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Functional Ingredients from Fishery By-products: Nutraceutical and Pharmaceutical Applications

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ABSTRACT

The sustainable utilization of fishery by-products has gained significant attention for their potential bioactive compounds with nutraceutical and pharmaceutical applications. Fish heads, skins, bones, and viscera, once considered waste, were now recognized for their rich content of proteins, peptides, omega-3 fatty acids, collagen, chitin, and various antioxidants. These compounds exhibited bioactivities such as anti-inflammatory, antioxidant, antimicrobial, and antihypertensive effects, making them valuable for health-promoting applications. Proteins and bioactive peptides derived from fishery by-products contributed to cardiovascular health, immune modulation, and metabolic regulation. Omega-3 fatty acids, mainly found in fish oils, support brain function, cardiovascular health, and inflammatory disease management. Chitin and chitosan from crustacean shells exhibited wound-healing, antimicrobial, and drug delivery properties. Marine collagen and gelatin, obtained from fish skins and bones, had applications in skin rejuvenation, joint health, and tissue repair. Additionally, fish-derived enzymes, such as pepsin and trypsin, have shown promising applications in the food industry, biomedicine, and wastewater treatment due to their biodegradability and functional properties. These functional ingredients were widely utilized in dietary supplements, functional foods, pharmaceuticals, and cosmeceuticals. Advances in bioprocessing technologies enhance their extraction and bioavailability, further promoting their commercialization. The valorization of fishery by-products not only reduced environmental waste but also supported a circular economy. This review explored the key bioactive compounds derived from fishery by-products, their health benefits, and their growing applications in nutraceutical and pharmaceutical industries.

KEYWORDS: By-products, bioactive compunds, functional foods, health supplements, sustainability

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1. INTRODUCTION

The seafood industry generates a large volume of waste, with nearly 50–60% of fish mass, which can be converted into by-products (Anonymous, 2020). Fish processing waste is generally divided into two categories: solid and liquid waste. Solid waste primarily consists of fish bones and flesh, while liquid waste comes from blood, water, and brine. Some of these by-products are repurposed as feed and oil for livestock, while others serve as raw materials for bio-based products like biofuels and compost (Pateiro et al., 2021).

A substantial portion of fish by-products, not intended for direct human consumption, is generated annually through fishing activities, accounting for 30–85% of the total weight of various catches. The proportion of edible fish to by-products varies based on species, size, season, and fishing location. These by-products include fish fins, gills, backbones, heads, belly flaps, liver, roe, skin, and viscera. Statistical data indicate that heads make up 9–12% of total fish weight, viscera 12–18%, skin 1–3%, bones 9–15%, and scales approximately 5% (Khan et al., 2020).

Given the geographically dispersed nature of fish production, landing, and processing, immediate local processing is the most effective strategy for converting fish waste into high-value products. Prompt collection and treatment are essential to maintaining quality and ensuring that fish by-products can be used as raw materials (Alfio et al., 2021; Ghosh et al., 2024). However, fish waste remains an underutilized resource, as its processing has not yet reached a fully optimized state. One of the biggest challenges in managing fish waste is the lack of value-added applications for the products and services derived from it (Saleh et al., 2020).

To address this issue, researchers have explored the extraction of bioactive compounds from fish proteins. During processing, valuable bioactive peptides, amino acids, and other nitrogenous substances can be obtained. Establishing efficient and safe extraction methods is crucial for maximizing the utilization of marine resources (Behera, 2022). Traditionally considered low-value, these by-products have recently gained attention for their bioactive components that offer significant health benefits (Venugopal, 2021). Proper utilization of these resources can enhance sustainability while creating new commercial opportunities in the nutraceutical and pharmaceutical sectors (Gómez-Guillén et al., 2011).

Fishery by-products such as fish heads, skins, bones, and viscera are rich in proteins, peptides, omega-3 fatty acids, collagen, chitin, and various antioxidants. These bioactive compounds exhibit numerous health benefits, including antioxidant, anti-inflammatory, antihypertensive, antimicrobial, and immune-modulating properties (Jimenez-Champi et al., 2024). Traditionally, fishery by-products were used in low-value applications such as animal feed and fertilizers, but recent advancements in biotechnology and processing techniques have unlocked their potential in high-value nutraceutical and pharmaceutical industries (Xia, 2024). Figure 1 illustrates the most common fishery by-products and their important bioactive components.

Additionally, utilizing fishery by-products aligns with the principles of a circular economy, reducing waste while extracting valuable compounds for health applications (Olaniran, 2024). Emerging technologies such as enzymatic hydrolysis, fermentation, and supercritical fluid extraction have improved the efficiency of recovering bioactive ingredients, further supporting sustainable practices in the seafood industry (Caruso, 2020). Government regulations and industry-driven initiatives continue to promote the utilization of these by-products, fostering innovation in product development and ensuring compliance with environmental standards (Anonymous, 2020).

Research has also highlighted the potential of fishery by-products in personalized nutrition and medicine, where bioactive compounds are tailored to address specific health concerns, such as cardiovascular diseases, metabolic disorders, and inflammatory conditions (Tacon, 2024). The increasing consumer preference for natural and marine-based supplements has further accelerated the demand for functional ingredients derived from fishery by-products, positioning them as essential components in modern health and wellness solutions (Calado et al., 2018). This review explored key bioactive compounds derived from fishery by-products and their nutraceutical and pharmaceutical applications.

2. MAJOR FUNCTIONAL INGREDIENTS FROM FISHERY BY-PRODUCTS

2.1. Proteins and peptides

Fish-derived proteins and bioactive peptides have been widely recognized for their health-promoting properties. These peptides, obtained through enzymatic hydrolysis of fish by-products, have demonstrated antihypertensive, antioxidant, and antimicrobial effects. Bioactive peptides regulate blood pressure by inhibiting angiotensin-converting enzyme (ACE), while their antioxidant properties helped combat oxidative stress (Venugopal, 2021). Additionally, fish-derived proteins enhanced the immune responses and muscle recovery, making them valuable in functional food and pharmaceutical applications.

Recent research has identified several bioactive peptides from fishery by-products with potential anti-obesity and

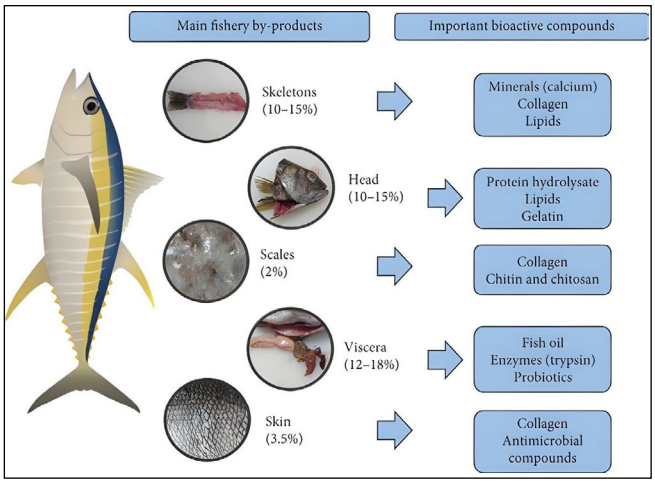

Figure 1: Most common fishery by-products and their most important components

anti-diabetic properties. These peptides could modulate glucose metabolism by influencing insulin secretion and glucose uptake in cells, making them promising candidates for managing metabolic disorders (Jimenez-Champi et al., 2024). Additionally, fish proteins have been found to exhibit antimicrobial properties, inhibiting the growth of harmful pathogens, which enhanced food safety and extended shelf life in food applications (Rathod, 2021).

Furthermore, certain peptides derived from fish by-products have been associated with neuroprotective effects, potentially played a role in preventing neurodegenerative diseases such as Alzheimer's and Parkinson's (Olaniran, 2024). The functional properties of fish-derived proteins and peptides continued to be explored, expanding their applications in nutraceuticals, pharmaceuticals, and functional foods.

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2.2. Omega-3 fatty acids

Omega-3 polyunsaturated fatty acids (PUFAs), including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), were abundantly found in fish heads, liver, and viscera. These essential fatty acids played a critical role in brain development, cardiovascular health, and inflammation regulation. Studies have shown that omega-3 fatty acids reduced the risk of heart disease, improved cognitive function, and supported mental health (Pateiro, M., 2021). The extraction of omega-3s from fishery by-products provided a sustainable alternative to traditional fish oil sources, further enhancing the circular economy of the seafood industry.

Recent studies indicated that omega-3 fatty acids might also play a role in reducing depression and anxiety by modulating neurotransmitter functions and reducing inflammation in the brain (Zhou, 2022). Additionally, these essential fatty acids have been linked to improved eye health, particularly in preventing age-related macular degeneration (Olaniran, 2024).

Furthermore, omega-3 fatty acids from fishery by-products have been explored for their potential anti-cancer properties. Research suggested that EPA and DHA might help inhibit tumor growth and proliferation by modulating inflammatory pathways and apoptosis in cancer cells (Venugopal, 2021). Their incorporation into functional foods and supplements continues to gain attention for their wide-range of health benefits.

2.3. Chitin and chitosan

Crustacean shells were rich in chitin, a biopolymer that could be converted into chitosan through deacetylation. Chitosan exhibited antimicrobial, wound-healing, and antioxidant properties, making it a valuable ingredient in biomedical and pharmaceutical applications (Ramakrishnan, 2023). It has been widely used in drug delivery systems, tissue engineering, and as a natural food preservative due to its biocompatibility and biodegradability.

Recent research has highlighted the potential of chitoan in weight management, as it could bind to dietary fats, reducing fat absorption and aiding in obesity prevention (Shagdarova et al., 2023). Additionally, studies suggest that chitosan might help regulate blood sugar levels, making it beneficial for diabetic patients (Sarkar, 2020).

Furthermore, chitosan has been investigated for its immunomodulatory properties, demonstrating the ability to enhance immune function and supported gut health by promoting the growth of beneficial gut microbiota (Moran, 2018). Its role in water purification, as an eco-friendly agent for heavy metal and toxin removal, further expands its applications beyond the health sector (Sheth, 2021).

2.4. Collagen and gelatin

Collagen and its derivative gelatin, extracted from fish skin and bones, have gained significant commercial interest in the nutraceutical, pharmaceutical, and cosmetic industries. Marine collagen was known for its superior bioavailability compared to terrestrial sources and played a crucial role in skin health, joint support, and wound healing (Geahchan,

2022). Gelatin, derived from collagen hydrolysis, was used in food formulations, pharmaceuticals, and encapsulation technologies for drug delivery systems (Furtado, 2022).

Recent studies suggested that marine collagen supplementation could improve skin elasticity and hydration while reducing signs of aging, making it a preferred ingredient in anti-aging products (Jimenez-Champi et al., 2024). Additionally, collagen peptides have been associated with improved bone mineral density, suggesting potential benefits in osteoporosis prevention (Venugopal, 2021).

Furthermore, collagen from fishery by-products has demonstrated anti-inflammatory and wound-healing properties, making it beneficial for tissue regeneration and biomedical applications (Olaniran, 2024). Its role in cartilage repair and joint health has also been explored, with studies indicating its effectiveness in alleviating symptoms of osteoarthritis (Lv, 2019). These multifunctional properties make collagen and gelatin from fishery by-products valuable in both medical and commercial industries (Ozogul, 2021). These compounds were also utilized in anti-aging products, where they helped improve skin hydration and elasticity, making them popular in beauty and personal care applications (Jadach, 2024).

2.5. Antioxidants and bioactive compounds

Fishery by-products were a rich source of natural antioxidants, including astaxanthin, tocopherols, and squalene. These compounds exhibited potent free radical scavenging properties, protecting against oxidative stress and reducing the risk of chronic diseases (Jimenez-Champi et al., 2024). Astaxanthin, a carotenoid found in shrimp and fish processing waste, has been widely researched for its anti-inflammatory and neuroprotective effects (Barros, 2014). Squalene, primarily obtained from shark liver oil, was used in cosmetic and pharmaceutical formulations due to its skin-protective and antioxidant properties (López-Puebla et al., 2025).

Recent studies have suggested that astaxanthin has cardioprotective effects by reducing oxidative stress and inflammation, which might help to prevent cardiovascular diseases (Venugopal, 2021). Additionally, tocopherols from fishery by-products have been found to enhance immune function and improve skin health by protecting against UV-induced damage (Gulzar, 2020).

Furthermore, bioactive compounds extracted from fishery by-products, such as polyphenols and flavonoids, have demonstrated antimicrobial properties, inhibiting the growth of pathogenic bacteria and extending the shelf life of food products (Olaniran, 2024). These compounds were being well utilized in functional foods, dietary supplements, and pharmaceutical applications for their health benefits. (López-Puebla et al., 2025).

2.6. Minerals and enzymes

Fish bones and scales provide essential minerals such as calcium, phosphorus, and magnesium, which contributed to bone health and metabolic functions. Enzymes derived from fishery by-products, such as proteases and lipases, have found applications in the food and pharmaceutical industries as they have numerous digestive and metabolic benefits (Muzaddadi, 2014). These bioactive enzymes aid in protein digestion, lipid metabolism, and anti-inflammatory responses.

Recent research suggested that fish-derived minerals played a role in preventing osteoporosis by enhancing calcium absorption and bone density (Jimenez-Champi et al., 2024). Additionally, marine-derived enzymes have been explored for their potential to aid in gut health by improving nutrient absorption and reducing inflammation in the digestive system (Han, 2024).

Furthermore, proteolytic enzymes extracted from fishery by-products have promising application in wound healing by promoting tissue repair and reducing scar formation (Olaniran, 2024). The growing interest in enzymatic supplements has led to the incorporation of enzymes derived from fish in functional foods and nutraceuticals to enhance their bioactivity and health benefits (Lal, 2023). Table 1 summarized the nutraceutical and pharmaceutical applications of various functional ingredients.

3. INDUSTRIAL STATUS AND TRENDS

The global market for fishery by-products has been growing due to increasing demand for sustainable and functional ingredients in food, pharmaceuticals, and cosmetics (Anonymous, 2020). Countries with well-developed seafood industries, such as Norway, Japan, and the United States, have made significant advancements in by-product processing and commercialization (Jimenez-Champi et al., 2024). Emerging economies were also investing in fishery by-product utilization to improve sustainability and economic value (Stevens, 2018).

Technological innovations, such as enzymatic hydrolysis and supercritical fluid extraction, have improved the efficiency of bioactive compound recovery (Ali, 2021). The application of nanotechnology and biotechnology in fisheries by-products was also expanding, leading to improved stability, bioavailability, and functionality of these ingredients (Ali, 2021). Consumer trends were shifting towards natural and marine-based supplements, further driving the demand for fishery-derived nutraceuticals and pharmaceuticals (Naseem, 2024). Regulatory bodies such as the FDA and EFSA were developing new guidelines to ensure the safety and efficacy of marine-derived functional ingredients, shaping industry standards and market expansion (Gómez-Guillén et al., 2011).

Table 1: Various nutraceutical and pharmaceutical applications of functional ingredients

Sl. No.	Functional ingredients	Nutraceutical and pharmaceutical applications	References
1.	Proteins and Peptides	Antihypertensive, antioxidant, antimicrobial, neuroprotective, metabolic disorder management	Venugopal, 2021
2.	Omega-3 Fatty Acids	Cardiovascular health, cognitive function, anti-inflammatory, mental health, eye health, potential anti-cancer properties	Olaniran, 2024
3.	Chitin and Chitosan	Antimicrobial, wound healing, obesity management, blood sugar regulation, immune support, water purification	Ramakrishnan et al., 2023
4.	Collagen and Gelatin	Skin health, anti-aging, joint support, wound healing, osteoporosis prevention, cartilage repair	Ozogul et al., 2021
5.	Antioxidants and Bioactive Compounds	Cardioprotective effects, immune function, UV protection, antimicrobial properties, neuroprotection	Venugopal, 2021; Olaniran, 2024
6.	Minerals and Enzymes	Bone health, metabolic support, gut health, inflammation reduction, wound healing	Jimenez-Champi et al., 2024

4. SUSTAINABLE UTILIZATION AND FUTURE PERSPECTIVES

The sustainable utilization of fishery by-products has gained significant attention due to its role in reducing waste, conserving marine resources, and promoting a circular economy (Anonymous, 2020). Advances in green extraction technologies, such as enzymatic hydrolysis and supercritical fluid extraction, have enhanced the recovery of bioactive compounds while minimizing environmental impact (Al Khawli, 2019). Implementing efficient processing methods can lead to increased commercial viability and encourage industries to integrate fishery by-products into various high-value applications (Stevens, 2018).

Government regulations and global sustainability initiatives were further driving the utilization of fishery by-products. Policies promoting zero-waste approaches and sustainable fishing practices have incentivized industries to invest in innovative product development (Olaniran, 2024). Additionally, collaborations between researchers and the food, pharmaceutical, and cosmetic industries were fostering the development of functional products enriched with bioactive compounds from marine sources (Jimenez-Champi et al., 2024).

Looking ahead, future research should focus on improving the bioavailability, stability, and efficacy of extracted compounds to enhance their nutraceutical and pharmaceutical applications. Emerging fields such as nanotechnology and biotechnology provided new opportunities for optimizing fishery-derived ingredients in drug delivery systems and personalized nutrition (Venugopal, 2021). Furthermore, consumer awareness of sustainable and natural health products was increasing demand for marine-based functional ingredients, shaping the future of the industry (Augusto, 2024).

5. CONCLUSION

The use of fishery by-products offered a sustainable way to reduce waste while providing valuable functional ingredients for nutraceutical and pharmaceutical applications. Advances in extraction and processing technologies improved bioavailability and commercial viability, enhancing industrial use. Collaboration among academia, industry, and policymakers drove innovation and regulatory compliance. Growing consumer demand for sustainable marine-based ingredients supported further expansion. Ongoing research into bioactive compound stability, efficacy, and delivery would promote economic growth, environmental conservation, and public health.

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