Review article
Journal of Central European Agriculture, 2025, 26(4), p.887-904
DOI: /10.5513/JCEA01/26.4.4799

Global approaches to the utilisation of discards from marine fisheries and aquaculture side streams: insights from Croatia

Globalni pristupi iskorištavanju nusproizvoda morskog ribarstva i akvakulture: uvidi iz Hrvatske

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Received: April 2, 2025; accepted: November 10, 2025

ABSTRACT

This paper explores the potential of side streams from aquaculture processing and the processing of landed discards from capture fisheries as valuable resources for various applications, including human consumption, animal feed and the production of high-value bioactive compounds. Effective utilisation of these side streams can improve sustainability by reducing waste and increasing resource efficiency in the fisheries and aquaculture sector. Marine aquaculture and capture fisheries are important components of Croatia's maritime economy and play a crucial role in seafood production and the country's economic development. The challenges associated with the processing and utilisation of these resources in Croatia have increased in complexity due to biological, technical and operational factors. The study provides an overview of the opportunities and obstacles in the global utilisation of marine side streams and uses findings from Croatia.

Keywords: by-product valorisation, circular bioeconomy, added value, landing obligations, natural resources

SAŽETAK

Rad istražuje potencijal nusproizvoda iz prerade u akvakulturi i iskrcanog odbačenog ulova ribolova kao vrijednih resursa za različite primjene, uključujući ljudsku potrošnju, stočnu hranu i proizvodnju visokovrijednih bioaktivnih spojeva. Učinkovito korištenje ovih nusproizvoda može poboljšati održivost smanjenjem otpada i povećanjem učinkovitosti resursa u sektoru ribarstva i akvakulture. Marikultura i ribolov važna su komponenta hrvatskog pomorskog gospodarstva i imaju ključnu ulogu u proizvodnji morskih plodova i gospodarskom razvoju zemlje. Složenost izazova, povezanih s preradom i korištenjem ovih resursa u Hrvatskoj, povećana je zbog bioloških, tehničkih i operativnih čimbenika. Studija pruža pregled mogućnosti i prepreka u globalnom korištenju morskih nusproizvoda, a koristi i uvide iz Hrvatske.

Ključne riječi: valorizacija nusproizvoda, kružna bioekonomija, dodana vrijednost, obveza iskrcaja, prirodni resursi

INTRODUCTION

The world population is growing by 80 million every year and is expected to reach 9 billion people by 2050. To meet food demand, global production must increase by 70 % (Ytrestøyl et al., 2015). While aquaculture has grown rapidly since the 1950s, capture fisheries have reached a plateau since the 1990s. In 2020, 90.3 million tonnes were caught in capture fisheries — a decrease of 4.0 % compared to the previous three-year average (FAO, 2022). Over 2,600 species are recorded in the FAO database, with fish accounting for around 85 % of marine catches, primarily small pelagic species, gadiformes and tuna (FAO, 2022). In 2016, aquaculture overtook capture fisheries in the supply of aquatic animals for consumption, reaching 52% in 2018 (FAO, 2020). FAO estimates of global capture fisheries production are widely used as benchmarks, yet their accuracy remains debated — especially in regions like the Mediterranean where small-scale and mixed-species fisheries are often underreported and where monitoring is limited (Milisenda et al., 2017; Gilman et al., 2020). This implies Croatian figures and reports may also be underestimated. Like other industries, aquaculture has an impact on the environment, which is why EU policy aims to sustainably increase production and diversity (EU Communication, 2021). In aquaculture, between 20 and 60 % of the raw material is discarded (Ferraro et al., 2010), with over 20 MT of side streams such as heads, skins, fins, bones and viscera. Reported discard rates in aquaculture vary widely which reflecting differences in species, product forms, and processing technologies. Within this global range, the Croatian aquaculture sector likely lies toward the upper end because of its species structure and processing patterns. Seabass and seabream dominate production (over 80 % of marine aquaculture output; STECF 2021) and automated filleting of these species in Croatian fish processing plants can generate over 45% by-product mass (Malcorps et al., 2021), whereas sardine canning yields less than 20%. Conversely, sardine and anchovy canning retain most of the biomass, producing less than 20 % residue (Soldo et al., 2019). These differences highlight that national strategies for by-product utilisation must be species-specific rather than based on global averages. In 2018, 88% of the 179 million tons of fish production was destined for direct consumption, the rest for non-food purposes (FAO, 2020). According to EC regulation (European Commission, 2002), animal by-products are not intended for human consumption, although marine by-products intended for food are excluded. The terminology includes waste, side streams, and by-products - rest raw materials. The term – waste - carries a regulatory connotation of materials destined for disposal. "Side streams" refers to all materials generated from marine fisheries and aquaculture that are not the primary, intended product. It includes both discards from capture fisheries and processing residues. By-products and rest raw materials originate from non-target species or from species that are not present in sufficient quantity, and arise from processing residues such as fish trimmings, bones and skins originate from fish processing (Rustad et al., 2011; Coppola et al., 2021). Unselective fishing and bycatch have become a global problem influenced by biological, technical and socio-economic factors (Arvanitoyannis and Kassaveti, 2008), with ~ 10 million metric tons discarded annually (Gilman et al., 2020). There is increasing interest in the conversion of by-products into valuable raw materials. Advances in fish protein and oil research are enabling conversion into high-value products that often exceed the value of fish fillets (Rustad et al., 2011). These materials are now used in animal feed, packaging, silage, fertilizers, biofuels and for human consumption (Arvanitoyannis and Kassaveti, 2008). About 25–35% of the side streams are processed into fishmeal and oil (FAO, 2020). However, their use in food raises concerns about safety, interactions with nutrients and processing methods. Critical issues include pre-treatment, extraction, bioavailability, ingredient compatibility, sensory properties and safety (Nawaz et al., 2020). In Croatia, marine aquaculture and capture fisheries contribute significantly to seafood production and economic growth. In 2022, Croatian marine aquaculture produced 23,101 tons of fish and shellfish. Concurrently, capture fisheries totaled approximately 63,000 tons, with small pelagics accounting for 90% of the volume. Based on standard industrial practices, an estimated 20% processing residue is generated from the capture fisheries and aquaculture production volume, yielding around 17,000 tons of valuable side streams annually. (Croatian Bureau of Statistics, 2022; Eurofish International Organization, 2022). However, the efficient and comprehensive valorisation of these substantial side streams requires a significant commitment, necessitating highly skilled personnel, advanced processing equipment, and compliant facilities. Consequently, investment in biorefining and automation is essential to ensure their efficient and sustainable utilisation. The utilisation and processing of side streams face growing challenges due to various biological and technical factors. This study examines the potential for valorisation of residues and side streams into high-value products, with a focus on Croatian practices. Effective management of side streams can reduce waste, increase profitability and support circular economy goals —sustainably strengthening the Croatian fisheries sector. For this review, the databases Web of Science, Scopus, and FAO publications from 2000 to 2023 were searched using keywords such as 'fish discards', 'aquaculture side streams', 'by-product valorisation', and 'Croatia fisheries'. Sources were included if they reported quantitative data on by-products, valorisation technologies, or economic aspects in the Mediterranean. Publications without primary data or lacking a focus on marine resources were excluded.

PROCESSING OF AQUACULTURE SIDE STREAMS AND LANDED DISCARDS FROM CAPTURE FISHERIES

Landing obligation

The term "discard" specifically refers to the portion of a capture fisheries catch that is unwanted and thrown back into the sea (alive or dead). It has a specific regulatory meaning under the EU's Common Fisheries Policy and the Landing Obligation. Discards in EU fisheries amount to more than 5 million tons/year (Pérez Roda et al., 2019). Discards vary in the Mediterranean, with bottom trawls responsible for the majority (Milisenda et al., 2017). Reasons include undersized fish, lack of quota, low market value, damage or illegality of the catch (European Commission, 2023). Discards valuable resources, damages marine ecosystems, undermines the sustainability of fisheries and raises ethical questions. They alter ecosystems by affecting scavenging behaviour, competition and community composition (Hall et al., 2000). Vulnerable bycatch species with slow reproduction are particularly affected (Gray and Kennelly, 2018). Reducing discards is a key concern of the EU Common Fisheries Policy (European Commission, 2021) and is considered essential for the long-term viability of the fleet and better resource utilisation (Gullestad et al., 2015). The 2015 landing obligation, which will be fully implemented in 2019, stipulates that all regulated species must be landed and counted against quotas. Undersized fish may not be sold for human consumption but must be used in products such as animal feed or pharmaceuticals. Producer organisations and EU countries are obliged to facilitate storage and find outlets that are not intended for human consumption. Joint efforts by EU institutions, non-governmental organisations, scientists, and the EFCA have improved understanding and led to tools such as the Northwest Waters Advisory Council's Choke Mitigation System (European Commission, 2023). Discard rates vary by gear —from 1 % for traps and longlines to 25–34 % for trawls; discard rates are lower for larger meshes (10–15 %) than for smaller meshes (50 %+) (Villasante et al., 2015). Croatia enforces spatial and temporal fishing regulations for purse seine nets (*srdelara*), electronically logs the discards of the entire PS fleet and warns vessels that exceed 5 % discards (Ares, 2017). However, evidence from Mediterranean fisheries suggests that compliance with the EU Landing Obligation remains problematic. STECF (2019) and Milisenda et al. (2017) reported discard rates of 25–35 % in comparable trawl fisheries, indicating that electronic reporting alone may underestimate actual discards. Croatian enforcement relies heavily on self-reporting, and limited port reception capacity constrains full landing of unwanted catches. This implies that official discard statistics may not reflect the real magnitude of potential by-product flows. There are still challenges such as limited use of selective fishing gear, poor handling, storage and processing, and lack of funds for equipment modernisation. Monitoring and compliance issues persist, compounded by insufficient awareness (STECF, 2019). Ports face logistical challenges in handling landings under the new regulations, especially those not intended for human consumption. Large Croatian ports such as Zadar, Split and Rijeka play a central role in this, but smaller ports can also handle significant quantities. The infrastructure for the collection of shellfish by-products is still underdeveloped (Hedley et al., 2015). The landing obligation represents a major shift, requiring investment in new businesses, cold storage and transportation infrastructure, and reward systems for selective fishing. Discard rates vary by year, depth and location. In the deep-sea rose shrimp fisheries, discards amounted to 32.9±15.4 % of the catch, mainly due to undersized species such as hake and *Trachurus* spp., which are covered by the discard ban (Milisenda et al., 2017; EU Regulation No. 1380/2013, 2013). Croatia has 118 designated commercial fishing ports (Official Newspaper, 2023). Table 1 contains the landing and discard data for 2022 for the 10 most important Croatian trawl ports.

The aspect of circular bioeconomy and sustainability

Recycling discarded marine materials supports a circular bioeconomy by transforming low-value residues into high-value products. In practice, circular-bioeconomy implementation in Croatia faces infrastructural and economic barriers like those observed in other Mediterranean states (Malcorps et al., 2021). High transport costs for low-volume by-products and the absence of regional collection centres limit economies of scale. While northern countries such as Norway integrate by-product valorisation into the primary processing chain, Croatian facilities usually sell side streams to foreign processors or divert them to low-value pet-food markets. Public–private cooperation, as promoted in Portugal's BlueBio initiatives (CIIMAR, 2019), could provide a model for overcoming these constraints.

Valuable compounds such as collagen, gelatin, omega-3s, functional proteins, and enzymes are extracted for use in nutraceuticals, pharmaceuticals, and cosmetics. These practices improve resource efficiency, reduce waste, support local economies, and enhance sustainability (Coppola et al., 2021). The circular bioeconomy—a growing concept—emphasises optimal use of biological resources and infrastructure to improve quality of life. Addressing global fish waste and utilising side streams for value-added production are key to this model, which promotes reuse and recycling to minimise waste (Coppola et al., 2021).

The European Commission (2018) defines the bioeconomy as the production and conversion of renewable biological resources and waste into food, feed, bio-based products, and energy—reducing reliance on fossil resources and limiting environmental impact. The "blue economy" further extends this by advocating sustainable marine resource use. With limited arable land, oceans are viewed as vital for resource sourcing (Choudhary et al., 2021). Consequently, fisheries and aquaculture are projected to exceed 200 million tons by 2030 (Summa et al., 2022).

However, the seafood sector lags behind land-based industries in reducing discards. Progress requires investment in infrastructure, policies for resource efficiency, and greater transparency in by-product use (FAO, 2016). Aquaculture faces narrow margins, making by-product utilisation essential for long-term viability (Stevens et al., 2018). European aquaculture heavily relies on imported ingredients like fishmeal, fish oil, and soy (Newton and Little, 2018), making it vulnerable to economic shocks and environmental criticisms (Troell et al., 2014). Feed production accounts for most environmental impacts in aquaculture (Bohnes et al., 2018), and continued dependence on fish-based feeds raises sustainability concerns (Naylor et al., 2021). Side streams across Europe remain underused (Newton and Jackson, 2016). Increased processing for convenience generates significant side streams (Shavandi et al., 2018). Croatia has recognised this and invested in the processing of high-value-added species to increase efficiency and diversify production (STECF, 2021).

Table 1. Top 10 Croatian trawl landing sites (by landing volume) in 2022 – Commercial landings and estimated discard (Ministry of Agriculture, Directorate of Fisheries, 2023)

Landing site	Commercial landings (kg)/(%per species)	Estimated landing discard kg*
TRIBUNJ	492,267.37	172,293.58
Deep water rose shrimp - *Parapenaeus longirostris*	34.36%	
European hake - *Merluccius merluccius*	26.87%	
Red mullet - *Mullus barbatus*	10.09%	
Norway lobster - *Nephrops norvegicus*	9.15%	
European flying squid & similar - *Todarodes sagittatus*	4.12%	
Other	15.41%	
ROGOZNICA	420,687.05	147,240.47
Deep water rose shrimp - *Parapenaeus longirostris*	35.83%	
European hake - *Merluccius merluccius*	25.47%	
Red mullet - *Mullus barbatus*	8.60%	
Whiting - *Merlangius merlangus*	5.68%	
Norway lobster - *Nephrops norvegicus*	5.51%	
Other	18.91%	
HVAR - VIRA	315,788.65	110,526.03
Red mullet - *Mullus barbatus*	45.28%	
European hake - *Merluccius merluccius*	33.37%	
Deep water rose shrimp - *Parapenaeus longirostris*	8.00%	
Common Pandora - *Pagellus erythrinus*	3.69%	
Angler fish and similars - *Lophius piscatorius*	2.03%	
Other	7.63%	
PRIMOŠTEN	188,870.30	66,104.61
Deep water rose shrimp - *Parapenaeus longirostris*	33.53%	
European hake - *Merluccius merluccius*	29.28%	
Norway lobster - *Nephrops norvegicus*	9.10%	
Red mullet - *Mullus barbatus*	8.98%	
European flying squid & similar - *Todarodes sagittatus*	3.77%	
Other	15.35%	

Continued. Table 1.

Landing site	Commercial landings (kg)/(%per species)	Estimated landing discard kg*
VELA LUKA	135,634.00	47,471.90
Deep water rose shrimp - *Parapenaeus longirostris*	50.59%	
European hake - *Merluccius merluccius*	20.50%	
Red mullet - *Mullus barbatus*	7.50%	
Norway lobster - *Nephrops norvegicus*	3.78%	
Angler fish and similars - *Lophius piscatorius*	3.17%	
Other	14.46%	
MURTER	113,971.81	39,890.13
European hake - *Merluccius merluccius*	45.58%	
Red mullet - *Mullus barbatus*	17.61%	
Deep water rose shrimp - *Parapenaeus longirostris*	14.17%	
European flying squid & similar - *Todarodes sagittatus*	4.13%	
Whiting - *Merlangius merlangus*	2.73%	
Other	15.78%	
DUBROVNIK - GRUŽ	104,331.46	36,516.01
Deep water rose shrimp - *Parapenaeus longirostris*	39.34%	
European hake - *Merluccius merluccius*	23.33%	
European flying squid & similar - *Todarodes sagittatus*	6.05%	
Red mullet - *Mullus barbatus*	5.13%	
Angler fish and similars - *Lophius piscatorius*	4.67%	
Other	21.47%	
KOMIŽA	92,230.30	32,280.61
Deep water rose shrimp - *Parapenaeus longirostris*	37.83%	
European hake - *Merluccius merluccius*	21.09%	
Norway lobster - *Nephrops norvegicus*	13.75%	
Red mullet - *Mullus barbatus*	5.87%	
Spotted flounder - *Citharus linguatula*	3.98%	
Other	17.48%	

Continued. Table 1.

Landing site	Commercial landings (kg)/(%per species)	Estimated landing discard kg*
OREBIĆ	89,462.36	31,311.83
Deep water rose shrimp - *Parapenaeus longirostris*	25.85%	
European hake - *Merluccius merluccius*	23.87%	
Red mullet - *Mullus barbatus*	12.11%	
Skate family - *Rajidae*	10.38%	
Angler fish and similar - *Lophius piscatorius*	4.75%	
Other	23.03%	
MALI LOŠINJ	79,397.55	27,789.14
Red mullet - *Mullus barbatus*	28.86%	
Musky octopus - *Eledone moschata*	10.86%	
European squid - *Loligo vulgaris*	9.46%	
European hake - *Merluccius merluccius*	8.61%	
Surmullet - *Mullus surmuletus*	5.16%	
Other	37.05%	
Total commercial landings	2 032,640.85	
Total estimated discard		711,424.30

* Based on (Milisenda et al., 2017), 35% of commercial landings were calculated for the estimation of landing discard

Utilising aquaculture by-products enhances both environmental and economic performance and contributes to food security (Newton et al., 2014; Ytrestøyl et al., 2015).

Fish processing

Fish processing involves multiple steps—stunning, sorting, gutting, de-boning—which generate 20–80% of the biomass being discarded or repurposed, depending on species and processing level (Ghaly et al., 2013). Large facilities process fish to reduce transport costs of inedible parts and ensure product safety by removing components prone to spoilage (Shavandi et al., 2018). Processing side streams presents technical and environmental challenges due to high microbial activity and rapid degradation. Prompt collection and processing are vital. Developing new products from side streams offers opportunities to add value, minimise loss, and deliver nutritious, long-shelf-life foods (FAO, 2022). Under EU regulation, such remains are Category 3 by-products—fit for consumption but not intended as food (European Commission, 2009). Transforming them into edible products requires adherence to GMP and HACCP systems, but this is often limited by facility, equipment, or labor constraints (Olsen et al., 2014).

ORIGIN AND STRUCTURE OF SIDE TREAMS

The amount of biomass being discarded from capture fisheries varies depending on the species and product. The majority of side streams are generated on land, while at-sea processing typically involves discarding entrails and heads overboard. Depending on the final product, land-based processing generates biomass such as fillets, heads, skin and bones (Karadeniz and Kim, 2014). Discards pose a problem for management and the environment, necessitating research into valorisation options. The conversion of side streams into economic resources through new technologies contributes to the reduction of discards (European Parliament, 2004). Aquaculture by-products include low-grade whole fish, skeletons, skin, viscera and shells. Common by-products include heads (9–12 %), viscera (12–18 %), bones (9–15 %), skin (1–3 %) and scales (5 %) (FAO, 2022). Newton et al. (2014) report that fish by-products typically contain 21 % head, 5 % liver, 4 % roe, 14 % backbone and 17 % fins, guts and gills. These figures vary by species, size and season (Stevens et al., 2018) (Figure 1).

For shellfish, by-products can account for up to 60 % of the total catch weight (Hou et al., 2016). Croatia produces side streams from aquaculture, capture fisheries and the other fishing industry. These include discarded whole fish, heads, bones, entrails and skin from cutting and filleting. They are rich in bioactive compounds such as proteins, omega-3 fatty acids, enzymes and minerals (Alverson et al., 1994). Their organic content is the key to unlocking their full value. Fish by-products are of increasing importance for food, biotechnology and pharmaceuticals due to their content of collagen, peptides, PUFAs and micronutrients such as vitamins A, D, riboflavin and minerals (Olsen et al., 2014; Kelleher, 2005; Ferraro et al., 2010; Coppola et al., 2021). Although global estimates provide general proportions of fish by-products, the chemical composition varies considerably among species common to the Adriatic. Sardine and anchovy heads, for example, contain elevated lipid levels (up to 15%), making them suitable for omega-3 oil extraction. Notably, by-products from aquacultured seabass and seabream—particularly their viscera and trimmings—also exhibit high lipid content, alongside valuable enzymes and collagen precursors. Identifying which anatomical fractions offer the greatest recovery potential for each species is essential for designing cost-effective valorisation chains in Croatia.

Traditional methods of discarded biomass management include landfilling, animal feed, and the use of fertilisers. However, landfilling causes environmental problems such as odour nuisance, pollution and ecosystem disruption. Strict regulations apply due to the high organic and mineral content. Various processing technologies — mechanical, biotechnological, ultrasonic

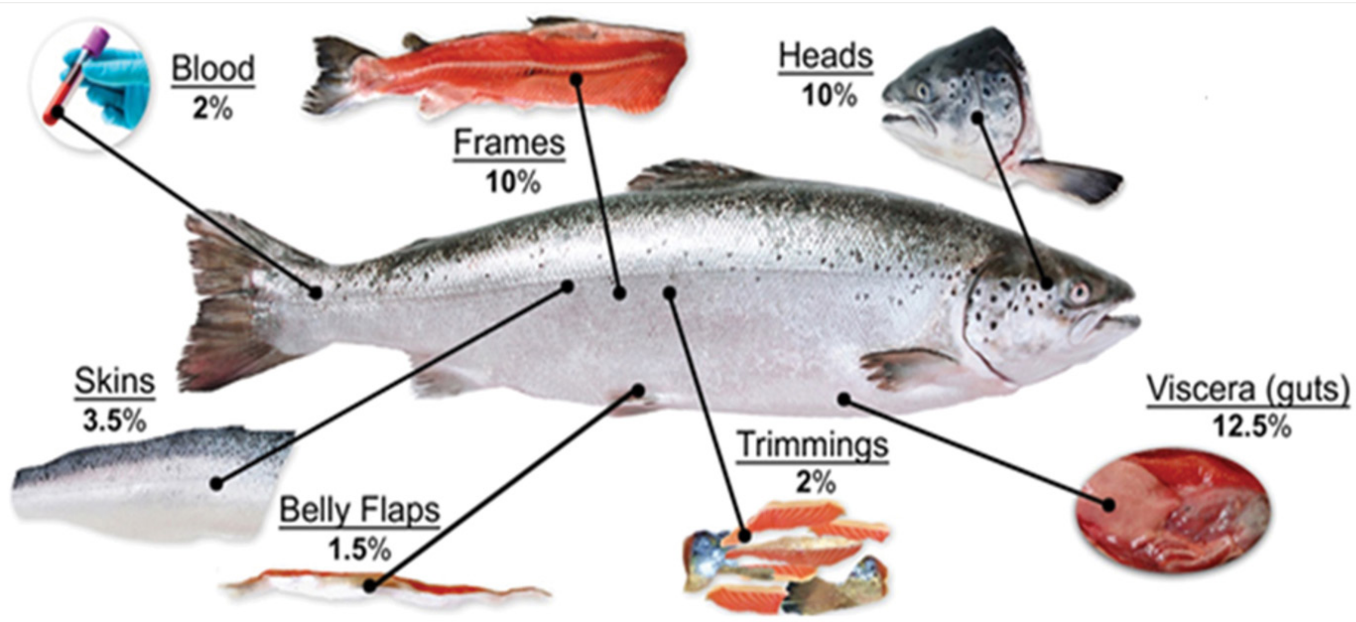

Figure 1. Atlantic salmon by-products (as a % of total wet weight) (Stevens et al., 2018)

and microwave processes — help to convert these side streams into products suitable for humans and animals (Saleh et al., 2021). The extraction of proteins, bioactive peptides, collagen, enzymes and oils from side streams offers considerable potential. In addition, lipids, calcium, glucosamine and chitosan from crustacean shells offer immense value for the development of high-quality products (STECF, 2021).

Protein is the most important component of these side streams, followed by lipids and minerals. A major advantage is that proteins obtained from animals generally have a higher nutritional value than plant proteins. Among them, fish proteins are in most cases more interesting than animal proteins (Friedman, 1996), because fish proteins are particularly rich in the essential amino acids valine and lysine (Ross et al., 2017). Malcorps et al. (2021) examined the nutritional composition of common processing by-products (heads, frames, trimmings, skin, and guts) from five key fish species farmed in Europe: Atlantic salmon (*Salmo salar*), European seabass (*Dicentrarchus labrax*), gilthead sea bream (*Sparus aurata*), common carp (*Cyprinus carpio*), and turbot (*Scophthalmus maximus*) (Figure 3).

They found that fully processing the fish, rather than just filleting it, significantly increases the total meat yield (64–77% compared to 30–56%). Additionally, by-products such as heads, frames, trimmings, and skin from species like Atlantic salmon, European seabass, gilthead sea bream, and turbot showed medium to high edible yields, fat content, and levels of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), highlighting their potential for direct human consumption. By-products less suitable for food use, like viscera, which had low ash content but medium to high levels of crude protein, lipids, and EPA and DHA, could be utilised in animal feed. While fish skin holds interesting nutritional value, its greatest potential lies in non-food sectors, such as fashion, cosmetics, and pharmaceuticals. For example, fish skin can be turned into exotic leather for accessories like bags, gloves, or shoes. The leather-making process involves tanning, which alters the skin's protein structure to create a durable and flexible material (Saranya et al., 2020). Malcorps et al. (2021) also emphasised the opportunity to enhance the food, feed, and non-food value of European aquaculture without needing to increase production or resources.

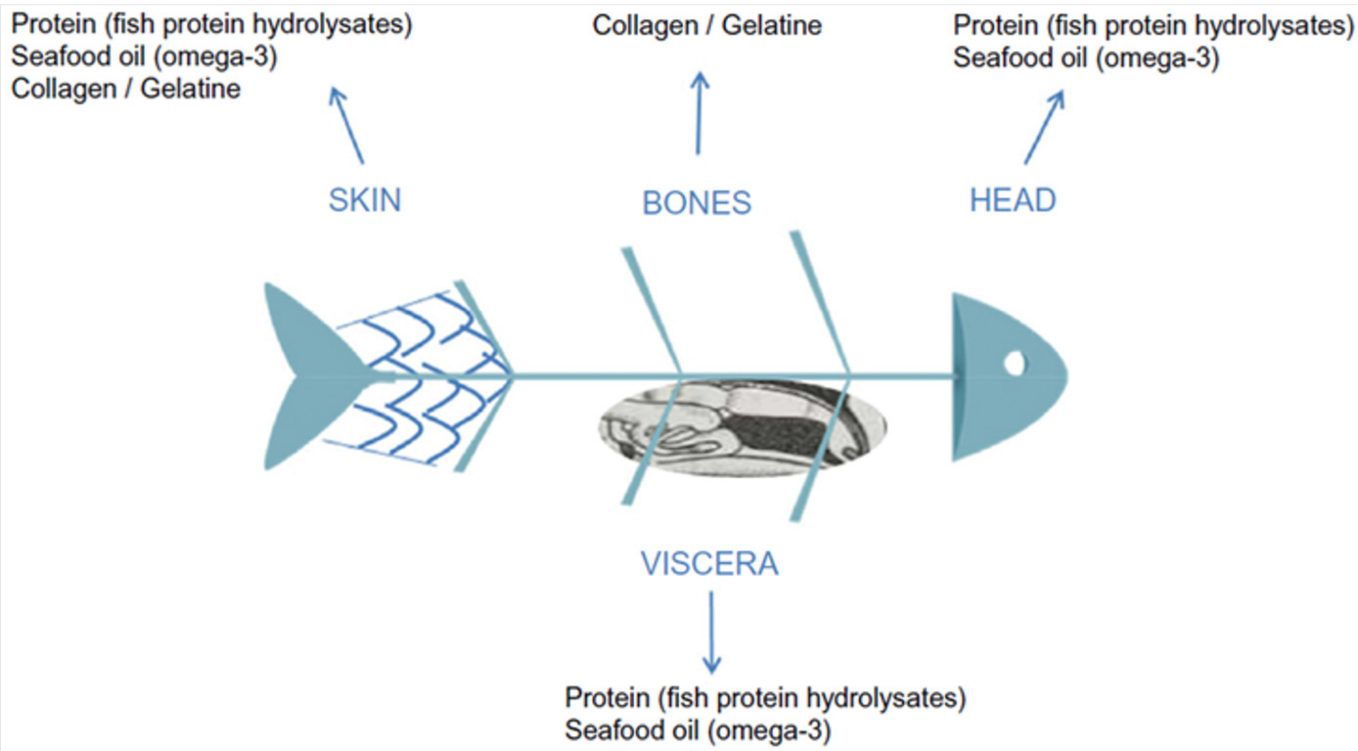

Figure 2. Scheme of main by-products from fish processing (López-Pedrouso et al., 2020)

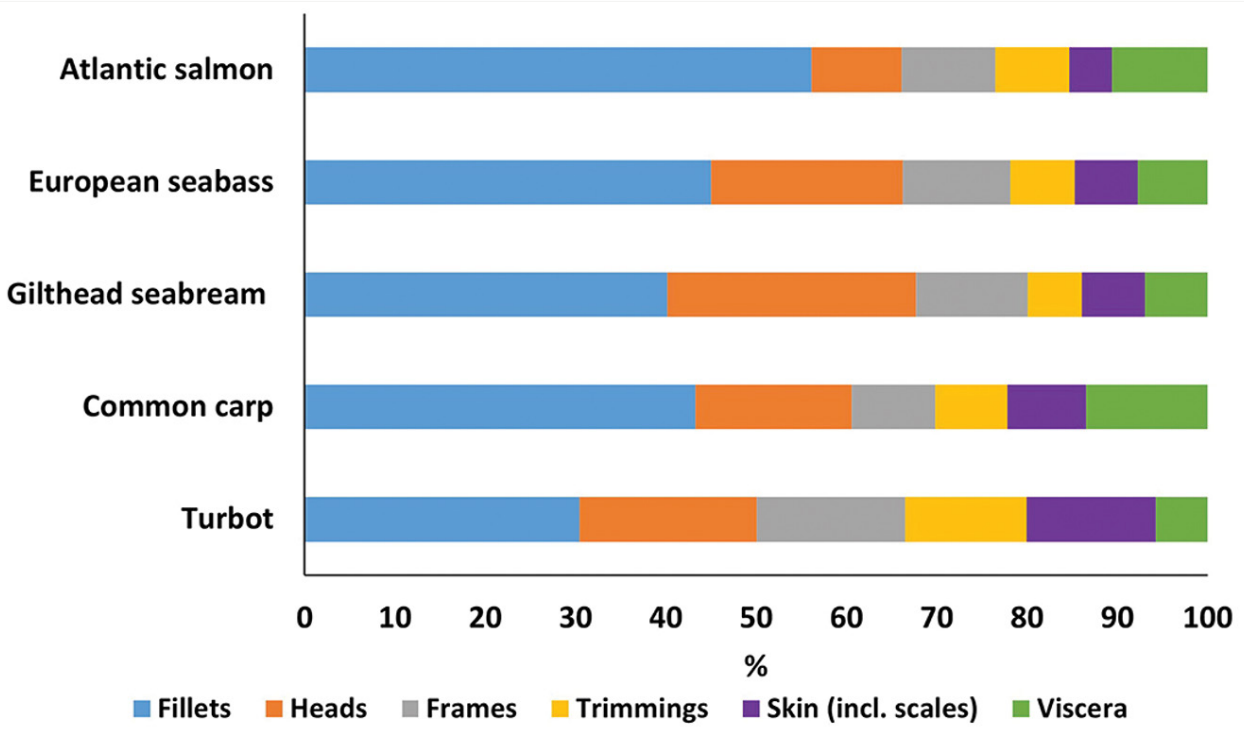

Figure 3. Proportion (%) of different processing fractions for five important European aquaculture species (Malcorps et al., 2021)

They stressed the need to shift consumer attitudes and address infrastructural and regulatory obstacles to fully capitalise on these by-products.

One of Croatia's leading mariculture companies contributes to the circular economy by turning "production waste" into a valuable resource. The total annual production of various fish species (European sea bass, gilthead seabream, meagre, ...) was 12 500 t in 2021 and 13 500 t in 2022. By-products of fish processing (guts, bones and scales) and low-quality fish are sold as raw materials to produce pet food. The quantity of by-products produced in the last two years is shown in Table 2. Mortality can also be added here as a raw material, mainly from category 3 by-products in a quantity of 500 tons/year.

Two tuna farms in the Zadar region produce between 1,000 and 1,500 tons of Atlantic bluefin tuna annually. Together, they collect about 500 tons of bluefin tuna by-products annually (about 250 tons per company). In addition to tuna, they also produce and process small pelagic fish (sardines, anchovies) (in both companies

Table 2. The amount of aquaculture side streams produced in one of Croatia's leading mariculture companies (data for the years 2021 & 2022) (company data source)

Month	Side streams (kg)	
	2021	2022
1	93,741	92,042
2	91,378	53,408
3	115,444	101,821
4	103,768	88,274
5	89,245	101,984
6	96,588	93,956
7	112,448	116,140
8	121,720	116,130
9	99,135	86,826
10	76,995	78,344
11	87,412	87,222
12	127,092	75,231
Total	1 216 987	1 093 400

about 1,000 tons per year), from which about 100-150 tons of by-products are obtained. All by-product biomass is exported. Unfortunately, the price and the place of delivery are trade secrets.

VALORISATION PATHWAYS

Fishmeal and fish oil

As it contains almost the same amount of proteins as fish meat, fish by-products were often used to make fishmeal (Mo et al., 2018). Fishmeal is the most valuable commodity produced from seafood side streams, and it can be used as commercial feed or fertiliser. Fish oil can be used for edible and non-edible applications (e.g. soap, glycerin or hydraulic oils) (Ferraro et al., 2010). According to estimates from the Marine Ingredients Organisation (IFFO, 2021), in 2020, about 86% of fishmeal was used in aquaculture, with 9% allocated to pig farming, 4% for other uses (mainly pet food), and 1% for poultry. During the same period, around 73% of fish oil was used in aquaculture, 16% for human consumption, and 11% for other purposes, including pet food and biofuel. IFFO data indicate that most fishmeal and fish oil still feed the aquaculture sector itself, creating a circular but resource-intensive dependency. For Croatia, which imports fishmeal for seabass and seabream feed, this raises a paradox: domestic side streams (sardine offcuts, tuna trimmings) could partially replace imported fishmeal, yet infrastructure for processing them locally is limited. Addressing this mismatch could reduce both costs and environmental footprint. Nevertheless, by 2020, over 27% of the global fishmeal production and 48% of fish oil production came from by-products, contributing positively to reducing waste (FAO, 2022). In contrast, Mediterranean utilisation efficiency remains considerably lower. STECF (2021) estimated that less than 15 % of regional side streams are channelled into fishmeal or oil, mainly because of dispersed landing sites and lack of rendering plants. Croatia exports most sardine offcuts and tuna trimmings unprocessed, losing potential added value. Establishing a small-scale rendering or oil-extraction facility near Zadar (as Croatia's main aquaculture production centre) could capture local side streams and partially substitute imported fishmeal in aquafeeds. Most of the time, fish by-products are thrown away without being recovered from fish waste, resulting in economic losses and environmental problems (Halim et al., 2016). Fishmeal from by-products differs nutritionally from whole fishmeal, containing less protein but more minerals (FAO, 2022). The global fish oil market was valued at $1,905.77 million in 2019 and is projected to reach $2,844.12 million by 2027, growing at a CAGR of 5.79% (Research and Markets Fish Oil, 2021). The EU produces around 120,000 tons of fish oil annually, led by Denmark, mainly for aquaculture, which uses up to 90% of global supplies (Wijesundera et al., 2021). Oils and fats make up a significant portion of fish processing biomass, influenced by species, fat distribution, age, sex, health, and season (Karkal and Kudra, 2020). Fish oils serve various sectors: industry, food, feed, aquaculture, and nutraceuticals. In Croatia, sardine by-products are used to produce high-quality oil, reducing reliance on whole sardines (Soldo et al., 2019). Up to 75% of the fish catch consists of non-retained or low-value parts, leading to economic losses and environmental challenges. Utilising by-products for fish oil and omega-3s enhances waste management and adds economic value through applications in food, cosmetics, and pharmaceuticals. EPA and DHA are key omega-3s in fish oil, vital for health (Tocher et al., 2019; Hamilton et al., 2020). Processing by-products into fish oil is especially valuable to aquaculture. Fish fat content ranges from 2% to 30%, varying by species, diet, habitat, and season (Senevirathne and Kim, 2012). One third of EPA/DHA from fish is wasted globally (Hamilton et al., 2020). Rising demand and value for these nutrients encourage better by-product use.

Pollutants in fishmeal and fish oil

Persistent organic pollutants (POPs) are chemical substances that persist in the environment and accumulate in the fatty tissue of living organisms. The content of POPs in feed and food has attracted considerable attention due to previous cases of contamination (SCAN, 2000; Huwe, 2002) and their potential risk to human health (SCF, 2000; Hites et al., 2004). High levels of organic pollutants have been found in several fish species and consequently also in fishmeal and fish oil produced from industrial fish and by-products (SCAN, 2000; Joas et al., 2001). Although only a small proportion of the fish oil and fishmeal produced contains levels of undesirable organic contaminants above the maximum permitted levels, the need to decontaminate products to comply with legislation could put producers relying on such raw materials at a global disadvantage (Oterhals and Nygård, 2008). Concerns about POP contamination are particularly relevant to the Adriatic, where semi-enclosed water can lead to pollutant accumulation. Analyses of Adriatic pelagic species (e.g., sardine) have shown detectable but generally compliant POP levels (Soldo et al., 2019). These findings highlight both the potential and the safety considerations for valorising local side streams into human-consumption products such as oils or nutraceuticals.

Fish protein hydrolysate

Interest in the production of fish protein hydrolysates is growing due to their content of nutrients and bioactive peptides that support human health. These hydrolysates offer a balanced amino acid profile, high digestibility and biologically active peptides (Liu et al., 2014; Saadi et al., 2015). Salmon hydrolysates have strong functional and nutritional properties. Hydrolysates from salmon muscle have been shown to prevent glucose intolerance, inflammation and dyslipidemia associated with obesity in mice (Chevrier et al., 2015; Roblet et al., 2016). Trout visceral hydrolysates showed antibacterial effects against *Flavobacterium psychrophilum* and *Renibacterium salmoninarum* and prolonged the bacterial lag phase (Wald et al., 2016). Protein extraction from fish by-products is primarily achieved by pH shift, whereby proteins from tissues such as muscle, skin and bone are solubilised and precipitated at their isoelectric point (Hayes et al., 2016). This is followed by enzymatic, thermal hydrolysis or autolysis (Halim et al., 2016; Villamil et al., 2017).

Peptides, collagen and gelatin

Peptides, isolated from fish by-products such as tuna bones, exhibit various biological activities, including antihypertensive, antioxidant, antithrombotic and immunomodulatory effects (Lee et al., 2014; Senevirathne and Kim, 2012). Peptides from collagen and gelatine show mineral-binding, antibacterial, lipid-lowering and bone- and skin-supporting properties (Darmawan et al., 2023). The body wall proteins of sea cucumber have also been hydrolysed to obtain functional peptides (Zhao et al., 2009). Isolation of proteins is usually done by enzymatic or chemical methods (Shahidi et al., 1995), with marine-derived peptides exhibiting antioxidant activity and low cytotoxicity (Sampath Kumar et al., 1995). Extraction can be carried out using liquid methods (Urakova et al., 2012) or microbial fermentation (Kim and Wijesekara, 2010). When processing cod, about 40 % of the raw material — swim bladders, viscera, skin, bones and fins - are by-products and provide sustainable sources of peptides (ALIF, 2014).

The demand for collagen and gelatin is increasing in the food and pharmaceutical sectors. Gelatin is derived from collagen, the main protein in skin, bone and connective tissue (Darmawan et al., 2023), by partial hydrolysis. Although chemically similar, gelatin is the denatured form of collagen (Senevirathne and Kim, 2012). Fish collagen and gelatin are rich in non-polar amino acids (>80 %) and differ from muscle proteins (Senevirathne and Kim, 2012). Fish gelatin has comparable properties to porcine gelatin, making it a viable alternative for food applications (Karim and Bhat, 2009). Fish collagen, which is seen as a substitute for bovine and porcine collagen, is gaining importance as a biomaterial for pharmaceutical and biomedical applications (Wijaya and Junianto, 2021). Marine-derived collagen and gelatin scaffolds offer biosafety, biocompatibility and low antigenicity (Coppola et al., 2021). Each type of collagen has different alpha chain structures; fish collagen typically contains two alpha-1 and one alpha-2 chain (Gelse et al., 2003). Type I collagen from fish bones is rich in glycine, alanine and proline, while the morphology varies between skin, bone and scale collagen (Wijaya and Junianto, 2021). Collagen from the swim bladders of cod, for example, is promising for cosmetics and biomedical applications (Sousa et al., 2019). Its antioxidant properties support its use in food preservation and healthcare, while fish-derived collagen can also serve as a food additive and packaging material (Coppola et al., 2021). Bioactive peptides and collagen derived from fish processing side streams have strong potential in the Mediterranean nutraceutical sector. However, commercial viability in Croatia is limited by small production volumes and the lack of purification facilities. Establishing pilot extraction lines—modelled on Norway's Nofima biorefinery—could help demonstrate the feasibility of peptide recovery from seabass and seabream skin. The biochemical profile of Adriatic species differs significantly from that of northern Atlantic fish commonly used in collagen and peptide extraction studies. Analyses of Adriatic sardine and anchovy oils show high omega-3 content but lower collagen yield (Soldo et al., 2019), while seabass and seabream skins provide superior gelatin quality but in smaller quantities. Therefore, Croatian research should rather prioritise optimising lipid and protein hydrolysate recovery rather than replicating the collagen-focused strategies typical of cold-water species.

Calcium and chitin

Fish bones are another side stream source, rich in calcium carbonate, suitable for making calcium phosphate bioceramics used in medical and dental fields (Senevirathne and Kim, 2012; Corrêa and Holanda, 2019). This inorganic calcium can also enrich foods like milk powder and pet food (Aydın and Altan, 2024). Crustacean shells and shellfish side streams represent a significant output of seafood processing, with nearly 8 million tons of crab, shrimp, and lobster shells generated annually - accounting for up to 60% of the total crab mass (Yan and Chen, 2015). Over 10 million tons of mollusk shells are produced annually, with 70% from oysters, clams, scallops, and mussels (Summa et al., 2022). Mussel shells alone make up 65–90% of live weight (Tokeshi et al., 2000; Morris et al., 2019). Improper disposal in landfills or the sea disrupts ecosystems (Murphy and Kerton, 2017; Bonnard et al., 2020). Shell side streams also accumulate during harvesting, often because of inadequate infrastructure and regulatory oversights in lower-income regions (Ishangulyyev et al., 2012; Topić Popović et al., 2023). Efficient use of these side streams improves environmental outcomes. Shrimp shells, as a by-product, contain high levels of calcium (3,000 mg/100 g) and phosphorus (Heu et al., 2003). These shells also contain chitin, a major natural polymer, which can be converted into chitosan and other derivatives with wide biological activity (Senevirathne and Kim, 2012). Chitin is found in arthropod exoskeletons and fungal cell walls (Alishahi and Aïder, 2012). Post-COVID, the global chitin and chitosan derivatives market, worth $7.9 billion in 2022, is expected to hit $24.9 billion by 2030, growing at a 15.3% CAGR (Chitin and Chitosan Derivatives, 2022). Natural chitin production is about 10^{11} tons annually (Hoell et al., 2010; Terkula Iber et al., 2021), mostly sourced from crustacean shells (Gortari and Hours, 2013; Terkula Iber et al., 2021). Recently, fish scales have also emerged as potential chitin sources, though less studied (Coppola et al., 2021). Fish bones and shellfish biomass represent another underexploited resource stream in Croatia. In addition to the previously mentioned aquacultured species, Adriatic demersal species such as hake (*Merluccius merluccius*) and red mullet (*Mullus barbatus*) produce bone fractions rich in calcium phosphate, suitable for use in food fortification or biomaterial synthesis (Corrêa and Holanda, 2019; Aydın and Altan, 2024). However, no Croatian facility currently converts fish bones into calcium supplements, despite pilot projects in Greece and Italy demonstrating technical feasibility.

Enzymes

The growing demand in the food and beverage industry, driven by population growth and the need to enhance food taste, quality, and texture, is fueling the continuous expansion of the enzyme market. Bioprospecting of aquatic organisms has uncovered numerous enzymes with catalytic properties that hold potential for various biotechnological applications. These aquatic species, often inhabiting extreme environments unlike terrestrial ecosystems, have evolved enzymes with distinctive characteristics, attracting significant interest from researchers (Shahidi and Kamil, 2001; Falch et al., 2007; Bruno et al., 2019; Coppola et al., 2021). Fish side streams, particularly internal organs like the stomach, pancreas, and intestine, are key sources of these enzymes. Many of these enzymes are cold-active, exhibit high catalytic efficiency even at low concentrations, and remain stable across a wide pH range. A comprehensive list of isolated and characterised fish enzymes was published by Venugopal (2016) and Shahidi et al. (2019).

Economic aspects of side-stream valorisation

The economic viability of valorising fisheries and aquaculture side streams depends on processing scale, technology costs, logistics, and market demand for derived products. Recent fish collagen prices generally range from €8 to €40 per kg, depending on the application and purity. Food-grade collagen costs around €8–12/kg, nutraceutical-grade about €10–12/kg, and cosmetic-grade can reach €20–40/kg due to higher quality and processing requirements (Rajabimashhadi et al., 2023). Crude fish oil and protein hydrolysates achieve €2–4/kg (Research and Markets, 2022) while recent fishmeal prices in Europe ranged around €1,470–1,520 per metric ton (World Bank, 2025). Side streams valorisation can substantially enhance profitability if processing is efficiently integrated into existing seafood operations. In Norway, smaller decentralised side stream processing plants have proven commercially feasible by co-locating units near landing ports and aquaculture facilities, thereby reducing raw material transport costs (Malcorps et al., 2021). In Croatia, the potential for economic returns exists but is constrained by fragmented landings, limited cold-chain infrastructure, and small processing volumes. Most sardines and anchovy side streams are currently exported or used in low-value applications such as animal feed. Establishing regional collection hubs could aggregate sufficient material to justify investment in hydrolysate or collagen production. Financial incentives through EU Blue Economy and Horizon Europe programmes could accelerate such investments. Integrating small processors and cooperatives into collective valorisation schemes would enhance economies of scale and domestic value retention. Ultimately, aligning technological feasibility with realistic market assessment and logistics planning is essential to transforming Croatia's seafood side streams from low-value residues into profitable, circular bioresources.

CONCLUSIONS

The valorisation of discards and side streams from marine fisheries and aquaculture presents a strategic opportunity to enhance sustainability, resource efficiency, and economic resilience in Croatia's seafood sector. Our review highlights that, while global practices offer valuable models, Croatia faces distinct challenges—particularly in infrastructure, regulatory enforcement, and market integration. Croatian aquaculture, dominated by European seabass and gilthead seabream, generates higher side-stream volumes than small pelagics, requiring tailored valorisation strategies. Despite EU landing obligations, discard reporting and port infrastructure remain insufficient, potentially underestimating side stream flows. High transport costs, lack of regional collection centers, and limited domestic processing capacity hinder the development of value-added chains. To address these challenges, we recommend investment in bio-refining and automation. Targeted funding for modern processing facilities and cold chain logistics can improve recovery rates and product quality. Introducing policy adjustments and incentives, such as reward systems for selective fishing and clearer guidelines for side-stream use, will enhance compliance and innovation. Future research priorities should focus on the biochemical profiling of species-specific side streams, assessing the techno-economic feasibility of valorisation pathways, and studying consumer acceptance of new marine-derived products. By aligning national strategies with EU circular bioeconomy goals and leveraging Croatia's rich marine biodiversity, the sector can transition from a linear model of disposal to a regenerative system of resource optimisation.

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