A REVIEW OF THE EFFICIENCY OF USING FISH BY-PRODUCTS

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Abstract

Efficient valorisation of fish by-products represents a strategic priority for improving resource utilization, profitability, and sustainability in the fish processing industry. This synthesis paper brings together scientific literature through reports, case studies, and research articles, analysing the efficiency of fish through different valorisation pathways. The results highlight a value hierarchy: high-value biomolecules (collagen, peptides, gelatine) provide the greatest profits, while fishmeal and fish oil ensure stable large-scale demand. Applications in bioenergy and fertilizers contribute indirectly by reducing waste management costs and supporting renewable energy systems. Case studies show that aquaculture industry revenues can be increased, but challenges persist, such as high technological costs, fragmented regulations, and limited consumer acceptance. The study emphasizes that integrated valorisation systems, aligned with the principles of the circular economy and the FAO's "Blue Transformation" initiative, offer the most promising approach for maximizing both economic and environmental outcomes. It also provides recommendations for scaling up fish by-product processing technologies and raising consumer awareness regarding the utilization of fish by-products.

Key words: *Blue Transformation, circular economy, sustainability, valorization*

INTRODUCTION

Fish is a valuable food, providing high-quality proteins, polyunsaturated fatty acids, vitamins A and D, as well as essential minerals, especially in small species consumed whole [1, 2]. The fish processing industry generates large quantities of by-products (heads, viscera, skin, bones, blood, scales) (Fig. 1) which have often been treated as worthless waste. It is estimated that between 30% and 70% of the mass of a captured fish consists of such post-harvest by-products [2]. Traditionally, these by-products were discarded or used in a limited way (for example, as animal feed), which led to the wasting of considerable nutritional and economic potential. According to the Food and Agriculture Organization of the United Nations (FAO), globally up to 35% of the fish taken from the sea is wasted along the value chain [3, 4] (a major loss of nutrients and resources).

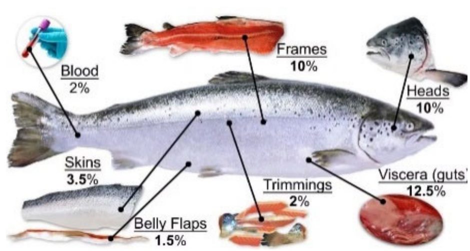

Fig.1 Fish by-products [5]

This waste not only undermines the profitability of the fishing and aquaculture industry, but also generates environmental

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problems (pollution, gas emissions from the decomposition of organic waste) and wastes opportunities to obtain value-added products.

In recent decades, the focus on circular economy and blue bioeconomy has brought to the forefront the need for the full valorization of marine resources. The concept of "zero waste" in fisheries and aquaculture promotes the use of every part of the catch or farmed fish, transforming waste into resources. FAO emphasizes that "blue" food systems must become circular, so that fish by-products are no longer discarded, but captured and reused in the food chain or in other industries, ensuring that no nutrient is lost [4]. The FAO "Blue Transformation" initiative (Figure 2) promotes exactly these objectives: increasing the efficiency of fish value chains, reducing losses and waste, and maximizing the use of fishery products, as part of a transition towards sustainability and food security.

The same principles are also reflected at the level of the European Union, which, through blue bioeconomy strategies, encourages member states to valorize by-products from fisheries and aquaculture in order to stimulate innovation, economic growth, and environmental protection [3, 4].

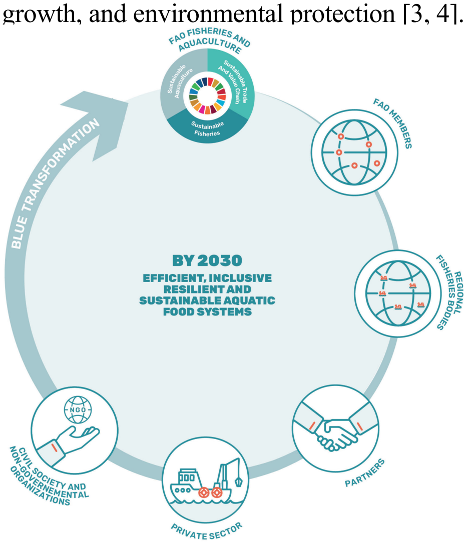

Fig. 2 "Blue Transformation" initiative [3]

From an economic perspective, fish by-products are no longer seen merely as worthless waste, but as secondary raw materials that can generate additional profits and competitive advantages. The scientific literature indicates that these by-products contain bioactive compounds with high commercial value (proteins and peptides with nutritional or pharmacological properties, oils rich in polyunsaturated Omega-3 fatty acids, collagen and gelatin, chitin and chitosan, pigments, minerals, and vitamins) [6-8]. Such components can form the basis of high-value products (for example, dietary supplements, pharmaceutical and cosmetic ingredients, medical biomaterials), which have prices much higher than the basic products (such as fish meal and oil) traditionally obtained from waste. At the same time, nutritionally valuable by-products can be reincorporated into the food chain, either as ingredients in food products intended for human consumption (e.g., protein powders, collagen supplements, fortified foods) or as feed for farm animals and aquaculture fish, contributing to the overall sustainability of the food sector [9].

Maximizing the valorization of by-products through "Blue bioeconomy" (Figure 3) brings multiple benefits: it increases the profitability of the fishery and aquaculture industry (through new products and additional revenues), reduces waste management costs (turning a potential cost into a source of income or energy), and minimizes the negative environmental impact (by decreasing the amount of organic residues entering water and soil). For instance, a remarkable case study is Iceland, which, through concerted policies and innovations, already utilizes approximately 80% of each captured fish (compared to only 50–60% in the rest of Europe).

This integrated "100% fish" approach has generated hundreds of new jobs and approximately 500 million USD in added market value in Iceland over recent decades [10], exemplifying the high economic potential of by-products.

Conversely, where by-products are neglected, the industry loses substantial opportunities: a global analysis indicated that approximately 12 million tons of fishery by-products were not collected to be transformed into useful ingredients, representing a "lost resource" that could have been valorized [2].

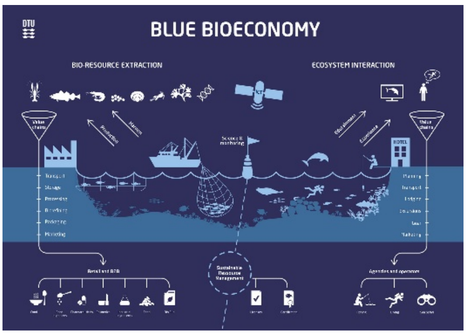

Fig.3 "Blue bioeconomy" [11]

This paper aims to review the scientific literature regarding the use of fish by-products, with a focus on the economic efficiency of different valorization routes. The hierarchy of added value has been studied (from high-value biomolecules to mass products such as fish meal/oil and applications for energy and agriculture), highlighting both economic benefits and encountered challenges.

Additionally, the context has been adapted at the European level (EU), where emerging policies and initiatives such as "Blue Bioeconomy" and "Blue Transformation" aim to promote the full use of marine resources, aligned with circular economy principles.

The ultimate goal is to identify ways in which fish by-products can contribute to the profitability and sustainability of the sector, as well as the necessary measures (technological, regulatory, market-related) to maximize these benefits.

MATERIAL AND METHOD

This study presents an analysis of the scientific literature regarding ways to reduce waste generated by the fishing and aquaculture industry through the valorization of by-products resulting from fish processing. The emphasis is on transforming these secondary resources, derived both from wild-caught fish and from aquaculture or bycatch, into value-added products capable of generating economic benefits and supporting the transition toward a circular economy. Additionally, the economic impacts and opportunities created by the use of by-products in related industries (food, pharmaceutical, cosmetic, agricultural, or energy) are evaluated, illustrating how their integration into the value chain contributes to increasing profitability and reducing losses in the fishery sector.

RESULTS

The fish processing industry generates by-products that can be valorized both in the food sector, as value-added products, and in various other industries. In this context, it is necessary to define a hierarchy of the value of these by-products, highlight the economic benefits for industry and communities, and analyze the main challenges and limiting factors [12, 13].

Valorization of by-products: hierarchy of economic value

1. Biomolecules and high-value products

The most profitable direction for valorizing fish by-products is the extraction of high-value bioactive compounds, used in industries such as pharmaceuticals, human nutrition (nutraceuticals), cosmetics, and biomedical applications. Numerous review studies highlight that fish by-products are a rich source of proteins and bioactive peptides, collagen and gelatin, Omega-3 fatty acids, chitin and chitosan, pigments (astaxanthin from shrimp shells, for example), essential amino acids, enzymes, and minerals [6, 14, 15]. Many of these substances have superior functional properties compared to their terrestrial counterparts. For example, collagen extracted from fish skin and bones has a lower molecular weight and high biocompatibility, being highly sought after in anti-aging supplements and skincare products: fish skin represents a valuable alternative to mammalian collagen (cattle/pig), which is also important for cultural or religious reasons [9, 16, 17]. Bioactive peptides derived through protein hydrolysis of by-products (hydrolyzed collagen, peptides from skin, bones, or viscera) have demonstrated antioxidant, antihypertensive, and immunomodulatory effects and are studied as ingredients in dietary supplements and functional foods. Such “fine” biomolecules can reach much higher prices per unit of mass compared to bulk products. For example, hydrolyzed marine collagen for nutraceutical or cosmetic use is sold at retail for >100 USD/kg, while fish meal (industrial product for feed) is priced around 1–2 USD/kg on the global market. This difference highlights the profit potential of directing by-products toward high-value market segments [18].

Several industrial case studies confirm the feasibility and profitability of extracting “premium” products from fish waste. In Iceland, the Codland initiative (launched in 2012) valorizes unused parts of Atlantic cod to obtain calcium supplements from bones, Omega-3 oil from liver and residuals, hydrolyzed marine collagen from skin, and even products for the fashion industry (tanned fish skin) [10]. These products have created new value chains, bringing additional revenue to producers. Similarly, Norwegian and Scottish companies process salmon waste (skin, bones) to extract marine peptides and high-quality salmon oil for human consumption, marketed as premium nutritional supplements. The literature shows that profitability per unit of raw material increases exponentially with the level of processing: from one ton of fish waste, it is possible to obtain either several hundred kilograms of meal with a value of a few hundred dollars, or a few kilograms of high-purity collagen peptides with a value of several thousand dollars. Of course, obtaining these products requires advanced technologies (specific enzymes for hydrolysis, membrane filtration, lyophilization, etc.) and ensuring food or pharmaceutical quality standards, which involves significant investments: an aspect discussed in the challenges section [19].

2. *Medium-value products and volume markets*

Another major valorization route, already well established at an industrial scale, is the conversion of by-products into fish meal and fish oil intended for animal feed (mainly for aquaculture and livestock). For decades, fish meal (rich in high-quality proteins) and fish oil (rich in Omega-3 fatty acids) have been globally traded products, used as key ingredients in feed for farmed fish, livestock, and pet supplements. Traditionally, these products were obtained from whole low-value fish (small, forage species). Today, however, a considerable proportion comes from by-products: in 2020, over 27% of the world’s fish meal production and approximately 48–51% of fish oil production were obtained from by-products (residues from processing both wild-caught and aquaculture fish) [2, 20]. This shift brings a dual benefit: it reduces pressure on forage fish stocks (by recycling otherwise wasted residues) and provides fish processors with additional income through the sale of residuals to meal or oil factories. Demand for fish meal and oil remains stable and large-scale, driven by the expansion of aquaculture (which requires feed rich in marine proteins and lipids) [2]. Economically, although the profit margin per ton is lower compared to niche products (collagen, etc.), the advantage is that almost any volume of by-products can be converted into meal or oil with relative technological ease. Processing units can valorize between 100,000 and 200,000 tons of raw material annually, generating standardized products that are easily marketable internationally. A clear example: in Norway and Denmark, fish slaughterhouses and processing plants systematically collect heads, frames, and viscera, sending them to rendering units where they are converted into meal and oil, achieving by-product utilization rates of over 90% in some areas [21]. These volume products ensure a steady revenue stream for the processing industry, economically stabilizing companies even if they do not bring the spectacular profits of luxury biomolecules. Moreover, by including meal and oil obtained from waste in aquaculture feed, a circular loop is created: fishing waste feeds farmed fish, reducing the need for new resources (catching fish for feed) and lowering feeding costs in aquaculture [9].

3. Low-value products used in bioenergy and agriculture

A third category of uses involves converting by-products into renewable energy (bioenergy) or agricultural inputs (fertilizers, soil improvers), contributing mainly to reducing environmental and waste management costs rather than achieving a high selling price. An example is the production of biofuel (Figure 4) through anaerobic fermentation of fish waste.

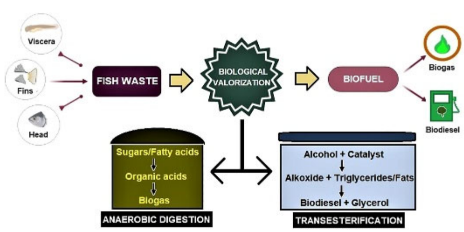

Fig. 4 The process of obtaining biofuels from fish [23]

Organic by-products (e.g., viscera, flesh residues, sludge from fish farms) can be introduced into anaerobic bioreactors, where bacteria decompose the material and produce a mixture rich in methane (approximately 70%). The resulting biogas can then be used as fuel for generating electricity or heat [8, 22].

Studies have shown that anaerobic digestion of fishery waste not only produces renewable energy but also releases nutrients (nitrogen, phosphorus) in an available form, transforming the remaining material into a digestate that can serve as a liquid organic fertilizer for plants. A recent experiment conducted at the University of Gothenburg demonstrated that integrating an anaerobic digester into a recirculating aquaculture system (aquaponics) allows the conversion of fish excreta and residues into biogas that powers the farm, while the resulting CO_2 fertilizes the plants, and the residual sludge becomes agricultural fertilizer. Thus, the farm reduces energy and waste disposal costs while obtaining a useful by-product (fertilizer). Although direct income from the sale of biogas or fish compost is modest, the savings achieved by avoiding waste management fees and by substituting conventional energy or chemical fertilizers are tangible economic benefits. Moreover, this practice decreases the ecological impact of waste: it reduces organic pollution (lowering the risk of eutrophication if the waste had been discarded) and decreases greenhouse gas emissions by capturing methane instead of allowing uncontrolled release from the waste [22].

Another example of agricultural use is the production of organic fertilizers and biostimulants from fish by-products. Fish hydrolysates (obtained through enzymatic or chemical decomposition of residues) have long been used as a natural fertilizer rich in nitrogen and trace elements ("fish emulsion" used in organic gardening). Additionally, innovative projects, such as the MariGreen initiative in the EU, develop fertilizers and biostimulants from residual materials from fisheries and aquaculture (including sludge and fish excreta) [24]. These products can enhance soil fertility and plant health, providing a way to valorize the nitrogenous and phosphorous components of the waste. However, in Europe, such uses still face legislative barriers: for example, Regulation (EC) No. 1069/2009 classifies certain fish residues and aquaculture excreta as material that cannot be applied directly to soil, requiring specific processing or even prohibiting their use as fertilizer. Despite these obstacles, European advisory groups argue that modifying regulations to allow controlled use of these by-products in agriculture would increase the economic efficiency of the fish value chain, turning a cost (sludge management) into a benefit (product sold as fertilizer) [8, 24].

Therefore, there is a clear hierarchy of value in fish by-product valorization: high-value biocompounds (collagen, peptides, Omega-3 oils for supplements, enzymes, pigments, etc.) generate the highest revenue per unit and support the development of niche markets with high margins; mass products (fish meal and oil) provide volume absorption and stable income, supporting key sectors (aquaculture, feed) by substituting primary resources; and bioenergy and agricultural applications provide indirect economic benefits through efficiency (reducing waste and energy costs) and synergies with other sectors (renewable energy, organic agriculture). For an integrated fish industry, the ideal model is a biorefinery in which one ton of by-product is sequentially processed: first the high-value components (e.g., pharmaceutical oils, collagen), then the remaining material is converted into feed meal/oil, and the final residues are digested for energy and fertilizer [6]. This circular model maximizes both revenue and environmental benefits: an approach at the core of "Blue Transformation" and circular economy initiatives in the EU and globally [3, 4].

Economic benefits for industry and communities

The valorization of by-products contributes to increasing the economic efficiency of the entire fish value chain. Instead of 20–50% of the harvested biomass being wasted at a cost (transport, disposal, compliance with environmental regulations), that fraction becomes a source of revenue. High recovery rates are directly reflected in profitability. Studies show that by fully processing each fish, the total yield of consumable products can increase from approximately 50% (often obtained from simple fillets) to over 70% of the fish mass [9, 18]. It has been estimated that if common fish in European aquaculture (salmon, perch, sea bream, pikeperch, etc.) were processed in their entirety, an average yield of 64-77% of edible/usable product would be obtained, instead of the typical yield of 30-56% obtained when only fillets are harvested. This means more finished product sold (food, ingredients) from the same amount of farmed or captured fish, thus increasing revenue without increasing catches (a crucial aspect in a world with limited marine resources). Additionally, by producing and selling by-products, processing companies can diversify revenue streams and reduce dependence on a single product (e.g., only fresh fillets). This diversification increases business resilience to market fluctuations: if the price of fresh fish drops, income from collagen or fish meal can partially compensate [25].

The positive impact is not limited to individual companies but extends to regional and coastal communities. The creation of new by-product valorization industries brings jobs and local investment. In Norway and Iceland, the development of the marine biotechnology sector and by-product processing has led to the emergence of dozens of innovative SMEs and several hundred specialized jobs (technicians, chemists, operators) in coastal areas. Moreover, the additional revenue from these activities contributes to regional GDP growth and enhances the international competitiveness of the fishery sector through a diversified product range. Countries with a strong fishing tradition that have embraced the marine circular economy (such as Iceland) now extract more economic value from the same quantity of resource compared to the past. An Icelandic study noted that, compared to the 1990s, increased use of by-products raised the value per kg of captured fish by nearly 30%, through additional revenue obtained from secondary products. For coastal communities, this translates into economic stability and new opportunities, from fishers receiving better prices for their catch (knowing that the entire fish will be used) to biotechnology companies developing near ports [10].

Another benefit is the reduction of environmental costs and risks, which indirectly impacts the economy. Fish waste management can be expensive (transport to processing units, storage, controlled composting, etc.) and can incur penalties if not compliant with environmental regulations.

Through valorization, these costs are reduced. For example, a Spanish canned fish factory that implemented a system to collect and convert waste into biogas and fertilizer reported a 20% reduction in operational energy and waste management costs in the first year. Furthermore, by avoiding the disposal of waste into the sea or landfill, companies prevent potential fines and improve public image, which becomes increasingly economically important (sustainable brands attract investment and customers). Thus, economic efficiency is reflected not only in immediate profit but also in realized savings and acquired brand value [22].

Challenges and limiting factors

Despite the obvious benefits, large-scale implementation of by-product valorization in the industry faces significant challenges. Among the most frequently mentioned in the literature and reports are: high technological costs, fragmentation and gaps in regulations, as well as limited acceptance by the market and consumers.

The production of high-value products (collagen, peptides, enzymes) often requires advanced technologies: dedicated processing lines, extraction or purification equipment, sterile conditions, and highly qualified personnel. Many fish processing companies operate with low margins and may hesitate to make the substantial investments required for such facilities, especially if market demand is uncertain. For example, collagen extraction involves multi-step processes (defatting, demineralization, enzymatic hydrolysis, ultrafiltration), and the cost of pilot plants can run into millions of euros. The lack of cost-efficient extraction strategies has been cited as the main reason why many marine biomolecules remain unexploited at a large scale. The absence of optimized technologies has prevented the industrial-scale exploitation of many valuable compounds from fish waste [6]. Even for fish meal and oil, economies of scale matter: processing by-products is financially feasible only if sufficient quantities are collected consistently. In areas with intensive seasonal activity (short fishing campaigns), it may be uneconomical to maintain a fishmeal plant operational year-round: some studies show that rendering units reach maximum efficiency in regions with high volumes and continuous raw material flow, otherwise much waste remains unused [21]. Solutions exist, such as centralizing by-product collection from multiple small plants to a large unit or using mobile technologies, but implementation requires coordination and joint investment.

Regulations regarding animal by-products are strict in the EU (to protect public health, prevent contamination, etc.).

Paradoxically, some rules discourage reuse. For example, as mentioned, current regulations may prohibit the use of sludge from fish farms as fertilizer, treating it as hazardous waste, even though it is agronomically valuable. Additionally, there are differences between countries in the interpretation of the rules: what is approved in one EU country (e.g., the use of hydrolyzed fish proteins in pig and poultry feed) may face bureaucratic obstacles in another. This fragmentation makes it difficult for companies to plan investments, especially if they intend to export by-product-derived products (which may be legally classified differently: as novel foods, technical substances, etc.). Four European Advisory Councils highlighted in 2024 that "outdated" EU rules on fish by-products limit commercial use and called for their update. Their recommendations include revising the Animal By-products Regulation (2009) to allow uses such as fertilizers from fish excreta, harmonizing sanitary standards between countries for oils and proteins obtained from waste, and clarifying the legal status of derived products (food, feed, etc.) to eliminate uncertainty that discourages investment [24]. Until these regulations are adapted to circular economy principles, some valorization streams will remain blocked or economically unattractive (companies will not invest if they are not certain they can legally market the resulting product).

Even if technology and legislation are resolved, a key factor remains consumer and end-user acceptance. The idea of consuming products derived from "fish waste" can encounter the so-called "yuck factor" in some segments of the public. For example, a market study on foods with ingredients obtained from marine by-products showed that transparency about origin can negatively influence some consumers' willingness to purchase, as they associate the term "waste" with low quality [26]. However, the same study indicated that educating consumers about the benefits of these ingredients (high nutritional value, sustainability) can increase their willingness to try them. In the food industry, some products incorporating by-products have succeeded when presented as functional or sustainable ingredients. For example, fish protein powders (fish protein concentrate) have been rebranded as marine protein supplements, avoiding the word "waste" in marketing, and found a niche market among athletes and health-conscious consumers. In cosmetics, marine collagen extracted from fish skin is promoted as premium and eco-friendly, which has led to good acceptance. Where the final market is feed or agriculture, acceptance is less of a problem (animals do not object, and farmers care about efficacy and price). However, in human nutrition, companies must overcome consumer prejudices. This aspect is also linked to regulations: in the EU, a novel food ingredient (e.g., peptides obtained from fish skin) must be authorized as "Novel Food," involving costly assessment procedures (costs which companies must later amortize on the market). When consumer perception acts as a limiting factor for sales dynamics, the allocation of investment resources entails an increased level of risk [27].

Another aspect concerns acceptance by the traditional industry. Some fishing/processing companies may be reluctant to change, preferring familiar methods. Implementing an integrated valorization chain often requires collaboration: fishers or processors must collect and properly store by-products (e.g., chilled, separated by category) for later processing. Without clear incentives (financial or regulatory), these additional efforts may be viewed skeptically. Therefore, advisory councils suggest intensifying collaboration between policymakers, research, and industry to demonstrate feasibility and benefits of these practices and to facilitate technology transfer [24].

Consequently, although the "hidden value" in fish by-products is high, unlocking it requires overcoming these barriers. Capital costs can be addressed through funding programs and public-private partnerships supporting the installation of pilot biorefineries. Regulations can be updated based on scientific evidence regarding the safety of processed by-products and the success of pioneering countries. Consumers can be won over through smart marketing and education, for example by promoting the products as part of the circular economy (many consumers value sustainability) and highlighting their benefits (nutrition, quality comparable to conventional products).

DISCUSSIONS

The analysis confirms that the economic efficiency of fish by-product valorization is real, but it manifests optimally only within an integrated system. Recent initiatives, such as the FAO "Blue Transformation" concept, advocate precisely for such integrated systems that align economic objectives with environmental ones. An ideal system is one in which every component of the fish value chain is circularly connected: fisheries and aquaculture provide raw material, primary processing delivers main food products but also systematically collected by-products, which then enter various secondary processing streams (biotechnology, feed, energy). Final waste almost disappears, being transformed either into energy or fertilizer products, closing the loop. Thus, the EU target of "zero waste" is achieved, similar to how Iceland has managed to utilize 80–100% of the harvested biomass [3, 4, 10]. The benefits are maximum: increased profits for the industry, new activity sectors generated, reduced impact on the marine environment (through using the existing catch instead of increasing pressure on resources), and on the climate (through waste reduction and bioenergy production).

The present study reveals that a value hierarchy already exists: compounds such as collagen, peptides, and chitosan provide the highest economic value per unit, fish meal and oil provide stable value at high volume, while uses in energy and agriculture provide complementary indirect value (through savings). An optimal strategy for the related industries would be to attempt to capture all these levels of value through a cascading approach: for example, an integrated factory could extract collagen from skin and bones, produce meal and oil from the remaining matter, and use the organic effluents for a biogas digester, obtaining revenues from multiple sources and reducing almost completely the eliminated waste. This model corresponds to the concept of the "marine biorefinery," increasingly discussed in the specialized literature [6]. Of course, for large-scale implementation of such a model, strategic and investment support is needed. FAO and the EU recognize this in their initiatives: FAO, through Blue Transformation, urges the creation of improved value chains and reduction of losses, highlighting that the use of by-products is a key tool for sustainability [3, 4, 28]. The EU, through programs such as Blue Bioeconomy Cofund, funds projects that seek new ways to obtain value from marine bioresources, including by-products. Moreover, industry councils explicitly call for measures such as financial incentives for innovation, legislative clarifications, and collaboration platforms between researchers and enterprises [10, 24].

Not least, an essential aspect is raising awareness and acceptance among the public. Once consumers (whether food buyers, farmers using fertilizer, or investors) understand that the use of fish by-products is beneficial (the resulting product is safe, high quality, and sustainably obtained), demand and support for these practices will increase. Education on the blue circular economy, labeling products as eco-friendly (for example, collagen supplements labeled as sourced from recycled resources), and information campaigns can play an important role.

Overall, the economic efficiency of using fish by-products is confirmed by multiple pieces of evidence: revenue growth, avoided costs, new markets created, and competitive advantage gained by regions that adopt this model. The remaining challenges, although considerable, can be overcome through an integrated vision and multi-actor collaboration. The global and European trend is clear: the future of the fisheries and aquaculture industry will be closely linked to its ability to valorize everything, not only for environmental sustainability, but also as a strategy to maximize economic efficiency in a competitive and resource-limited world.

CONCLUSIONS

The valorization of fish by-products represents a major opportunity both economically and ecologically.

High-value biocompounds, such as collagen, peptides, or Omega-3 fatty acids, provide high profit margins and allow diversification into industries such as pharmaceuticals, cosmetics, and nutraceuticals, while volume products, such as fish meal and oil, ensure the utilization of large quantities and support global food security.

The uses of fish by-products in bioenergy and agriculture contribute to reducing waste management costs and creating a sustainable circular loop, even if the direct financial value is more modest.

Adopting an integrated marine biorefinery model, which combines all these levels of valorization, provides good economic results and contributes to environmental sustainability.

Achieving the full valorization potential of fish by-products depends on overcoming obstacles related to high technological costs, regulatory rigidity, and market reluctance, which requires sustained investment in research and infrastructure, harmonization of the legislative framework, and better consumer awareness.

The efficient use of fish by-products constitutes a solution for waste reduction and the protection of fishery resources, as well as a viable economic strategy for the sustainable development of the sector.

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