Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 16(2), 778-790, 2026
Journal of the Institute of Science and Technology, 16(2), 778-790, 2026

ISSN: 2146-0574, eISSN: 2536-4618

Su Ürünleri / *Fisheries* **DOI: 10.21597/jist.1776673**

Derleme Makalesi / *Review Article*

Geliş tarihi / *Received*: 02.09.2025 **Kabul tarihi / *Accepted*: 27.11.2025**

Atıf İçin: Karadaş, N. F. (2026). Sürdürülebilir Su Ürünleri Yetiştiriciliği Endüstrisi İçin Atıkların Biyoaktif Kaynaklara Dönüştürülmesi. *Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, 16(2), 778-790.

To Cite: Karadaş, N. F. (2026). Conversion of Waste into Bioactive Resources for Sustainable Aquaculture Industry. *Journal of the Institute of Science and Technology*, 16(2), 778-790.

Sürdürülebilir Su Ürünleri Yetiştiriciliği Endüstrisi İçin Atıkların Biyoaktif Kaynaklara Dönüştürülmesi

Naime Filiz KARADAŞ[1*]

Öne Çıkanlar:
- Balık endüstrisi
- Atık madde
- Biyoaktif kaynak

Anahtar Kelimeler:
- Kolojen
- Antimikrobial
- Sağlık
- Balık
- Atık

ÖZET:

Tahminler, 2050 yılına kadar dünya nüfusunun 9,7 milyara yakın olacağını gösteriyor. Bu hızlı büyüme, gıda kaynaklarına ekstra baskı uygulayarak güvenli ve sürdürülebilir beslenme stratejilerini her zamankinden daha önemli hale getirecek. Olası çözümler arasında su ürünleri yetiştiriciliği özel bir yere sahip. İstikrarlı bir hayvansal protein kaynağı sağlıyor ve diğer birçok gıda üretim sistemiyle karşılaştırıldığında daha küçük bir çevresel ayak izi bırakıyor. Ancak sektör büyük bir zorlukla karşı karşıya: balıkçılık ve su ürünleri yetiştiriciliğinden elde edilen avın yaklaşık üçte biri (yaklaşık %35'i) kayboluyor veya atılıyor. Bu atıkların hem çevresel hem de ekonomik maliyetleri var. Ancak son zamanlarda, sürdürülebilirlik ve daha iyi atık yönetimi konusundaki farkındalık, bu atık malzemelerin faydalı kaynaklara dönüştürülmesine olan ilgiyi artırdı. Örneğin balık derisi, pulları ve mukusu, kolajen, antimikrobiyal peptitler, glikoproteinler, polisakkaritler ve omega-3 yağ asitleri gibi değerli bileşik kaynakları olarak araştırılıyor. Bu bileşenler dokuların onarılmasına, iltihabın azaltılmasına, mikroplarla savaşılmasına ve antioksidan görevi görmesine yardımcı olabilir. İşleme ve ekstraksiyon yöntemlerindeki gelişmeler, bu tür bileşiklerin geri kazanılmasını ve döngüsel bir sistemin parçası olarak ekonomiye geri kazandırılmasını kolaylaştırmaktadır. Bu, yalnızca atıkları azaltmakla kalmayıp, aynı zamanda Birleşmiş Milletler Sürdürülebilir Kalkınma Hedefleri'nde (SDG 12 (Sorumlu Tüketim ve Üretim) ve SDG 14 (Su Altında Yaşam) belirtilenler de dahil olmak üzere daha geniş kapsamlı çevresel hedefleri de desteklemektedir. Bu inceleme, deniz atıkları ve deniz ürünleri yan ürünlerinin kullanımının ekonomik ve çevresel değerine daha yakından bakmaktadır. Kolajen, jelatin, protein izolatları ve biyoaktif peptitler gibi yüksek değerli bileşenlere odaklanmakta ve bunların gıda ve kozmetikten sağlık hizmetlerine ve hayvan yemine kadar çeşitli sektörlerde nasıl kullanılabileceğini ele almaktadır.

Conversion of Waste into Bioactive Resources for Sustainable Aquaculture Industry

Highlights:
- Fish Industry
- Waste material
- Bioactive source

Keywords:
- Collagen
- Antimicrobials
- Healing
- Fish
- Waste

ABSTRACT:

Projections suggest that by 2050 the world's population will be close to 9.7 billion. Such rapid growth will put extra pressure on food supplies, making secure and sustainable nutrition strategies more important than ever. Among the possible solutions, aquaculture has a special place. It provides a steady source of animal protein and, compared with many other food production systems, leaves a smaller environmental footprint. Yet the sector faces a major challenge: about one-third of the catch from fisheries and aquaculture roughly 35% is lost or thrown away. This waste has both environmental and economic costs. Recently, however, awareness of sustainability and better waste management has sparked interest in turning these discarded materials into useful resources. Fish skin, scales, and mucus, for example, are now being explored as valuable sources of compounds like collagen, antimicrobial peptides, glycoproteins, polysaccharides, and omega-3 fatty acids. These components can help repair tissues, lower inflammation, fight microbes, and act as antioxidants. Advances in processing and extraction methods are making it easier to recover such compounds and feed them back into the economy as part of a circular system. This not only cuts down on waste but also supports broader environmental goals, including those outlined in the United Nations Sustainable Development Goals especially SDG 12 (Responsible Consumption and Production) and SDG 14 (Life Below Water). This review takes a closer look at the economic and environmental value of using marine waste and seafood by-products. It focuses on high-value ingredients such as collagen, gelatin, protein isolates, and bioactive peptides, and discusses how these can be used across a range of industries, from food and cosmetics to healthcare and animal feed.

[1] Naime Filiz KARADAŞ (**Orcid ID:** 0000-0003-3488-3481), Ataturk University, Faculty of Fisheries, Erzurum, Türkiye

***Sorumlu Yazar/*Corresponding Author*:** Naime Filiz KARADAŞ, e-mail: filizkaradas66@gmail.com

INTRODUCTION

By 2050, the world's population is expected to climb to around 9.7 billion (United Nations, 2022). Such rapid growth will make it even more urgent to address global food security and nutrition challenges. Solving this issue will require more than just producing greater quantities of food it will also demand better nutritional quality, reduced waste, and smarter use of resources. Land and water are limited, and adapting to the disruptions caused by climate change is no longer optional but necessary (Loboguerrero et al., 2019).

Aquaculture is increasingly recognized as a vital solution to meet the world's growing demand for protein in a way that supports sustainability. In 2018, total production from both inland and marine environments amounted to approximately 179 million tonnes**.** This level showed only slight fluctuations over the next two years, with 177 million tonnes in 2019 and 178 million tonnes in 2020 (FAO, 2022). Reports by the FAO further indicate that in 2019, fish and other aquatic foods supplied nearly 17% of the global consumption of animal-derived protein and represented about 7% of overall protein intake**,** underlining their rising importance in human diets worldwide (FAO, 2022).

The aquaculture industry continues to face a major challenge in the form of waste generation. On a global scale**,** nearly 35% of the total catch from fisheries and aquaculture is either lost or discarded**.** Although the rates differ depending on the region, they usually remain between 30% and 35%**,** but in areas such as North America and Oceania**,** losses can reach up to 50%, primarily at the consumer stage (FAO, 2022). In terms of by-products, 30–70% of the fish's live weight does not enter the food chain. Typical proportions include heads (9–12%)**,** viscera (12–18%)**,** skin (1–3%)**,** bones (9–15%)**,** and scales (around 5%) (FAO, 2022; Wu et al., 2022). Despite being rich in proteins, lipids, pigments, and bioactive compounds, a large share of these resources is not efficiently recovered (FAO, 2022; Ganjeh et al., 2023). In the case of shellfish such as shrimp, crab, and lobster waste levels are even more striking: approximately 75% of the total biomass, mostly heads, tails, and shells, is discarded (Mutalipassi et al., 2021). If properly utilized, these materials could serve as significant sources of protein and nutrients, yet their current underuse contributes to economic losses and environmental problems (FAO, 2022; Mutalipassi et al., 2021).

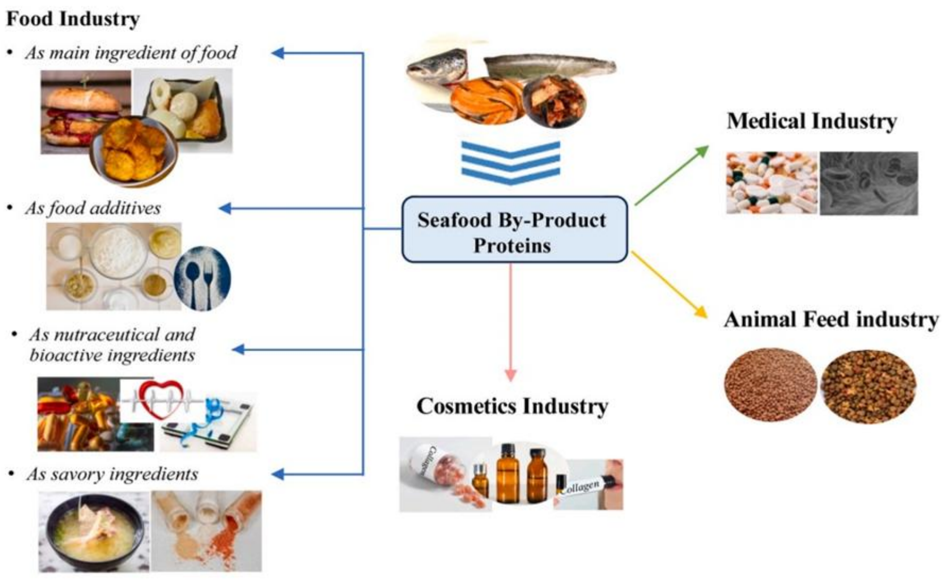

Fig. 1. Industrial applications of proteins derived from seafood by-products (Zhang et al., 2024)

With the rising focus on sustainability and the principles of the circular economy, seafood processing residues are being viewed as increasingly valuable resources. On a dry weight basis, these by-products may contain up to 60% protein (Sasidharan & Venugopal, 2020). The protein fraction is nutritionally comparable to that of meat and eggs, since it provides a well-balanced composition of essential amino acids along with abundant muscle proteins (Vidanarachchi et al., 2014; Sasidharan & Venugopal, 2020; Liu, Huang et al., 2021). Such qualities position them as a strong candidate for alternative protein sources in the human diet. Yet, the recovery of these proteins is complicated: they are highly susceptible to oxidation and degradation, largely due to the presence of polyunsaturated fatty acids and proteolytic enzymes (Altintzoglou et al., 2021; Ganjeh et al., 2023). Recent innovations in processing and extraction technologies, however, have improved recovery efficiency, making industrial-scale utilization more feasible. These advancements not only help in reducing food losses but also contribute to food security and the mitigation of environmental pressures associated with seafood production (FAO, 2022).

FAO data show that in 2020, total global fisheries and aquaculture output reached 240 million tonnes. Rising consumer demand for seafood is expected to push production even higher in the coming years (FAO, 2022). While this growth has boosted food supply and supported economies, it has also created a large stream of waste. Each year, roughly 20 million tonnes of waste are generated from global fisheries, including processing residues and by-products such as fins, heads, skin, viscera, scales, shells, bones, and even non-target species (Rustad, 2003; Mozumder et al., 2022).

Converting seafood waste into value-added products offers both environmental and economic benefits, turning discarded materials into resources with tangible market potential. These approaches are closely aligned with the idea of zero waste and contribute directly to the United Nations Sustainable Development Goal 14, which emphasizes the protection and sustainable use of marine ecosystems (Gilman et al., 2020). Although the concept of utilizing marine by-products has been explored for many years, conventional applications have largely been restricted to low-value outputs such as fishmeal, silage, fertilizers, aquaculture feed, and other feed ingredients (Coppola et al., 2021).

Marine by-products offer considerable potential as raw materials for producing a wide range of high-value goods (Figure 1). At present, waste containing muscle tissue and viscera is mainly used on a limited scale to make fishmeal, fish oil, and silage (Coppola et al., 2021). Yet these materials possess distinctive functional traits and notable biological activities, making them suitable for converting into fine chemicals used in pharmaceuticals and cosmeceuticals. This approach can open up an extra stream of revenue for companies that process marine resources (Caruso et al., 2020). In the case of food-grade fish, processing typically generates by-products such as heads (9–12%), viscera (12–18%), skin (1–3%), bones (9–15%), and scales (around 5%). The exact proportions depend on factors like species, size, processing methods, and the technology employed (Ferraro et al., 2013). Among these, fish skin, bones, and scales are particularly rich in valuable substances such as collagen, gelatin, fish oil, and calcium phosphate, all of which have applications in the cosmeceutical industry.

Research has shown that collagen, gelatin, and their derivatives from marine by-products can serve effectively as active ingredients in cosmetic formulations. In regions where religious sensitivities are high, replacing porcine- or bovine-derived components with marine-based alternatives not only supports the creation of halal- and kosher-certified cosmetics but also aligns with sustainable production goals.

History of Recycling

For centuries, communities around the world have found ways to use every part of fish and shellfish, ensuring that little went to waste. In many Indigenous societies, for instance, fish heads, skin, and bones were repurposed into food, clothing, or decorative items—practices that supported livelihoods while keeping waste to a minimum (Pérez-Lloréns et al., 2021). In Medieval Europe, these by-products began serving other purposes, such as enriching soil as fertilizer or acting as raw materials in glass and ceramic production (Koenigsberger, 2014). By the 19th century, the large-scale production of fishmeal and fish oil had taken hold, especially for use in animal feed (Hassoun et al., 2022; Zhang et al., 2023). The wars of the 20th century further drove research into bioactive substances, including the nutritional benefits of fish liver oil.

More recently, the concept of *Blue Fashion* has emerged, introducing fish-derived materials into the fashion world. Some companies have pioneered unique uses Tidal Vision LLC, for example, produces fibers from crab shells for T-shirts and makes wallets from salmon skin, while RayFish Footwear crafts shoes from stingray leather. In places like Iceland and Canada, firms such as Nordic Fish Leather and 7 Leagues Leather have developed techniques to turn fish skin into durable, high-quality leather (FAO, 2018; Helmer, 2023). At the same time, advances in food science have made it easier to extract high-value compounds like omega-3 fatty acids (EPA, DHA), collagen, peptides, and chitosan from these by-products (Pal & Suresh, 2016; Pinela et al., 2022). Finland's Super Ground® process is one example this method allows entire fish, bones included, to be processed and consumed without losing any nutritional value (Fusaro, 2023).

Industrial Applications

In recent years, there has been a clear rise in interest in recovering proteins from seafood processing by-products and turning them into high-value products. This growing focus has gone hand in hand with notable progress in recovery technologies and processing methods (Sasidharan & Venugopal, 2020). While the industry still faces hurdles such as scaling production, keeping costs manageable, and ensuring consistent quality practical applications are becoming increasingly viable. Within this context, proteins in the form of isolates, hydrolysates, bioactive peptides, collagen, and gelatin extracted from seafood by-products are now finding use in a wide range of sectors, from food and animal feed to healthcare and cosmetics. Their appeal lies not only in their strong nutritional profile but also in the valuable functional and biological properties they can offer.

Food industry

In recent years, isoelectric precipitation protein (ISP) isolates obtained from seafood processing by-products have found increasing application as valuable ingredients in the food industry (Surasani et al., 2022; Aqua Food, 2023). Thanks to their strong gel-forming ability, these isolates are particularly suited for use in products such as fish patties, fish sausages, and surimi-type preparations (Panpipat & Chaijan, 2017; Nisov et al., 2021). The gelation characteristics of ISP isolates are influenced by factors such as processing technique and the protein-to-lipid ratio, with alkaline-extracted isolates generally forming firmer gel structures (Chomnawang & Yongsawatdigul, 2013; Surasani, 2018). In addition to these functional qualities, ISP isolates are rich in essential amino acids and exhibit high digestibility (Tian et al., 2017; Surasani, 2018). Pilot-scale trials have demonstrated improvements in product texture and a reduction in cooking losses when these isolates are incorporated into fish-based foods (Nguyen et al., 2020; Szymczak et al., 2024). In Sweden, several companies have successfully brought this technology to industrial scale, introducing new classification systems for minced fish production

(WASEABI, 2023; Pelagic Seafood, 2023). These developments highlight the potential of seafood by-products as a sustainable and economically attractive raw material for the food sector.

Medical industry

Marine collagen has gained considerable attention in the biomedical field thanks to its favorable characteristics, including biocompatibility, biodegradability, low antigenicity, thermal stability, and ability to promote cell adhesion (Lim et al., 2019). Beyond its role in injectable dispersions, microparticles, nanocapsules, and drug delivery systems, it is also incorporated into specialized wound dressings containing L-cysteine hydrochloride (Lengyel et al., 2019; Langasco et al., 2019). In tissue engineering, collagen sourced from fish offers a promising alternative to mammalian-derived collagen for repairing bone, cartilage, tendon, skin, and vascular tissues. For example, collagen obtained from blue shark cartilage—when combined with hydroxyapatite and chitosan—has shown notable osteogenic potential (Elango et al., 2016). Similarly, both pepsin- and acid-extracted collagen scaffolds from tilapia skin, as well as electrospun bovine collagen scaffolds, have been reported to accelerate wound healing in animal studies (Zhang et al., 2022). On an industrial scale, the Icelandic company Kerecis has developed a method to process Atlantic cod skins into omega-3-rich medical dressings, used in the treatment of burns and diabetic ulcers; these products have FDA approval and are employed in hospitals and military healthcare settings (Kerecis, 2023). Collectively, such innovations illustrate how seafood processing residues can be transformed into high-value medical materials.

Animal feed industry

By-products from seafood processing are increasingly valued as affordable and eco-friendly inputs for the animal feed sector, primarily because of their high protein levels and substantial energy content (Ganjeh et al., 2023). Using these materials—often unsuitable for direct human diets—as feed components can notably cut overall production expenses, since feed commonly represents 65–75% of operational costs. Within this context, isoelectric precipitation protein (ISP) isolates have emerged as a noteworthy replacement for traditional fishmeal, offering a balanced amino acid profile, significant amounts of omega-3 fatty acids, and essential minerals (Hinchcliffe et al., 2019). However, additional investigations are still needed to clarify their effects on animal growth efficiency. Another promising approach involves the use of protein hydrolysates derived from seafood residues. These products are characterized by high digestibility, nutritional balance, and palatability, while also providing health-promoting functions such as antimicrobial, antioxidant, and anti-inflammatory activities (Da Rocha et al., 2018). Moreover, their advantageous technological propertiesincluding solubility, resistance to heat, water-binding ability, and emulsification capacity make them highly suitable for incorporation into feed formulations (Khan et al., 2022).

Several companies across the globe have invested in this sector. In the United States, H.J. Baker produces high-protein feeds for poultry and aquaculture under the brand PRO-PAK®, while Petfood Enterprise uses hydrolysates from Scottish salmon to improve flavor and reduce allergenic potential in pet foods. Pacific Bioproducts repurposes marine by-products for multiple applications, and AlaSkins specializes in natural dog treats made from Alaskan fish skins (H.J. Baker, 2023). In Europe, Scogal in France manufactures fishmeal and hydrolysates from fish waste, and Norway's Pelagia produces certified organic fishmeal (NorsECO®) from sustainable sources. Scan Bio, also based in Norway, recovers protein concentrates and fish oil from processing residues (Scogal, 2023). In Asia, companies such as Wenxi and Hualong in China develop oyster-derived peptides as feed supplements, while Vietnam's Vinh Hoan transforms fish waste into protein-rich fish powder for animal feed (Rushan Ocean Development Bureau, 2023). Overall, the incorporation of seafood by-products into animal feed not only supports sustainable resource management but also delivers tangible economic benefits by lowering feed costs. As adoption grows worldwide, these practices are becoming an important alternative for meeting the nutritional demands of livestock and aquaculture in a sustainable way.

Cosmetics industry

Collagen derived from fish predominantly Type I has gained wide acceptance in the cosmetics sector for its ability to improve skin elasticity, enhance moisture retention, and promote wound healing. Its halal compatibility and minimal zoonotic risk further increase its appeal (De Luca, 2016; Sionkowska et al., 2020). In its hydrolyzed form, the lower molecular weight facilitates incorporation into both oral supplements and topical formulations. Commercially available products such as Peptan®F and Cartidyss® have been reported to contribute positively to skin health (Maia Campos et al., 2021). Similarly, fish oil a rich source of polyunsaturated fatty acids like EPA and DHA, is utilized for its photoprotective properties, benefits in acne management, and potential to alleviate symptoms of chronic skin disorders. Chitin and its derivatives—most notably chitosan—extracted from crustacean shells, are incorporated into various cosmetic applications including UV-protective emulsions, anti-aging masks, moisturizing films, and antimicrobial formulations. Moreover, natural calcium phosphates (CaP), especially hydroxyapatite (HA) produced from fish bones and scales, are being explored as functional ingredients in sunscreens and skincare products. Collectively, these marine-derived compounds present promising, sustainable alternatives for the development of high-value cosmetic products (Siahaan et al., 2022).

Health Effects

In recent years, there has been a marked rise in research focused on incorporating bioactive compounds derived from fish processing waste into food products. For functional and nutraceutical applications aimed at disease prevention, the stability, biological activity, and bioavailability of these compounds are crucial determinants of efficacy. Nevertheless, understanding of their behavior during food processing and within complex food matrices remains limited. As an example, high-quality oil obtained through fermentation of sea bass waste has been explored as a dietary supplement for both human and animal consumption (Marti-Quijal et al., 2020).

Fish-derived nutraceuticals have been associated with multiple health benefits, including delaying aging, preventing both acute and chronic diseases, and promoting longevity. The rapid pace of urbanization and increasingly stressful lifestyles have contributed to the global expansion of the nutraceutical market (Bakare et al., 2020). Bioactive phytochemicals—such as polyphenols, flavonoids, and carotenoids exhibit a wide range of therapeutic activities, including anti-inflammatory, antioxidant, antimicrobial, and antiallergic effects (Ashraf et al., 2020). Similarly, concentrated lipids, highly digestible proteins, and essential micro- and macronutrients sourced from fish and their by-products hold promise for addressing global malnutrition challenges (Bakare et al., 2020). Protein hydrolysates from fish waste are utilized to produce bioactive peptides, which, in animal studies, have shown beneficial effects on bone and skin health, cholesterol regulation, and weight management. Fish oil, particularly rich in eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), provides antithrombotic, anti-inflammatory, cardioprotective, and neuroprotective benefits. Regular intake of 3–4 grams of omega-3 fatty acids per day has been linked to reductions in plasma triglyceride levels by around 30%. In addition, fish oil has demonstrated protective effects against cardiovascular disease, improved survival following myocardial infarction, and a reduction in overall mortality risk. It is also a significant dietary source of vitamin D, with herring and cod liver oils being especially abundant in this micronutrient (Gasco et al., 2020).

Future Perspectives

The recovery of proteins from seafood industry by-products is poised to play a strategically important role in ensuring food security, promoting sustainability, and advancing circular economy objectives. Progress in this field requires the development of innovative extraction technologies alongside the strengthening of the technological infrastructure needed to transition from laboratory-scale experiments to pilot and full-scale industrial production. This upscaling process should be guided not only by technical optimization but also by comprehensive cost–benefit analyses and industrial integration strategies. Successful knowledge transfer and technology adoption will depend on interdisciplinary collaboration, bringing together expertise from biotechnology, food engineering, economics, environmental sciences, and regulatory fields to overcome technical constraints and accelerate commercialization.

Within this framework, systematic life cycle assessments (LCA) are essential to evaluate the environmental impacts associated with producing recycled proteins and to design strategies for minimizing these effects. Similarly, economic modeling aimed at assessing the feasibility of large-scale recycling projects should account not only for production costs but also for market conditions, consumer demand, and competition within the sustainable products sector. The establishment of internationally recognized standards for product safety and quality assurance will be critical for accessing global markets. In parallel, educational initiatives and awareness campaigns designed to improve public understanding will foster greater societal acceptance of recycled protein sources.

During market development, tools such as sustainability labeling, carbon footprint reporting, and green certifications can help build consumer trust. Moreover, the enhancement of waste management policies and the integration of seafood processing activities into sustainable raw material supply chains are key for ensuring the long-term success of innovations in this domain. In conclusion, the future of protein recovery from seafood by-products depends on a holistic approach that combines technological advancement, economic feasibility, regulatory compliance, and societal endorsement. By implementing such multidimensional strategies, it will be possible to create a sustainable food system that not only meets global protein demands but also promotes efficient resource utilization and reduces environmental impact.

Economic Evaluation

The valorization of fish waste has gained attention as a sustainable strategy that aligns closely with the core principles of circular economy and zero-waste biorefinery models. This approach not only helps reduce the environmental pollution associated with fish processing but also unlocks significant economic potential by making better use of biological resources that are often overlooked. In particular, the adoption of green extraction technologies contributes to environmental sustainability while supporting local employment opportunities in coastal and fishing communities (Hussain et al., 2025).

In recent years, the circular economy concept has been widely embraced as a key framework for minimizing the environmental footprint of industrial activities and promoting sustainable development. This model emphasizes the reuse, recycling, and recovery of products, materials, and processes with the goal of regenerating natural resources and reducing waste generation (Nobre & Tavares, 2021). With the global population growing and consumption patterns evolving, the traditional linear "take-make-consume-dispose" production model has become increasingly unsustainable, intensifying problems like pollution, resource depletion, and climate change. As a result, governments, industries, and civil society groups are progressively adopting circular and regenerative economic models focused on turning waste streams into valuable resources (Velenturf & Purnell, 2021). The fish processing industry presents a notable opportunity to apply circular economy principles effectively. Processing operations such as bleeding, gutting, filleting, and cutting generate by-products that can account for approximately 60–70% of the fish's total weight. These by-products typically include heads, scales, fins, skin, viscera, and skeletons (de Medeiros et al., 2019). Due to their high moisture content and enzymatic activity, these materials spoil quickly and pose considerable environmental risks if not handled and valorized properly. Traditionally, they have been relegated to low-value uses such as fishmeal, fertilizers, and animal feed; however, the industry is shifting towards more innovative applications that offer greater economic returns (Puja et al., 2024). This shift aims to maximize both the economic and environmental value of fish processing waste by converting it into high-value products, thereby reducing disposal costs and lessening environmental impacts. Such efforts align well with the United Nations Sustainable Development Goals (SDGs) targeted for 2030 (Thirukumaran et al., 2022).

Fish waste is a rich source of valuable compounds with diverse industrial applications. Collagen extracted from fish scales and bones is widely used in the medical and cosmetic fields, while gelatin derived from fish skin finds application in edible films and coating materials. Viscera can be processed to obtain hydrolysates rich in peptides and enzymes, which have important roles in biotechnology (Sun et al., 2023). Oils obtained from fish waste are abundant in omega-3 fatty acids and enjoy strong demand within nutraceutical and pharmaceutical markets. Additionally, lipids extracted from fish waste present promising options for biofuel production, offering sustainable alternatives in the energy sector. Fully valorizing these resources not only reduces environmental burdens but also fosters economic growth, technological innovation, and job creation, all within the circular economy framework (Penarubia et al., 2023).

In summary, integrating fish waste processing into innovative biorefinery models based on circular economy principles holds critical importance for environmental protection and economic advancement. This strategy supports the conservation of natural resources while adding value throughout the fisheries and aquaculture sectors.

CONCLUSION

The conversion of waste generated by the seafood industry into valuable bioactive compounds plays a pivotal role in advancing sustainability objectives. This process not only helps reduce the environmental harm caused by waste accumulation but also opens avenues for creating innovative products that enhance the economic value of the sector. Recovering proteins, lipids, peptides, and other functional molecules is particularly important for reintegrating seafood by-products into the value chain. The utilization of these bioactive substances across various biotechnological applications addresses waste management challenges while providing sustainable solutions in healthcare, food production, cosmetics, and pharmaceuticals.

Employing environmentally friendly green extraction techniques during this conversion process reduces both energy consumption and chemical usage, thereby lessening negative environmental impacts. However, widespread industrial adoption of these technologies requires thorough economic evaluations and technical refinements to ensure feasibility and efficiency. In summary, transforming seafood industry waste into bioactive ingredients represents a complex yet promising strategy that simultaneously advances environmental protection, economic development, and innovative technological progress.

REFERENCES

Altintzoglou, T., Honkanen, P., & Whitaker, R. D. (2021). Influence of the involvement in food waste reduction on attitudes towards sustainable products containing seafood by-products. *Journal of Cleaner Production*, 285, Article 125487. https://doi.org/10.1016/j.jclepro.2020.125487

Al Khawli, F., Pateiro, M., Domínguez, R., Lorenzo, J. M., Gullón, P., Kousoulaki, K., & Barba, F. J. (2019). Innovative green technologies of intensification for valorization of seafood and their by-products. *Marine Drugs*, *17*(12), 689. https://doi.org/10.3390/md17120689

Ashraf, S. A., Adnan, M., Patel, M., Siddiqui, A. J., Sachidanandan, M., Snoussi, M., & Hadi, S. (2020). Fish-based bioactives as potent nutraceuticals: Exploring the therapeutic perspective of sustainable food from the sea. *Marine Drugs*, 18(5), 265. https://doi.org/10.3390/md18050265

Aqua Food. (2023). Customer event – taste testing salmon proteins. https://aquafood. se/ (Accessed 30 November 2024).

Baker's, H. J. (2023). H.j.baker- Established, 1850. https://hjbaker.com/. (Accessed 30 November 2024)

Bakare, A. H., Adeola, A. A., Otesile, I., Obadina, A. O., Afolabi, W. A., Adegunwa, M. O., & Alamu, E. O. (2020). Nutritional, texture, and sensory properties of composite biscuits produced from breadfruit and wheat flours enriched with edible fish meal. *Food Science & Nutrition*, *8*(11), 6226-6246.. https://doi.org/10.1002/fsn3.1919

Caruso, G., Floris, R., Serangeli, C., & Di Paola, L. (2020). Fishery wastes as a yet undiscovered treasure from the sea: Biomolecules sources, extraction methods and valorization. *Marine Drugs*, *18*(12), 622. https://doi.org/10.3390/md18120622

Chomnawang, C., & Yongsawatdigul, J. (2013). Protein recovery of tilapia frame byproducts by pH-shift method. *Journal of Aquatic Food Product Technology*, 22(2), 112–120. https://doi.org/10.1080/10498850.2011.629077

Coppola, D., Lauritano, C., Palma Esposito, F., Riccio, G., Rizzo, C., & de Pascale, D. (2021). Fish waste: From problem to valuable resource. *Marine Drugs*, *19*(2), 116. https://doi.org/10.3390/md19020116

Da Rocha, M., Alemán, A., Baccan, G. C., López-Caballero, M. E., Gómez-Guillén, C., Montero, P., & Prentice, C. (2018). Anti-inflammatory, antioxidant, and antimicrobial effects of underutilized fish protein hydrolysate. *Journal of Aquatic Food Product Technology*, *27*(5), 592-608. https://doi.org/10.1080/10498850.2018.1461160

De Luca, C., Mikhal'chik, E. V., Suprun, M. V., Papacharalambous, M., Truhanov, A. I., & Korkina, L. G. (2016). Skin antiageing and systemic redox effects of supplementation with marine collagen peptides and plant-derived antioxidants: a single-blind case-control clinical study. *Oxidative Medicine and Cellular Longevity*, *2016*(1), 4389410. https://doi.org/10.1155/2016/4389410

de Medeiros, E. F., da Silva Afonso, M., dos Santos, M. A. Z., Bento, F. M., Quadro, M. S., & Andreazza, R. (2019). Physicochemical characterization of oil extraction from fishing waste for biofuel production. *Renewable Energy*, *143*, 471-477. https://doi.org/10.1016/j.renene.2019.04.165

Elango, J., Zhang, J., Bao, B., Palaniyandi, K., Wang, S., Wenhui, W., & Robinson, J. S. (2016). Rheological, biocompatibility and osteogenesis assessment of fish collagen scaffold for bone tissue engineering. *International Journal of Biological Macromolecules*, *91*, 51-59. https://doi.org/10.1016/j.ijbiomac.2016.05.067

FAO. (2018). BlueFashion: From lake Turkana to the runway. FAO stories. Food And Agriculture Organization of the United Nations. https://www.fao.org/fao-stories/article/

FAO. (2022). The state of world fisheries and aquaculture 2022. Towards Blue Transformation. https://doi.org/10.4060/cc0461en. Rome, FAO.

FAO. The State of World Fisheries and Aquaculture 2022: Toward Blue Transfromation; FAO: Rome, Italy, 2022.

Ferraro, V., Carvalho, A. P., Piccirillo, C., Santos, M. M., Castro, P. M., & Pintado, M. E. (2013). Extraction of high added value biological compounds from sardine, sardine-type fish and mackerel canning residues. A review. *Materials Science and Engineering: C*, *33*(6), 3111-3120. https://doi.org/10.1016/j.msec.2013.04.003

Fusaro, D. (2023). Ready to eat fish bones in the name of sustainability? Food Processing. https://www.foodprocessing.com/ingredients/animal-proteins/article/33000393/ready-to-eat-fish-bones-in-the-name-of-sustainability. (Accessed 30 November 2023).

Ganjeh, A. M., Saraiva, J. A., Pinto, C. A., Casal, S., & Silva, A. M. (2023). Emergent technologies to improve protein extraction from fish and seafood by-products: an overview. *Applied Food Research*, *3*(2), 100339. https://doi.org/10.1016/j.afres.2023.100339

Gasco, L., Acuti, G., Bani, P., Dalle Zotte, A., Danieli, P. P., De Angelis, A., ... & Roncarati, A. (2020). Insect and fish by-products as sustainable alternatives to conventional animal proteins in animal nutrition. *Italian Journal of Animal Science*, *19*(1), 360-372. https://doi.org/10.1080/1828051X.2020.1743209

Gilman, E., Perez Roda, A., Huntington, T., Kennelly, S. J., Suuronen, P., Chaloupka, M., & Medley, P. A. H. (2020). Benchmarking global fisheries discards. *Scientific Reports*, *10*(1), 14017. https://doi.org/10.1038/s41598-020-71021-x

Hassoun, A., Siddiqui, S. A., Smaoui, S., Ucak, İ., Arshad, R. N., Garcia-Oliveira, P., ... & Bono, G. (2022). Seafood processing, preservation, and analytical techniques in the age of Industry 4.0. *Applied Sciences*, *12*(3), 1703. https://doi.org/10.3390/app12031703

Helmer, J. (2023). Seafood byproducts reel in a new wave of innovators responsible Seafood Advocate. https://www.globalseafood.org/advocate/seafood-byproductsreel-in-a-new-wave-of-innovators/. (Accessed 30 November 2023).

Hinchcliffe, J., Carlsson, N. G., Jönsson, E., Sundell, K., & Undeland, I. (2019). Aquafeed ingredient production from herring (Clupea harengus) by-products using pH-shift processing: Effect from by-product combinations, protein solubilization-pH and centrifugation force. *Animal Feed Science and Technology*, *247*, 273-284. https://doi.org/10.1016/j.anifeedsci.2018.07.014

Hussain, I. A., & Yasmin, R. (2025). Transforming Fish Waste for Economic and Environmental Gains. *Scientia Review*, *1*(1), 1-11.

IFFO. By-Product. Available online: www.iffo.com/product (accessed on 13 September 2024).

Kerecis. (2023). Intact fish skin for tissue regeneration - Kerecis.com. https://www.ker ecis.com/. (Accessed 30 November 2025).

Khan, S., Rehman, A., Shah, H., Aadil, R. M., Ali, A., Shehzad, Q., ... & Xia, W. (2022). Fish protein and its derivatives: The novel applications, bioactivities, and their functional significance in food products. *Food Reviews International*, *38*(8), 1607-1634. https://doi.org/10.1080/87559129.2020.1828452

Khan, S., Rehman, A., Shah, H., Aadil, R. M., Ali, A., Shehzad, Q., & Xia, W. (2022). Fish protein and its derivatives: The novel applications, bioactivities, and their functional significance in food products. *Food Reviews International*, *38*(8), 1607-1634. https://doi.org/10.1080/87559129.2020.1828452

Koenigsberger, H. G. (2014). *Medieval Europe 400-1500*. Routledge. https://doi.org/10.4324/9781315836447

Langasco, R., Cadeddu, B., Formato, M., Lepedda, A. J., Cossu, M., Giunchedi, P., (2019). Microparticles, microspheres, and microcapsules for advanced drug delivery. *Scientia Pharmaceutica,* 87(3), Article 20. https://doi.org/10.3390/scipharm87030020

Lengyel, M., K´ allai-Szabo, ´ N., Antal, V., Laki, A. J., & Antal, I. (2019). Microparticles, microspheres, and microcapsules for advanced drug delivery. *Scientia Pharmaceutica*, 87(3). Article 20. https://doi.org/10.3390/scipharm87030020

Lim, Y. S., Ok, Y. J., Hwang, S. Y., Kwak, J. Y., & Yoon, S. (2019). Marine collagen as a promising biomaterial for biomedical applications. *Marine Drugs*, 17(8), Article 467. https://doi.org/10.3390/md17080467

Liu, Y., Huang, Y., Wang, Z., Cai, S., Zhu, B., & Dong, X. (2021). Recent advances in fishy odour in aquatic fish products, from formation to control. *International Journal of Food Science and Technology,* 56(10), 4959–4969. https://doi.org/10.1111/ijfs.15269

Loboguerrero, A. M., Campbell, B. M., Cooper, P. J. M., Hansen, J. W., Rosenstock, T., & Wollenberg, E. (2019). Food and earth systems: Priorities for climate change adaptation and mitigation for agriculture and food systems. *Sustainability*, 11(5), Article 1372. https://doi.org/10.3390/SU11051372

Maia Campos, P. M. B. G., Franco, R. S. B., Kakuda, L., Cadioli, G. F., Costa, G. M. D. A., & Bouvret, E. (2021). Oral supplementation with hydrolyzed fish cartilage improves the morphological and structural characteristics of the skin: a double-blind, placebo-controlled clinical study. *Molecules*, *26*(16), 4880. https://doi.org/10.3390/molecules26164880

Marti-Quijal, F. J., Remize, F., Meca, G., Ferrer, E., Ruiz, M. J., & Barba, F. J. (2020). Fermentation in fish and by-products processing: An overview of current research and future prospects. *Current Opinion in Food Science*, 31, 9-16. https://doi.org/10.1016/j.cofs.2019.08.001

Mutalipassi, M., Esposito, R., Ruocco, N., Viel, T., Costantini, M., & Zupo, V. (2021). Bioactive compounds of nutraceutical value from fishery and aquaculture discards. *Foods*, 10(7), Article 1495. https://doi.org/10.3390/FOODS10071495

Mozumder, M. M. H., Uddin, M. M., Schneider, P., Raiyan, M. H. I., Trisha, M. G. A., Tahsin, T. H., & Newase, S. (2022). Sustainable utilization of fishery waste in Bangladesh—A qualitative study for a circular bioeconomy initiative. *Fishes*, *7*(2), 84. https://doi.org/10.3390/fishes7020084

Nelluri, P., Rout, R. K., Tammineni, D. K., Joshi, T. J., & Sivaranjani, S. (2024). Technologies for management of fish waste & value addition. *Food and Humanity*, *2*, 100228. https://doi.org/10.1016/j.foohum.2024.100228

Nobre, G. C., & Tavares, E. (2021). The quest for a circular economy final definition: A scientific perspective. *Journal of Cleaner Production*, *314*, 127973. https://doi.org/10.1016/j.jclepro.2021.127973

Nguyen, T. T., Heimann, K., & Zhang, W. (2020). Protein recovery from underutilised marine bioresources for product development with nutraceutical and pharmaceutical bioactivities. *Marine Drugs*, 18(8), Article 391. https://doi.org/10.3390/md18080391

Nisov, A., Kakko, T., Alakomi, H. L., Lantto, R., & Honkap¨ aa, ¨ K. (2021). Comparison of enzymatic and pH shift methods to extract protein from whole Baltic herring (Clupea harengus membras) and roach (Rutilus rutilus). *Food Chemistry*, 373, Article 131524. https://doi.org/10.1016/j.foodchem.2021.131524

Panpipat, W., & Chaijan, M. (2017). Functional properties of pH-shifted protein isolates from bigeye snapper (Priacanthus tayenus) head by-product. *International Journal of Food Properties*, 20(3), 596–610. https://doi.org/10.1080/10942912.2016.1171778

Pelagic Seafood. (2023). Fish burgers and nuggets. https://pelagicseafood.se/. (Accessed 30 November 2024).

Pinela, J., Fuente, B. D. L., Rodrigues, M., Pires, T. C., Mandim, F., Almeida, A., ... & Barros, L. (2022). Upcycling fish by-products into bioactive fish oil: The suitability of microwave-assisted extraction. *Biomolecules*, *13*(1), 1. https://doi.org/10.3390/biom13010001

Pal, G. K., & Suresh, P. V. (2016). Sustainable valorisation of seafood by-products: Recovery of collagen and development of collagen-based novel functional food ingredients. *Innovative food science & emerging technologies*, *37*, 201-215. https://doi.org/10.1016/j.ifset.2016.03.015

Perez-Llor´ens, J. L., Acosta, Y., & Brun, F. G. (2021). Seafood in mediterranean countries: A culinary journey through history. *International Journal of Gastronomy and Food Science*, 26, Article 100437. https://doi.org/10.1016/j.ijgfs.2021.100437

Peñarubia, O., Toppe, J., Ahern, M., Ward, A., & Griffin, M. (2023). How value addition by utilization of tilapia processing by-products can improve human nutrition and livelihood. *Reviews in Aquaculture*, *15*, 32-40. https://doi.org/10.1111/raq.12737

Rustad, T. Utilisation of marine by-products. J. Environ. Agric. *Food Chem*. 2003, 2, 458–463.

Rushan Ocean Development Bureau. (2023). Reply from rushan municipal Ocean Development Bureau to proposal No. 7 of the second session of the eleventh CPPCC committee “recommendations on further promoting the industrialization of rushan oysters.”. http://www.rushan.gov.cn/art/2023/8/2/art_71905_3853549.html. (Accessed 30 November 2023).

Scogal. (2023). Accueil - English - scogal. https://www.scogal.fr/en/accueil-english /#about.us.

Sasidharan, A., & Venugopal, V. (2020). Proteins and co-products from seafood processing discards: Their recovery, functional properties, and applications. *Waste and Biomass Valorization*, 11(11), 5647–5663. https://doi.org/10.1007/S12649-019- 00812

Szymczak, M., Kaminski, P., Szymczak, B., Shen, C., Matak, K. E., & Jaczynski, J. (2024). Process scale-up for the application of fish protein isolate obtained from processing co-products by isoelectric solubilization/precipitation. *Food and Bioprocess Technology*, 1–16. https://doi.org/10.1007/s11947-024-03319-x

Surasani, V. K. R. (2018). Acid and alkaline solubilization (pH shift) process: a better approach for the utilization of fish processing waste and by-products. *Environmental Science and Pollution Research*, *25*(19), 18345-18363. https://doi.org/10.1007/s11356-018-2319-1

Surasani, V. K. R., Mandal, A., Sofi, F. R., & Joshi, S. (2022). Utilization of pangas protein isolates and by-products in fish sausages: Effect on quality attributes and acceptability. *Journal of Food Processing and Preservation*, 46(8), Article e16798. https://doi.org/10.1111/jfpp.16798

Sionkowska, A., Adamiak, K., Musiał, K., & Gadomska, M. (2020). Collagen based materials in cosmetic applications: A review. *Materials*, *13*(19), 4217. https://doi.org/10.3390/ma13194217

Siahaan, E. A., Agusman, Pangestuti, R., Shin, K. H., & Kim, S. K. (2022). Potential cosmetic active ingredients derived from marine by-products. *Marine Drugs*, *20*(12), 734. https://doi.org/10.3390/md20120734

Sun, J., Sun, M., Zang, J., Zhang, T., Lv, C., & Zhao, G. (2023). Highly stretchable, transparent, and adhesive double-network hydrogel dressings tailored with fish gelatin and glycyrrhizic acid for wound healing. *ACS Applied Materials & Interfaces*, *15*(36), 42304-42316. https://doi.org/10.1021/acsami.3c09615.

Tian, Y., Wang, W., Yuan, C., Zhang, L., Liu, J. J., & Liu, J. J. (2017). Nutritional and digestive properties of protein isolates extracted from the muscle of the common carp using pH-shift processing. *Journal of Food Processing and Preservation*, 41(1), Article e12847. https://doi.org/10.1111/jfpp.12847

Thirukumaran, R., Priya, V.K.A., Krishnamoorthy, S., Ramakrishnan, P., Moses, J., Anandharamakrishnan, C., (2022). Resource recovery from fish waste: Prospects and the usage of intensified extraction technologies. *Chemosphere* 299, 134361. https://doi.org/10.1016/j.chemosphere.2022.134361

United Nations. (2022). World Population Prospects 2022: Summary of results. United Nations. https://www.un.org/development/desa/pd/content/World-Population-Pro spects-20

Velenturf, A.P., Purnell, P., (2021). Principles for a sustainable circular economy. *Sustainable Prod. Consumption* 27, 1437–1457. https://doi.org/10.1016/j. spc.2021.02.018.

Vidanarachchi, J. K., Ranadheera, C. S., Wijerathne, T. D., Udayangani, R. M. C., Himali, S. M. C., & Pickova, J. (2014). Applications of seafood by-products in the food industry and human nutrition. In S. Kim (Ed.), *Seafood processing by-products Trends and applications* (pp. 463–528). John Wiley & Sons, Ltd. https://doi.org/10.1007/978-1-4614-9590-1_23

Zargar, V., Asghari, M. & Dashti, A. (2015). A review on chitin and chitosan polymers: structure, chemistry, solubility, derivatives, and applications. *Chemical and Biochemical Engineering* Reviews, 2(3), 204-226. https://doi.org/10.1002/cben.201400025

Zhang, J., Abdollahi, M., Alminger, M., & Undeland, I. (2022). Cross-processing herring and salmon co-products with agricultural and marine side-streams or seaweeds produces protein isolates more stable towards lipid oxidation. *Food Chemistry*, 382, Article 132314. https://doi.org/10.1016/j.foodchem.2022.132314

Zhang, J., Akyol, Ç., & Meers, E. (2023). Nutrient recovery and recycling from fishery waste and by-products. *Journal of Environmental Management*, 348, Article 119266. https://doi.org/10.1016/j.jenvman.2023.119266

Zhang, J., Ahmmed, M. K., Regenstein, J. M., & Wu, H. (2024). Recent advances of recycling proteins from seafood by-products: Industrial applications, challenges, and breakthroughs. *Trends in Food Science & Technology*, *149*, 104533. https://doi.org/10.1016/j.tifs.2024.104533

WASEABI. (2023). Turning fish parts into valuable products and ingredients. https://cor dis.europa.eu/article/id/436670-turning-fish-parts-into-valuable-products-and-ingr edients.

Wu, H., Forghani, B., Abdollahi, M., & Undeland, I. (2022a). Five cuts from herring (Clupea harengus): Comparison of nutritional and chemical composition between coproduct fractions and fillets. *Food Chemistry* X, 16, Article 100488. https://doi.org/10.1016/j.fochx.2022.100488