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Evaluating the potential of fisheries waste in promoting sustainable aquaculture practices

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Abstract
Substantial waste is produced by the commercial fishing sector, as parts like viscera, skeletal remains, scales, and skin are frequently treated as refuse, causing both ecological strain and the loss of valuable resources. Yet, there is a growing movement to view these leftovers as untapped assets. Through modern bioprocessing techniques, this discarded matter can be converted into premium goods, including medicines, health supplements, renewable energy, and eco-friendly packaging. By embracing this circular approach, the seafood industry can better align with international sustainability targets. This article investigates the multifaceted potential of these marine by-products, the framework of the circular economy, and the systemic hurdles that remain in achieving a fully sustainable supply chain.

Keywords: Food, collagen, gelatin, chitosen, fishmeal, fishoil

Introduction

As the human population rises, the need for fish and other marine foods is expected to climb, while climate-related shifts are forecast to curb the productivity of wild-capture fisheries (Tacon, 2002) [19]. Within this context, aquaculture has become essential for meeting global nutritional demands. Data from the Food and Agriculture Organization (FAO, 2019) [7] indicate that aquaculture is now the world’s fastest-expanding food-production sector, growing at an average rate of 6.6 % per year over the last ten years (Bayrakli and Duyar, 2019, 2021; Duyar and Bayrakli, 2023) [2, 3, 5]. Presently, about half of all seafood consumed worldwide comes from farmed sources, and projections suggest that aquaculture will soon overtake wild-caught fisheries in total output (FAO, 2019) [7].

The seafood processing and aquaculture industries are vital drivers of national economic development. According to FAO (2022) [6] data, global capture fisheries yielded 90.3 million tons in 2020, valued at approximately $141 billion. This output is highly concentrated, with China, Indonesia, Peru, India, Russia, the United States, and Vietnam accounting for 49% of the total. Given that 85% of this yield consists of finfish, these resources are increasingly recognized as essential sources of nutrition, providing a healthy dietary alternative that is particularly crucial for developing nations (Aspevik *et al.*, 2017; Torres *et al.*, 2018) [1, 20].

However, fish processing results in substantial waste, with by-products such as muscles (10%), skin and trimmings (3.5%), bones (9%–15%), heads (10%), viscera (12.5%), and scales (3.5%) making up roughly 60% of the raw material (Stevens *et al.*, 2018; Sasidharan and Venugopal, 2020) [18, 17]. As climate change and resource depletion continue to pose significant challenges, scientists are increasingly focused on refining processing technologies to better utilize these by-products, with a particular emphasis on the recovery of valuable bioactive compounds (Fraterrigo *et al.*, 2023) [9].

Repurposing seafood waste presents a significant economic and industrial opportunity for the fishing sector. By transforming these by-products into high-value goods, companies can improve overall resource efficiency and bolster their profitability. Furthermore, reclaiming these materials provides a sustainable source of essential bioactive compounds, helping to meet the nutritional needs of an expanding global population while simultaneously mitigating the environmental risks typically associated with disposal (Phadke *et al.*, 2021) [14]. Currently, while some processing facilities do utilize waste as a base for fish meal or animal feed, these methods often yield minimal financial returns (Tugiyono *et al.*, 2020) [21]. Despite these existing efforts, a substantial portion of seafood by-products is still discarded through incineration or sent to landfills, leading to ongoing environmental degradation, public health risks, and wasted economic potential (Lionetto and Esposito, 2021) [12].

The Scope of Fish Waste and By-products

By-products from fish processing are categorized as either solid or liquid. The solid fraction consists of items like skin, scales, fins, bones, and heads, whereas the liquid component encompasses visceral fluids, blood, and processing wastewater. Previously regarded as mere ecological pollutants, these materials are now being repurposed into high-value commodities through advanced technical processes, including supercritical fluid extraction, fermentation, and enzymatic hydrolysis.

Composition of fish byproducts/waste composition

The term 'byproduct' refers to something that is not typically considered a saleable product but can be utilized after processing. At the same time, 'waste' denotes unfit materials for feed or food purposes and must be composted or disposed of (Kumar *et al.*, 2022) [11]. The EC regulation of animal byproducts (EC No. 1774/2002) defines these byproducts as whole or partial animal bodies or products that are considered unsuitable for human consumption. Although terms such as co-streams, co-products, discards, and waste are often used interchangeably, 'waste' generally implies material with no value (Sachindra and Mahendrakar, 2014) [15]. Various terms such as 'byproduct', 'co-product', 'fish waste', 'fish offal', 'fish visceral mass', and 'fish discards' are used to describe non-edible parts of seafood processing (Kumar *et al.*, 2022) [11]. Stevens *et al.*, (2018)

[18] defined byproducts as all edible or non-edible materials that remain after the main products are prepared. Common byproducts of finfish include frames (bones with attached flesh), trimmings, blood, head, skin, and viscera (guts). The fractions of byproducts as a percentage of the total wet weight of Atlantic salmon are reported as heads (10%), belly flaps (1.5%), skin (3.5%), viscera (12.5%), frames (10%), trimming (2%), and blood (2%) (Stevens *et al.*, 2018) [18].

Fish meal

Fish meal is a nutrient-dense supplement derived from whole fish or marine processing remnants. Primarily utilized in the agricultural sector, it serves as a staple protein source for livestock including swine and poultry and is a critical component in aquaculture diets, while also finding niche use in organic fertilizers.

Raw Material Sources

Production utilizes a variety of marine life, including small pelagic species like anchovies, sardines, herring, menhaden, and mackerel. Furthermore, manufacturers repurpose the offcuts, trimmings, and excess organic matter discarded during human-grade fish processing.

Nutritional Profile

Typically boasting a crude protein content between 60% and 72%, fish meal also contains 8–12% fat, 10–20% ash, and low moisture levels (typically under 10%). Its value lies in its high concentration of essential amino acids notably methionine and lysine alongside beneficial omega-3 fatty acids and a spectrum of vitamins (A, D, and various B-complex vitamins).

The Manufacturing Workflow

The production cycle follows several distinct phases:

1. **Thermal Processing:** The raw materials are cooked to trigger protein coagulation and release trapped oils and moisture.
2. **Mechanical Extraction:** The mix is pressed to isolate solid proteins from liquids.
3. **Dehydration and Milling:** The solids are dried until moisture drops to 8–10%, then milled into a fine, uniform powder.
4. **Preservation:** The final product is sealed in airtight packaging to maintain stability.

Varieties and Benefits

There are several categories of this product, including whole-fish meal, by-product varieties, and defatted versions. It is prized for its palatability, excellent mineral content (calcium, phosphorus, and iron), and its ability to provide a balanced nutritional profile that plant-based proteins often struggle to replicate.

Quality Assurance and Challenges

Maintaining quality requires strict measures: using fresh raw inputs, carefully regulating moisture to inhibit mold, and incorporating antioxidants to prevent the fats from turning rancid. Proper storage in cool, low-humidity environments is essential for shelf life.

Despite its benefits, the product faces significant hurdles. It is generally more expensive than botanical protein alternatives, and the industry faces intense scrutiny regarding the sustainability of fish stocks. Additionally, its high fat content makes it prone to spoilage if exposed to high temperatures, requiring careful logistical management.

Fish Silage

When fish is unsuitable for human consumption, it is common practice to process it into fish meal for the animal feed industry. However, this is not always feasible if a facility is inaccessible or if the strong odors associated with traditional processing plants pose a community issue. In such cases, alternative methods like fish silage production are highly effective, especially for farms located near fishing ports.

Fish silage is a liquid product derived from whole fish or fish scraps through a process of enzymatic liquefaction. This preservation method requires no additives other than acid. The breakdown of tissue can be triggered by adding mineral acids, such as sulfuric acid, or organic acids, like formic acid. Alternatively, fermentation can be induced by adding a carbohydrate source like molasses along with lactic acid bacteria; the resulting lactic acid effectively stabilizes the mixture.

The end result is a stable, malt-scented liquid that retains all the moisture of the original raw material. This technique is cost-effective and requires minimal infrastructure, particularly when handling non-oily fish. If oily fish is used, the mixture is typically heated to 70–90°C, allowing the oil to be separated via centrifugation or decantation. Fish silage serves as an excellent nutrient source for livestock. It can be fed to animals in its liquid state or combined with solid carriers like rice bran to create a dry, manageable feed.

Fish oil

Extracted from the fatty tissues of oily species or repurposed from processing remnants like livers, heads, and entrails, fish oil serves as a potent source of long-chain omega-3 fatty acids. Specifically, it is packed with eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), both of which are vital for supporting optimal health in humans and animals alike. Typical aquatic sources for this oil include salmon, sardines, anchovies, mackerel, menhaden, and herring.

The manufacturing process typically begins by cooking the fish to liberate moisture and lipids, followed by pressing the mixture to extract the liquids from the solid matter. Centrifugation or decanting is then employed to isolate the pure oil from water and residual impurities. To ensure high quality and long-term stability, the crude oil undergoes a refining sequence that includes neutralization, degumming, deodorization, and bleaching.

While raw, unrefined fish oil is often directed toward the animal feed industry, refined versions are prepared for human use in the form of fortified food products, liquid supplements, or softgel capsules. Thanks to its anti-inflammatory characteristics and its positive impact on brain health, cardiovascular function, and physical development, fish oil is highly valued in the pharmaceutical, nutraceutical, and aquaculture sectors.

Maintaining the integrity of the product relies heavily on the freshness of the source material and rigorous handling protocols to preclude oxidation. To preserve the oil's efficacy, it should be fortified with antioxidants, such as tocopherols, and kept in a dark, climate-controlled environment.

Fish powder

Fish powder is a pulverized, dehydrated substance derived from whole fish, filets, or remnants from processing, such as bones, heads, and scraps. This manufacturing process serves to stabilize fish protein, resulting in a portable, long-lasting product suitable for use in dietary supplements, livestock nutrition, and human cuisine. To create this powder, raw materials are first cleaned and cooked before being dehydrated at controlled, mild temperatures to ensure essential nutrients remain intact. The finished product is then pulverized into a consistent, fine grain. Depending on the intended use and quality standards, the dehydration phase may utilize various techniques, including freeze-drying, hot-air circulation, or traditional sun-drying.

Collagen and gelatin

Discarded fish skin serves as a potent raw material for the extraction of collagen and gelatin, substances that are in high demand across the biomedical, culinary, and beauty sectors. As a primary structural protein found in connective tissues, collagen is responsible for the resilience and suppleness of skin and ligaments. Whether sourced from freshwater varieties like catfish and tilapia or cold-water marine species, this protein is packed with vital amino acids—notably glycine (25%–30%), proline (15%–20%), and hydroxyproline (10%–15%) all of which are instrumental in supporting skin health and moisture retention (Salvatore *et al*., 2020) [16].

Gelatin, which is essentially collagen that has undergone partial hydrolysis, is distinguished from standard fish muscle proteins by its dense collection of non-polar amino acids, such as valine, alanine, proline, and glycine (Feng *et al*., 2020) [8]. Beyond its structural utility, fish-derived gelatin possesses remarkable biological benefits, including antioxidant and blood-pressure-regulating effects, largely driven by its specific glycine-proline-alanine amino acid chains (Coppola *et al*., 2021) [4].

The process of hydrolysis enables the transformation of collagen into smaller, manageable peptides. Compared to gelatin sourced from mammals, fish-derived gelatin is increasingly favored for its superior bioactive qualities and a significantly reduced risk of pathogen transmission (Joy *et al*., 2024) [10]. These attributes make it an excellent choice for a variety of food items such as confectionery products and jellies as well as specialized pharmaceutical applications like supplement coatings and capsules. Furthermore, repurposing fish-processing waste to create these valuable biopolymers supports circular economy principles, transforming what would be trash into a profitable, sustainable resource. Ultimately, the conversion of fish skin into collagen and gelatin offers a multifaceted advantage, bridging the gap between industrial efficiency and environmental responsibility.

Shark Fins

The commercial worth of shark fins is determined by several factors, including their dimensions, pigmentation, specific type, and overall grade. These fins are primarily categorized as either "white" or "black," a distinction based on the concentration and quality of the fin rays they contain; generally, black fins command a lower price in the market.

At the centre of shark fin soup production are the translucent, cartilaginous rods found within the fins. These rays can be harvested from either fresh or dried fins. For dried specimens, the fins must first be rehydrated for two to three days in an acidic solution (pH 2.5 to 5.0), whereas fresh fins require significantly less preparation time. Once softened, the fins undergo a one-hour treatment in a 10% acetic acid bath heated to 60 °C, with the exact duration adjusted according to the size of the material. Following this, the rays are carefully removed by hand, thoroughly rinsed, and sun-dried. Once the moisture content is reduced to 5–8%, the finished rays are packaged in polyethylene bags for storage. This ingredient remains a highly prized delicacy across various nations, including China and the Philippines (Mohanty, 2020) [13].

Chitosan

Chitosan is a derivative of chitin, historically derived from the discarded shells and heads of prawns in seafood processing plants. While these byproducts were traditionally repurposed as fertilizers or animal feed additives, they now serve as the primary raw material for extracting high-value chitosan through a multi-stage chemical process involving deproteinization, demineralization, and deacetylation.

The procedure begins with deproteinization, where prawn waste is thoroughly rinsed and treated with a 3% caustic soda solution for one hour to eliminate crude proteins. Following another wash, the material undergoes demineralization by being submerged in a 5% acid solution for 30 minutes, which strips away the mineral components. The resulting substance is chitin, which typically retains about 60% moisture.

To finalize the transformation into chitosan, the chitin undergoes deacetylation. This involves rinsing the chitin and heating it in a 40% caustic soda solution for approximately 90 minutes. Once completed, the material is cleaned, sun-dried, and ground into a fine powder. For storage, the finished chitosan is sealed in polyethylene bags and kept at room temperature. In contemporary applications, chitosan has gained significant recognition as an effective coagulant aid for sewage treatment (Mohanty, 2020) [13].

Conclusion

The substantial volume of waste produced by fish processing sectors presents an untapped opportunity for creating value-added goods. Given that marine resources are finite, it is imperative to manage them with greater diligence. Currently, the potential of fish by-products remains largely unrealized; therefore, investing in technological innovations for deep-level valorization is essential. By refining these waste-management processes, industries can not only bolster the circular economy and mitigate environmental bio-burden but also pioneer the development of innovative food ingredients sourced from the blue economy.

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