learning-based predictive modeling for extraction optimization, and Internet-of-Things integration for supply chain management can significantly improve operational efficiency and product quality consistency [8, 35]. Technological solutions should be scaled and adapted to local contexts, avoiding uniform approaches that fail to account for infrastructure limitations, capacity constraints, and socio-economic realities [157, 223].

7.3 Economic and market development challenges

The market development of ingredients derived from fish byproducts faces significant challenges, including consumer skepticism, limited awareness of functional benefits, competition from established terrestrial alternatives, and price sensitivity in commodity applications [49, 194]. Differentiation strategies that highlight enhanced sustainability profiles, hypoallergenic properties, the lack of zoonotic disease risks, and distinctive functional characteristics can support premium positioning within specialized market segments [81, 226].

The economic feasibility of valorisation initiatives depends on achieving adequate economies of scale, ensuring a stable supply of raw materials, effectively managing logistics and cold-chain requirements, and successfully navigating regulatory approval processes [30, 205]. Cooperative processing models, shared infrastructure facilities, and public-private partnerships can address investment barriers that significantly affect small and medium enterprises and artisanal fishing communities [40, 80, 157].

7.4 Sustainability assessment and circular economy integration

A comprehensive sustainability assessment should extend beyond limited technical efficiency metrics to include environmental, economic, and social dimensions throughout entire value chains. Rebound effects, burden shifting among impact categories, and unintended consequences such as competition with direct human food applications or increased pressure on wild fish stocks, necessitate thorough evaluation using system-level analytical frameworks [30, 223]. Participatory approaches that engage fishing communities, processors, retailers, consumers, and civil society organisations are crucial for ensuring that valorisation strategies effectively promote inclusive and equitable development outcomes while also honouring cultural values and traditional knowledge systems [39, 40, 157].

8 Conclusion

Fish processing produces significant organic byproducts, accounting for 30–70% of the total captured biomass. The transformation of these byproducts into high-value compounds is essential for shifting from linear waste disposal to circular bioeconomic systems. The strategic valorisation of integumentary, skeletal, visceral, and crustacean-derived materials via advanced extraction technologies produces bioactive compounds, biomaterials, and biofuels applicable in biomedical, nutraceutical, cosmetic, feed, and energy sectors, while promoting environmental sustainability, economic resilience, and global food security goals. The realisation of this potential on an industrial scale is limited by the heterogeneity of raw material composition, rapid perishability dynamics, the high energy intensity of processes, significant capital requirements, and varying regulatory frameworks across jurisdictions. Integrated biorefinery architectures that combine green extraction methods with comprehensive life-cycle and techno-economic assessments offer promising avenues for enhanced resource efficiency and greater economic viability. Achieving this vision necessitates coordinated progress across three interrelated areas: standardized regulatory frameworks that promote innovation while safeguarding product safety; specific policy tools such as green procurement mandates and focused investment incentives; and tailored technology configurations that reconcile high-value niche applications with large-volume commodity markets suitable for various geographical and institutional contexts. The preceding section on future perspectives outlines research priorities and strategic development pathways to address these complex challenges.

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