Unlocking the Potential of Fish Nutrition, Products, and By-Products for Food Security and, Environmental Sustainability: Current Knowledge Gaps and Future Research Directions

[1]Regan Nicholaus and [2]Angela Aluko*
[1] Department of Natural Sciences
[2]Department of Food Science and Technology
[1,2]Mbeya University of Science and Technology, P.O Box 131 Mbeya, Tanzania
DOI: https://doi.org/10.62277/mjrd2026v7i30009

ARTICLE INFORMATION

Article History

Received: 09th November 2025
Revised: 17th June 2026
Accepted: 28th August 2026
Published: 15th September 2026

Keywords

Aquaculture
Fish byproducts
Food security
Nutrition
Sustainability
Value-added product

ABSTRACT

Fish and aquaculture products are critical to global food security, human nutrition, livelihoods, and environmental sustainability. Despite extensive research on fish nutrition, processing, and by-product utilisation, current efforts often fail to fully harness the potential of fish-derived resources, particularly by-products, for broader societal and ecological benefits. Fish provide high-quality protein, essential fatty acids, vitamins, and minerals, while by-products such as skin, bones, viscera, and scales can be transformed into value-added products including fishmeal, fish oil, bioactive peptides, and organic fertilisers. However, integration of these resources into circular and sustainable food systems remains limited, constrained by technological, economic, and policy-related barriers. Environmental impacts of aquaculture, such as inefficient resource use, waste generation, and ecosystem disruption, further challenge the sector's contribution to sustainable development. This review synthesises the current knowledge gap on fish nutrition, products and by-product valorisation, highlighting their roles in enhancing food security, promoting environmental sustainability, and improving human well-being. It identifies critical knowledge and application gaps, including the need for scalable processing technologies, standardised nutritional assessment methods, comprehensive life-cycle analyses, and inclusive approaches that integrate food, feed, functional ingredients, and ecological benefits. Strategic recommendations are provided to guide future research, innovation, and policy-making, emphasising sustainable aquaculture practices, circular utilisation of by-products, and holistic management of environmental and nutritional outcomes. By addressing these gaps and adopting integrative strategies, the aquaculture sector can maximise its contributions to resilient food systems, environmental stewardship, and human health and well-being.

*Corresponding author's e-mail address: angelaluko10@gmail.com (Aluko, A.)

1.0 Introduction

Global population growth, resource scarcity, and escalating environmental pressures highlight the urgency of strengthening food systems with sustainable and nutritious solutions (FAO *et al.,* 2024; United Nations, 2024). Within this context, fish and marine-derived products are receiving renewed attention not only as dietary staples but also as key drivers of food security, environmental sustainability, and human well-being.

Globally, millions of tonnes of food waste and by-products are generated annually by the food processing industry. This waste poses a significant threat to environmental sustainability, economic productivity, and public health, while also representing a substantial loss of valuable resources, posing a serious threat to the environment, the economy, and human health. Fruit peels, vegetable pomace, cereal bran, oilseed cakes, dairy whey, meat trimmings, and fish processing leftovers are examples of food by-products, which are secondary materials produced during the processing of agricultural commodities. Despite having significant levels of proteins, dietary fibre, vital fatty acids, vitamins, minerals, antioxidants, and other bioactive substances, many of these materials have historically been thrown away or converted to low-value uses like animal feed or landfill disposal.

Food by-products are now considered significant resources that can be converted into functional foods, nutraceuticals, medicines, cosmetics, biodegradable packaging materials, and bioenergy thanks to recent developments in food science. The circular bioeconomy, which prioritises increasing resource efficiency, reducing waste production, and developing sustainable value chains, is centred on this shift. The Sustainable Development Goals, especially SDGs 2 (Zero Hunger), 12 (Responsible Consumption and Production), and 13 (Climate Action), can be achieved with the help of the valorisation of food by-products (European Commission, 2020; FAO *et al.,* 2024; Ore Areche *et al.,* 2024).

Among food processing by-products, fish processing residues represent one of the most nutrient-dense yet underutilised resources. Depending on the species and processing method, between 30% and 70% of the whole fish may become by-products, including heads, bones, skins, scales, fins, frames, and viscera. These materials are exceptionally rich in high-quality proteins, collagen, gelatin, omega-3 polyunsaturated fatty acids (EPA and DHA), essential amino acids, minerals such as calcium and phosphorus, and numerous bioactive peptides with antioxidant, antimicrobial, antihypertensive, and anti-inflammatory properties.

These by-products are becoming more widely acknowledged as useful raw materials for the production of functional food ingredients, dietary supplements, fish protein hydrolysates, collagen peptides, gelatin, fish oils, nutraceuticals, pharmaceuticals, cosmetics, organic fertilisers, and biodegradable biomaterials. Their efficient use promotes sustainable seafood production and circular food systems by lowering environmental pollution linked to fish processing waste and raising the economic value of fisheries and aquaculture (Välimaa *et al.,* 2019; Ghalamara *et al.,* 2024; Ore Areche *et al.,* 2024).

According to the Food and Agriculture Organization (FAO) of the United Nations (2026), 90% of global aquatic animal production is used for human consumption; 53% of aquatic animal foods are supplied by aquaculture, while 47% come from capture fisheries. In international trade, finfish contribute 68%, crustaceans 22%, and molluscs and other aquatic invertebrates 11% of total export value.

Fish is particularly valued for its high-quality essential amino acids, long-chain omega-3 fatty acids (docosahexaenoic acid and eicosapentaenoic acid), bioavailable minerals such as iron and zinc, and vital vitamins (Maulu *et al.,* 2024; Obiero et al., 2019). Owing to this nutrient richness, fish is widely regarded as "nature's superfood" (FAO, 2017). Moreover, global fish consumption is rising faster than population growth, driven by increasing incomes, greater awareness of health benefits, and rapid urbanisation (Obiero *et al.,* 2019).

Beyond primary products such as fillets, there is growing recognition of the nutritional and functional potential of fish by-products, including heads, bones, skins, viscera, and scales that are often discarded. These materials, which can represent 55–65% of a fish's total weight, contain significant amounts of protein and bioactive compounds, making them a largely untapped resource (Ghalamara *et al.,* 2024). In addition to nutritional contributions, fisheries and aquaculture provide economic value through the production, trade, and marketing of both wild and farmed fish (Cai & Leung, 2016).

The sustainability of aquaculture, however, depends heavily on innovation in fish nutrition, such as alternative proteins through the use of insect meal, e.g., black soldier fly larvae (Oteri *et al., 2021),* and nanotechnology to increase nutrient bioavailability (Mitra et *al.,* 2025). Reliance on fishmeal and fish oil is increasingly challenged by high costs, limited supply, environmental concerns, and nitrogen pollution (Rombenso *et al.,* 2022). As a result, alternative ingredients such as vegetable proteins, microalgae (e.g., *Schizochytrium* sp.), camelina meal, seaweed, microbial products, and insect meals are being explored. These novel feeds show promise in supporting fish growth, maintaining health and omega-3 content, and lowering the environmental footprint of aquaculture systems (Rombenso *et al.,* 2022). Despite these advances, the FAO's Fisheries and Aquaculture Department has noted that quantitative data on aquaculture's socioeconomic and environmental performance remain fragmented across the literature. This scattered information often leads to the underutilisation or even misuse of available evidence (Obiero *et al.,* 2019). Framing these developments within the Sustainable Development Goals (SDGs) underscores their global relevance. Innovations in fisheries, fish nutrition, and by-product utilisation align closely with several SDGs: SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water) (Obiero *et al.,* 2019).

Ultimately, fish nutrition, products, and by-products hold immense untapped potential to advance food security, sustainability, and human well-being (FAO, 2024). Realising this potential requires integrated strategies that promote responsible utilisation, value addition, and technological innovation in fisheries and aquaculture. It also calls for addressing information gaps, strengthening policies, and enhancing research capacity. This study, therefore, aims to synthesise current knowledge, highlight key limitations, and propose future directions for maximising the role of fish and fish products in building sustainable and equitable food systems.

2.0 Literature Review Method

This review followed the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework for the identification, screening, eligibility assessment, and inclusion of relevant studies. Peer-reviewed articles were retrieved from Web of Science, ScienceDirect, and Scopus. The literature search was conducted over three months, from May to July 2025. Only articles published between 2010 and 2026 were considered to capture the most recent developments in fish nutrition, fish products, and fish by-products related to food security, environmental sustainability, and human health. After duplicate records were removed, titles and abstracts were screened against predefined inclusion and exclusion criteria. Eligible studies then underwent full-text assessment before being included in the final review.

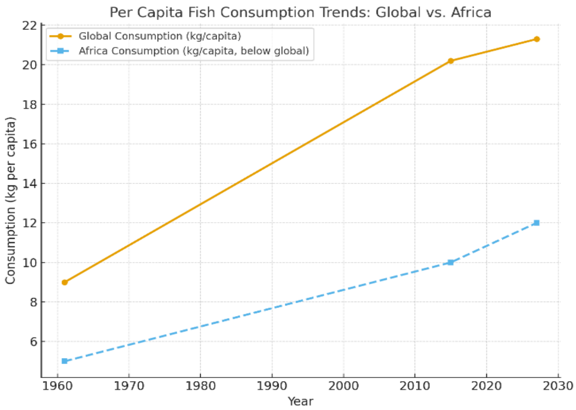
3.0 Results and Discussion

3.1 Contribution of Fish to Food and Nutrition Security

Several studies have highlighted the significant potential of fish in improving food and nutrition security for vulnerable populations, particularly women and young children in rural communities (Obiero *et al.,* 2019). On a global scale, per capita fish consumption rose from 9.0 kg in 1961 to 20.2 kg in 2015 (Figure 1), reflecting an average annual growth rate of about 1.5% (FAO, 2018). According to projections by the Organisation for Economic Co-operation and Development (OECD, 2018), global consumption is expected to reach up to 21.3 kg per person by 2027, from 20.5 kg during the 2015–2017 period (Figure 1).

In Africa, however, the situation is more pressing; even though fish accounts for about 19% of the continent's animal protein intake, annual per capita consumption remains below global averages (Chan *et al.,* 2019). This gap is driven by Africa's rapidly growing population, which has already outpaced the growth in fish supply. With most wild fish stocks fully exploited, aquaculture production will need to more than double by 2050 to meet the projected demand (Cai & Leung, 2016). Factors such as population growth, rising incomes, urbanisation, greater awareness of the health benefits of fish, and innovations in processing, packaging, and distribution are expected to continue fuelling demand (Obiero *et al.,* 2019).

Figure 1
Global per Capita Fish Consumption (kg/year) from 1961 to 2015, Based on FAO Food Balance Sheets (2018). Source by FAO, OECD, Chan et al. (2019) & Maula etal. (2024)



Beyond its role as a direct source of nutrition, fish also makes important indirect contributions to food and nutrition security through income generation and livelihood support. Income derived from fish production enhances household purchasing power, enabling families to access a more diverse and nutritious diet (Maulu *et al.,* 2024). Furthermore, the fisheries and aquaculture sector creates employment opportunities throughout the value chain, with women playing central roles in processing, marketing, and trading fish and fish products (Maulu *et al.,* 2024).

Despite these significant contributions, the income pathway remains under-represented in food and nutrition security evaluations because studies have historically focused on food intake and fish consumption rather than the socioeconomic ways that fisheries enhance household well-being. Furthermore, it is more challenging to measure the indirect association between fisheries-derived income and nutrition since it is complicated and impacted by elements like market access, household decision-making, gender dynamics, and seasonal income variability (HLPE, 2014: Béné *et al.*, 2015). As a result, the livelihood benefits of fisheries consequently, nutrition policies and development programmes often overlook the livelihood benefits of fisheries (Bennett et al., 2021). in nutrition policies and development programmes (Bennett *et al.*, 2021).

Moreover, fisheries play a crucial social and economic role in Africa. The sector contributes to the development of areas such as employment, income, and foreign exchange earnings for many nations, making it an important socioeconomic pillar (Table 1). Revenues from fishing and related activities not only strengthen national economies but also enhance household purchasing power, thereby improving food and nutrition security (Muringai *et al.,* 2021). At the global level, fish is among the most highly traded commodities, positioning aquatic environments, including oceans, seas, lakes, rivers, and wetlands, at the heart of economic growth and sustainable development (UNCTAD) (Muringai *et al.,* 2021).

Table 1
Selected Socio-Economic Indicators of Fisheries and Aquaculture

Indicator	Latest estimate	Significance	Reference
Global fisheries and aquaculture production	≈191 million tonnes (2024)	Demonstrates growth in aquatic food production	FAO SOFIA (2026)
First-sale value of global production	>USD 490 billion	Major contributor to the global food economy	FAO SOFIA (2026)
People directly employed in fisheries and aquaculture	>62 million	Employment generation	FAO SOFIA (2026)
People whose livelihoods depend on fisheries	≈600 million	Livelihood support across the value chain	FAO SOFIA (2026)
Global fish trade value	>USD 190 billion/year	One of the world's most traded food commodities	UNCTAD (2024)

Indicator	Latest estimate	Significance	Reference
Developing countries' share of global fish export value	>50%	Foreign exchange earnings	UNCTAD (2024)
Africa's fisheries contribution to GDP	≈1.3%	Economic development	AU-IBAR (2024)
Employment in African fisheries and aquaculture	>12 million people	Rural livelihoods	AU-IBAR (2024)
Women's participation in fish processing and marketing in Africa	50–60%	Gender empowerment and household income	FAO (2024); AU-IBAR (2024)
Share of capture fisheries employment in small-scale fisheries	**≈90%**	Importance for poverty reduction	FAO SOFIA (2026)

3.1.1 Fish Nutrient Composition

Fish species, age, physiological health, season, aquatic environment, and feeding schedule all affect their nutritional makeup (Table 2). Because it directly affects the deposition of proteins, lipids, fatty acids, vitamins, minerals, and other bioactive compounds in muscle tissues, feed composition is one of the most significant factors influencing fish meat quality in aquaculture (Glencross *et al.,* 2020; Rombenso *et al.*, 2022). For instance, diets high in fish oil or marine-derived components raise the levels of long-chain omega-3 polyunsaturated fatty acids, especially docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA). However, substituting vegetable oils may lower these healthy fatty acids unless they are composited by other sources like microalgae (Tocher, 2015; Rombenso *et al.*, 2022).

In a similar manner, using insect meal, microbial proteins, and other innovative feed components can improve the sustainability of aquaculture production while influencing the amino acid composition, mineral availability, and overall nutritional value of farmed fish (Oteri et al., 2021; Rombenso *et al.*, 2022). However, increasing knowledge emphasises fish's nutritional and health-promoting benefits as a rich source of important nutrients and high-quality protein (Muringai *et al.*, 2021). About 16–21% of fish muscle, which makes up 50–60% of their body weight, is protein (Pal *et al.*, 2018). These proteins fall into three major categories: stromal proteins (about 3%), sarcoplasmic proteins (20–30%), and myofibrillar proteins (70–80%). A 100 g serving of fish can provide approximately 15–25% of the recommended daily protein intake for adults (45–65 g), underscoring its significance in meeting dietary protein requirements (Muringai *et al.,* 2021).

Importantly, fish protein is also 5–15% more bioavailable than plant-based proteins, making it a particularly efficient source of nutrition (Elavarasan, 2018). In addition to proteins, fish lipids are an important source of long-chain polyunsaturated fatty acids (LCPUFAs), including arachidonic acid (ARA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) (de Bruyn *et al.,* 2021). Species such as sardines, mackerel, anchovies, and certain salmon varieties are especially rich in EPA and DHA (Table 1), making them valuable dietary sources of these essential fatty acids (Muringai *et al.,* 2021). The lipid content of fish, however, can vary considerably depending on species, aquatic environment, feeding patterns, spawning season, and physiological state (Muringai *et al.,* 2021). Beyond macronutrients, fish also provide highly bioavailable micronutrients, including calcium, iodine, iron, zinc, phosphorus, selenium, and fluorine, as well as essential vitamins such as A, B, and D (; (Elavarasan, 2018; Pal *et al.,* 2018). These combined nutritional properties position fish as a unique and indispensable component of a balanced diet.

Table2

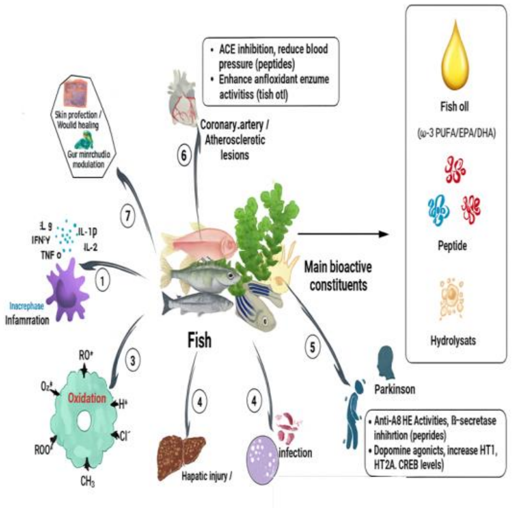
Nutrient Composition of Selected Fish Species

Fish Species	Protein (%)	EPA + DHA (g/100g)	Iron (mg/100g)	Calcium (mg/100g)	Vitamin D (µg/100g)	Source(s)
Sardine	20	1.5	2.9	382	13	USDA/FoodStruct; Santos *et al.* 2020; OSU SNIC
Mackerel	19	1.8	1.6	218	16	USDA/FoodStruct; OSU SNIC
Tilapia	18	0.3	0.9	20	3	NutritionValue.org; OSU SNIC
Catfish	17	0.2	1.5	15	2	Canada Food Tables/USDA; OSU SNIC
Salmon	21	2.2	0.8	12	10	MyFoodData; OSU SNIC

3.1.2 Benefits to Human Nutrition and Health

For many impoverished or rural populations, fish, especially small fish, may be the most readily available, reasonably priced, or favoured source of animal protein (Muringai *et al*., 2021). Researchers widely acknowledge that fish consumption offers significant nutritional and health advantages (Fig. 2), primarily due to its rich content of omega-3 fatty acids. These benefits include lowering blood pressure and cholesterol levels, supporting cardiovascular health, enhancing cognitive function, reducing inflammation, and helping to prevent certain cancers and inflammatory conditions such as arthritis (Muringai *et al*., 2021; Ore Areche *et al., 2024).* However, the rising demand for seafood has led to overfishing and the depletion of many fish stocks, raising concerns about the long-term sustainability of marine resources (Ore Areche *et al., 2024).*

Figure 2
Health Benefits of Eating Fish and Their Accompanying Bioactive Components (Saba et al., 2024)



This situation underscores the need for a paradigm shift towards more sustainable seafood production and utilisation. Beyond environmental considerations, fish consumption delivers wide-ranging health benefits, including improved maternal and child health outcomes, enhanced cognitive development, reduced childhood stunting, stronger immune function, and lower risk of cardiovascular disease (Khalili & Sampels, 2018; Marinda *et al.,* 2018). According to the FAO and World Health Organization, the combined intake of EPA and DHA from fish, particularly oily species, can lower the risk of coronary heart disease mortality by up to 36% (Muringai *et al.,* 2021). Similarly, Vianna *et al.* (2020) report that regular fish consumption reduces coronary heart disease-related deaths in adults by about 20%. Beyond cardiovascular health, fish intake is strongly linked to improved foetal and infant neurodevelopment, making it especially important for women of childbearing age, pregnant women, and nursing mothers (Muringai *et al.,* 2021).
Docosahexaenoic acid (DHA), a key polyunsaturated fatty acid, plays a critical role in optimal brain and neural system development during pregnancy and the first two years of life (Muringai *et al.,* 2021). Additionally, fish enhances the absorption of essential micronutrients such as iron and zinc from plant-based foods when consumed together, further contributing to improved nutritional outcomes (Ahern *et al.,* 2021).

3.1.3 Risks to Human Health

Although fish is a rich source of essential nutrients with proven health benefits, the consumption of contaminated fish presents notable risks to human health. Fish can accumulate a range of hazardous organic and inorganic compounds, some of which are highly toxic (Muringai *et al.,* 2021). According to the Scientific and Technical Advisory Panel of the Global Environment Facility (STAP), the most concerning contaminants include heavy metals such as cadmium, organic tin, and methylmercury (Muringai *et al.,* 2021).
Among these, methylmercury is considered the most dangerous. It is neurotoxic, impairing the peripheral nervous system in adults and the central nervous system in children, and is associated with symptoms such as ataxia, visual constriction, loss of skin sensation, and hearing and speech impairment (Bellinger *et al.,* 2019). Prenatal exposure is particularly harmful, potentially causing birth defects, severe mental retardation, or foetal mortality (Muringai *et al.,* 2021).
Evidence from country-level studies further illustrates these risks. In Nigeria, Adegbola *et al.* (2021) reported that consumers of fish from the polluted Ogun and Eleyele rivers face significant non-carcinogenic health risks. Similarly, in Zimbabwe, Manjengwa *et al.* (2019) found that 43% of fish consumers experienced gastrointestinal disorders, including bloody diarrhoea and loose stools after consuming fish from Lake Chivero. Another major concern is cyanobacteria, which are common in inland waters and produce cyanotoxins such as microcystins, nodularins, and cylindrospermopsins. These toxins

can bioaccumulate in fish tissues and cause gastrointestinal illness, hepatotoxicity, nephrotoxicity, and skin irritation in humans (Muringai *et al.,* 2021).

The rapid expansion of aquaculture has also been accompanied by increased use of antibiotics, antiparasitic drugs, and disinfectants to control disease outbreaks. While these chemicals improve fish survival, their indiscriminate use may result in drug residues in edible tissues and contribute to the emergence of antimicrobial-resistant bacteria, posing a growing public health concern (FAO, 2024; WHO, 2023).

In addition to environmental pollutants, post-harvest handling, processing, storage, and distribution can present risks. Fish may be exposed to mycotoxins, particularly aflatoxins and ochratoxin A, if improper drying and storage procedures are used, especially when fish are dried in humid settings or kept with mould-infested grains and oilseeds. Fish do not naturally create mycotoxins; however, cross-contamination during storage and marketing or tainted fish feed in aquaculture can cause contamination. Growth impairment, immunosuppression, liver cancer, and decreased nutritional utilisation have all been linked to long-term aflatoxin exposure (Claeys *et al.,* 2020; FAO, 2022).

Fish are also susceptible to contamination by persistent organic pollutants (POPs), including polychlorinated biphenyls (PCBs), dioxins, furans, and organochlorine pesticides such as DDT. These lipophilic contaminants accumulate in fatty fish and may persist for many years in aquatic ecosystems. Long-term exposure has been linked to endocrine disruption, reproductive disorders, developmental abnormalities, immune dysfunction, and increased cancer risk (WHO & FAO, 2023).

Emerging contaminants, including microplastics and nanoplastics, have become a growing concern in marine and freshwater ecosystems. Fish may ingest plastic particles directly or indirectly through the food chain. These particles can carry toxic chemicals such as bisphenol A (BPA), phthalates, and heavy metals, which may subsequently enter the human food chain. Although the long-term health effects are still under investigation, evidence suggests potential impacts on oxidative stress, inflammation, endocrine function, and gastrointestinal health (UNEP, 2023). After harvesting, improper handling and insufficient temperature control can further promote microbial deterioration and the production of biogenic amines, particularly histamine in scombroid fish species such as tuna and mackerel. Scombroid poisoning, which manifests as flushing, headache, nausea, vomiting, diarrhoea, and allergic-like responses, can be brought on by consuming high doses of histamine (Codex Alimentarius Commission, 2023).

Additional chemical risks can be introduced by thermal processing techniques, such as roasting, grilling, and smoking. While high-temperature cooking can yield heterocyclic aromatic amines (HAAs), incomplete combustion during smoking can form polycyclic aromatic hydrocarbons (PAHs). When exposure is extended, both classes of chemicals are known to have the potential to cause cancer (EFSA, 2023).

Despite these difficulties, many risk-benefit analyses find that when efficient monitoring systems, good aquaculture practices, appropriate processing, hazard analysis and critical control point (HACCP) principles, and regulatory standards are applied throughout the fish value chain, the nutritional and health benefits of fish consumption typically outweigh the associated risks (FAO, 2026).

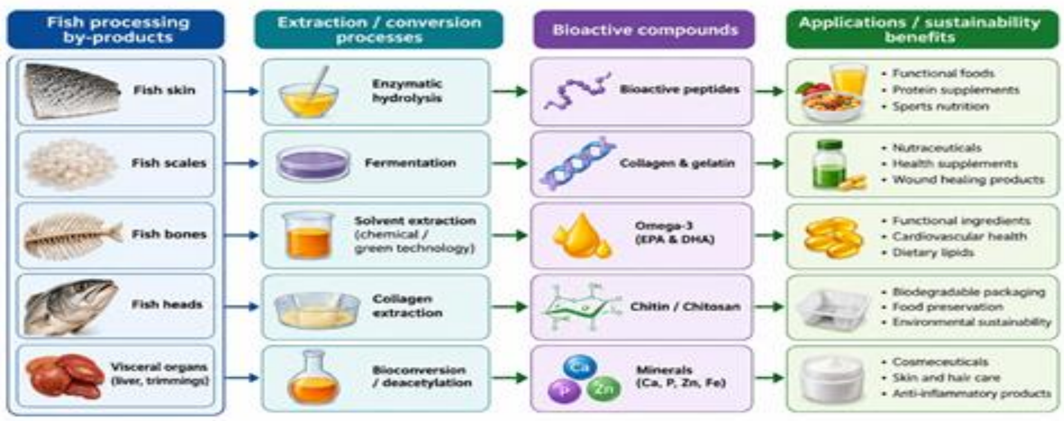
Furthermore, spoilage, microbiological contamination, parasites, natural poisons, and chemical pollutants, many of which are undetectable by appearance alone, may present health concerns to fish prior to ingestion. Fish that are spoilt frequently have a bad smell, hazy eyes, discoloured gills, mushy meat, and a lot of slime, all of which are signs of degradation and increased microbial activity (FAO, 2024). However, risks including histamine, ciguatoxins, pesticide residues, and mercury are typically invisible and need to be detected in a lab (WHO, 2024). Thus, rather than depending solely on sensory assessment, customers should buy fish from reliable suppliers and rely on food safety monitoring systems (Codex Alimentarius Commission, 2023).

3.2 Insufficient Development of Functional and Medicinal Fish Products

Emerging evidence highlights that fish-derived compounds such as collagen, gelatin, omega-3 fatty acids, bioactive peptides, and chitin (Fig. 3) can be effectively utilised in the formulation of functional foods, nutraceuticals, pharmaceuticals, and biomedical products, offering health benefits that include cardiovascular protection, improved cognitive function, anti-inflammatory effects, enhanced skin and bone health, and immune modulation (Ore Areche *et al.,* 2024). Fish oils rich in omega-3 fatty acids are widely commercialised as dietary supplements, while peptides generated through protein hydrolysis have demonstrated antihypertensive, antioxidant, antimicrobial, and antidiabetic activities.

Figure 3

Pathways of Fish - Derived Bioactive Compounds (Ghaly et al. (2013), Caruso (2016), FAO (2024), and Ahmed et al. (2022)



Recent technological advances, including enzymatic hydrolysis, fermentation, membrane filtration, supercritical fluid extraction, nanoencapsulation, and microencapsulation, have significantly improved the recovery, stability, and bioavailability of fish-derived bioactive compounds. These technologies increase product functionality and promote the valorisation of fish processing by-products, thereby supporting circular bioeconomy principles and reducing environmental waste (Ore Areche *et al.,* 2024). Despite these developments, high-income nations continue to dominate the commercial development of fish-based functional foods and nutraceuticals. Developing nations have not yet taken full use of these prospects, especially those in portions of Asia and Africa where seafood resources are plentiful. Several interrelated issues are blamed for this discrepancy.

First, the isolation, characterisation, and validation of bioactive chemicals are hampered by insufficient laboratory capacity and research infrastructure. Advanced analytical tools, including LC-MS/MS, GC-MS, NMR spectroscopy, and pilot-scale bioprocessing facilities, all necessary for creating high-value marine products, are lacking in many universities and research centres (FAO, 2024).

Second, the industrial adoption of improved extraction methods is hampered by high operating and capital expenses. For many small and medium-sized businesses (SMEs) in developing economies, processes like supercritical CO_2 extraction, nanoencapsulation, and membrane separation require significant financial investment, dependable electricity, qualified staff, and routine maintenance.

Third, the conversion of research discoveries into commercially viable goods is hampered by weak ties between government, business, and academia. Inadequate technology transfer mechanisms, a lack of venture capital, and insufficient regulatory incentives for innovation prevent many promising laboratory-scale breakthroughs from being commercialised.

Fourth, in many developing nations, consumer awareness and commercial demand for functional foods produced from fish are still quite low. While customers mostly buy fish as a traditional source of protein, functional meals are frequently considered high-end goods. Market adoption may be further hampered by a lack of nutrition knowledge, cultural preferences, and worries about flavour, odour, or product appearance (FAO, 2024).

The erratic supply and uneven quality of fish processing by-products are another significant constraint. Skins, bones, scales, and viscera are poorly collected, handled, and managed throughout the cold chain due to the informal nature of many fish processing plants. As a result, valuable raw materials quickly decay before being transformed into high-value compounds. Establishing dependable industrial supply chains is made more difficult by the seasonality of fish availability.

Furthermore, many low- and middle-income nations still have inadequate regulation and quality assurance frameworks for functional foods and nutraceuticals. Private investment is discouraged, and market entry is delayed by the lack of standardised standards, restricted certification capacity, and protracted product approval processes (WHO, 2023).

Coordinated funding for industrial development, policy, and research is needed to overcome these limitations. Investment in biotechnology labs, pilot processing facilities, and innovation hubs that focus on aquatic bioresources should be given top priority by governments. While lowering the risks of commercialisation, public-private partnerships can help transfer technology from academic institutions to business. Researchers and business owners would have easier access to cutting-edge technologies if regional centres of excellence offered common access to sophisticated analytical tools.

Developing countries should also promote appropriate and scalable processing technologies that are economically feasible under local conditions. Rather than relying exclusively on expensive extraction systems, industries can adopt lower-cost enzymatic hydrolysis, microbial fermentation, ultrasound-assisted extraction, and membrane technologies that require lower energy inputs while producing commercially valuable ingredients. Such technologies are particularly suitable for small and medium enterprises and can substantially improve the utilisation of fish processing waste.

Strengthening fish value chains through improved cold-chain infrastructure, standardised by-product collection systems, and quality assurance protocols would increase the availability of high-quality raw materials for bioactive compound extraction. In parallel, supportive regulatory frameworks, tax incentives, innovation grants, and access to affordable financing would encourage private-sector investment in fish-based functional food industries.

Consumer acceptance can be enhanced through nutrition education campaigns highlighting the health benefits of fish-derived bioactive compounds, alongside product development strategies that incorporate these ingredients into familiar foods such as biscuits, beverages, dairy alternatives, soups, noodles, and complementary foods. Such approaches may improve market penetration while contributing to healthier diets.

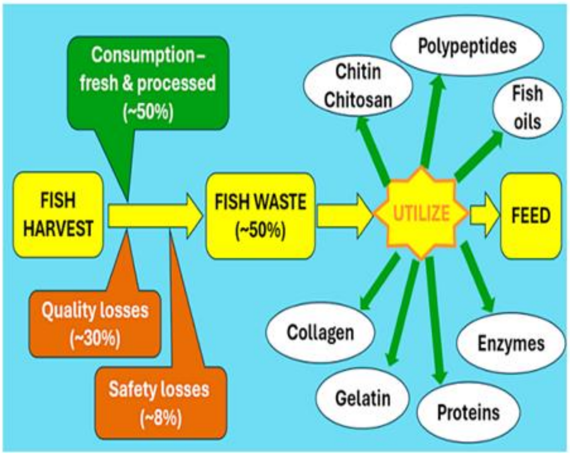
Future studies should assess the bioactive potential, safety, stability, and consumer acceptability of regionally accessible and underutilised fish species. Fish-derived functional foods will be more nutritionally advantageous, commercially feasible, and environmentally sustainable if life-cycle evaluation and techno-economic analysis are incorporated into product development. In addition to improving nutrition, lowering post-harvest losses, generating jobs, and boosting revenue creation in developing nations, such initiatives would facilitate the shift toward a circular blue bioeconomy (FAO, 2024; World Bank, 2024; OECD, 2023).

3.3 Underutilisation of By-Products

Current research and commercial practices in fisheries tend to overemphasise the fillet yield, often overlooking the substantial nutritional and functional potential of fish by-products. These by-products, which can account for up to 60% of total fish mass, are rich in collagen, omega-3 fatty acids, particularly EPA and DHA, and minerals such as calcium and zinc, and bioactive peptides. Despite their value, these resources remain underutilised, especially in regions struggling with food insecurity. A promising pathway to maximise seafood resources is the development of high-value products (Fig. 4). Such products extend beyond conventional food uses and include nutraceuticals, pharmaceuticals, cosmetics, and industrial applications. Importantly, they are derived from parts of seafood commonly discarded, such as fish skin, bones, viscera, shellfish exoskeletons, and seaweed biomass.

Fish by-products, including heads, bones, skins, viscera, and scales, are a largely unexplored resource with substantial potential for application in food fortification and human nutrition (Table 2). Nutritionally, these by-products are rich sources of fat-soluble vitamins (A, D, and E), minerals (calcium, phosphorus, magnesium, zinc, and iodine), omega-3 polyunsaturated fatty acids (EPA and DHA), essential amino acids, collagen, gelatin, and high-quality protein (Guerard, 2010; Tacon & Metian, 2015). They have been successfully incorporated into staple and value-added foods recently to improve nutritional quality, according to several studies. For instance, adding fish bone powder to bread, biscuits, noodles, crackers, and complementary foods has significantly increased the amounts of calcium, phosphorus, and protein while preserving acceptable sensory qualities at the right inclusion levels. (Abdel-Moemin, 2015; Toppe *et al.*, 2018).

Figure 4
Sea Food Product Process (Ore Areche et al., 2024)



Protein quality, essential amino acid composition, antioxidant activity, and digestibility have all been greatly enhanced by the use of fish protein hydrolysates made from fish frames, skins, and viscera in soups, drinks, meat products, and baked goods (Chalamaiah *et al.*, 2012; Kristinsson & Rasco, 2000). Similarly, fish collagen and gelatin derived from skins and scales have been added to dairy products, confections, edible films, and functional drinks to increase protein content, improve textural qualities, and supply bioactive peptides linked to bone, joint, and skin health (Liu *et al.*, 2015). To add EPA and DHA to foods while reducing oxidative deterioration and unwanted fishy flavours, fish oils recovered from processing by-products have also been microencapsulated and added to milk, yoghurt, bread, infant formulas, and nutrition bars (Gómez-Estaca *et al.*, 2016; Jacobsen *et al.*, 2013).

Small fish powders made from whole fish, including bones and heads, have been added to cereal-based porridges and complementary foods in low- and middle-income countries. This practice has greatly increased calcium, iron, zinc, vitamin B_{22}, and high-quality protein, which helps reduce micronutrient deficiencies in children and women of reproductive age (Byrd *et al.*, 2020; Bogard *et al.,* 2015; Kaimila *et al.*, 2020). These results indicate that fish by-products are a cost-effective and sustainable source of nutrient-dense ingredients that can enhance the nutritional value of frequently consumed foods while also lowering processing waste and promoting the ideas of the circular bioeconomy.

Fish heads and bones supply the calcium and phosphorus needed for healthy bones, while fish skin contains collagen and gelatin, which contain bioactive peptides with immunomodulatory, antihypertensive, and antioxidant properties (Benjakul & Regenstein, 2019). Viscera, particularly liver, are rich in vitamin A and omega-3 fatty acids, making them suitable for fortifying staple foods or producing nutritional supplements (FAO & WHO, 2024; Patted *et al.,* 2024; Munk *et al.*, 2024).

Fish by-products are usually processed by boiling, steaming, drying, enzymatic hydrolysis, or fishmeal manufacturing to make them suitable for human consumption (Table 3). Because it increases digestibility and lowers anti-nutritional factors, enzymatic hydrolysis is especially useful for creating protein hydrolysates, bioactive peptides, and oils appropriate for functional food applications (Benjakul & Regenstein, 2019; Kristinsson & Rasco, 2000). Because fish by-products are prone to lipid oxidation, microbial contamination, and the buildup of heavy metals or biotoxins, safety considerations are crucial.

To preserve nutrient integrity and avoid spoilage or off odours, fish oils should be handled carefully, quickly cooled after harvest, pasteurised, and encapsulated (Domínguez *et al., 2019).* Cultural considerations, perceived safety, and sensory qualities all affect consumer acceptability. When properly processed, fish by-products can be added to flours, protein powders, and fortified meals to boost the nutritional value of bread, noodles, snacks, and complementary foods while preserving their palatable flavour and texture (Guerard, 2010). Awareness of the advantages for health and the preservation of the environment can increase acceptance even further. In summary, fish by-products provide a sustainable solution for enhancing human nutrition, reducing food waste, and promoting circular food chains. Future studies should concentrate on creating culturally appropriate fortified goods that are appropriate for a range of populations, assessing long-term safety, and refining processing techniques for maximum nutrient retention.

Table 3
Nutritional Composition, Processing Methods, Safety Considerations, and Applications of Selected Fish By-Products for Human Consumption and Food Fortification

Fish By-Product	Nutrients	Processing Methods	Safety Considerations	Applications
Bones	Calcium, phosphorus, magnesium, and collagen	Boiling, drying, grinding, and enzymatic hydrolysis	Heavy metals, microbial contamination	Bone powder for fortification, supplements, functional foods
Heads	Protein, omega-3 fatty acids (EPA, DHA), and vitamin A	Boiling, steaming, drying, and fishmeal production	Lipid oxidation, microbial spoilage	Soups, sauces, fishmeal, protein hydrolysates
Skin	Collagen, gelatin, bioactive peptides	Drying, hydrolysis, and enzymatic extraction	Microbial contamination, off-flavor	Collagen supplements, gelatin, protein hydrolysates, functional foods
Viscera (liver, guts)	Vitamin A, omega-3 fatty acids, protein	Boiling, drying and enzymatic hydrolysis	Lipid oxidation, heavy metals, biotoxins	Nutritional supplements, fish oil extraction, and food fortification
Scales	Collagen, minerals	Drying, grinding, and hydrolysis	Microbial contamination	Collagen powders, bioactive peptides, functional ingredients
Whole Fish By-Products (mixture)	Protein, essential amino acids, omega-3s, minerals, vitamins	Fishmeal production, hydrolysates, drying	Microbial spoilage, oxidation	Fortified flours, snacks, protein powders, and complementary foods

3.4 Environmental Sustainability

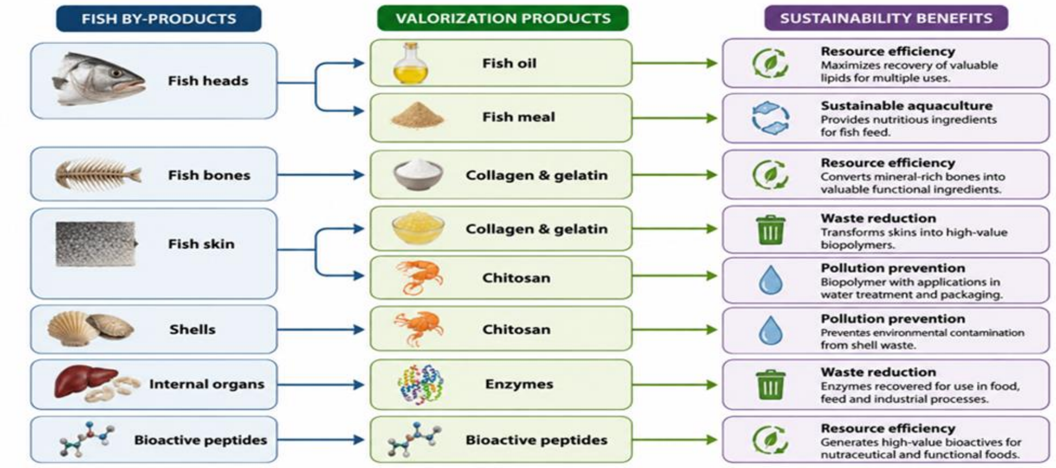
The utilisation of seafood by-products and processing waste for high-value product development also plays a critical role in promoting environmental sustainability (Toor & Ramzan, 2023). By adopting circular economy principles where resources are reused efficiently and waste generation is minimised, the seafood industry can significantly reduce its environmental footprint while contributing to broader conservation goals. Repurposing by-products helps prevent pollution and waste accumulation, thereby reducing reliance on landfills and incineration, both of which can have harmful ecological effects (Fig. 5).

Moreover, transforming by-products into value-added products enhances resource efficiency by ensuring that the nutritional and functional potential of seafood resources is fully utilised. This not only mitigates the environmental impacts of seafood processing but also minimises resource wastage. Ultimately, embracing sustainable processing practices strengthens the economic viability of the seafood sector while safeguarding the long-term health of marine ecosystems and supporting the resilience of coastal communities (Ore Areche *et al.,* 2024).

Additionally, empowering small-scale fisheries economically, alongside strengthening policy and governance frameworks, fosters sustainable practices and enhances community resilience to environmental and economic challenges. Integrating climate resilience into fisheries management and aquaculture ensures adaptability to changing conditions, safeguarding local and global food security. Furthermore, conserving biodiversity is vital for maintaining the ecosystems that support fisheries, underpinning the long-term sustainability of both marine environments and fishing livelihoods (Gul *et al.,* 2024).

Figure 5

The Utilisation of By-Products and Waste From Seafood Processing for the Production of High-Value Products, Promoting Environmental Sustainability (Ghaly et al. (2013); Caruso (2016); FAO (2024): Ore Areche et al., 2024)



3.4.1 Poor Valorisation of Fish Waste and Its Environmental Burden

Fish processing generates substantial volumes of organic waste, much of which is discarded in landfills or water bodies, contributing to environmental pollution (Table 4). Although technologies are available to convert fish waste into biofertilisers, animal feed, and biogas, their adoption remains limited, particularly in developing economies where investment and infrastructure are often lacking. This challenge is compounded by insufficient research on scalable, low-cost, and context-specific technologies that could advance sustainable fish waste management and support circular bioeconomy applications. Harnessing seafood by-products and waste for the production of value-added products not only reduces environmental pollution but also aligns with circular economy principles, thereby promoting more sustainable and resource-efficient fisheries and aquaculture systems (Ore Areche *et al.,* 2024).

Table 4

Fish Waste Streams, Environmental Issues, and Valorization Opportunities

Waste Type	Current Disposal	Environmental Issue	Valorization Opportunity
Fish Heads	Discarded in landfills or water bodies (FAO, 2024; Rustad *et al.,* 2011)	Pollution, methane emission	Protein hydrolysates, fish oil, soups
Fish Bones	Discarded (FAO, 2024; Caruso, 2016)	Water contamination	Bone powder, calcium supplements, functional foods
Fish Skin	Discarded as processing waste (FAO, 2024; Ghaly *et al.,* 2013)	Waste burden	Collagen, gelatin, nutraceuticals
Viscera (Liver)	Disposed of as waste (Ghaly *et al.,* 2013; FAO, 2024)	Odor, water pollution	Fish oil, vitamin A supplements
Scales	Discarded as solid waste (FAO, 2024; Arvanitoyannis & Kassaveti, 2008)	Solid waste accumulation	Collagen powders, bioactive peptides

3.5 Limited Integration of Fish-Based Nutrition in Food Security Policies

Although fish is widely recognised as a "superfood", national food and nutrition policies, particularly in low- and middle-income countries (LMICs), often overlook its strategic role in addressing malnutrition. Opportunities to integrate fish-based products, such as fish powder, fish protein hydrolysates, and dried small fish, into school feeding programmes, maternal nutrition initiatives, and emergency food interventions remain largely underutilised.

Although fish has been increasingly included in supplementation and complementary feeding programmes due to its well-known nutritional benefits in preventing malnutrition, its integration is still restricted in maternal and adolescent nutrition, school feeding programmes, therapeutic foods for malnutrition, nutrition-sensitive aquaculture, and national food and nutrition policies. The contribution of fisheries and aquaculture to lowering micronutrient deficiencies and enhancing diet quality, especially among vulnerable populations, would be increased by strengthening these areas (FAO, 2024).

Consequently, policy frameworks and nutrition interventions frequently fail to consider fish's potential in combating protein-energy malnutrition and micronutrient deficiencies. Historically, fish and fisheries have been excluded from key food policy discussions and related funding, despite their substantial contributions to livelihoods and food and nutrition security (Bennett *et al.,* 2021). For example, SDG 2 (Zero Hunger) primarily emphasises agricultural systems, focusing on resilient farming practices, soil quality, gene banks, subsidies, and land access, with little mention of fisheries or guidance relevant to fish production systems (Muringai *et al.,* 2021).

To improve overall food and nutrition security, policymakers and development organisations should explicitly include fish in national strategies, recognising it as a critical food production system rather than merely a natural resource. Promoting fish consumption, particularly among marginalised and underprivileged populations, raises awareness of its health benefits and enhances dietary quality (Muringai *et al.,* 2021). Small indigenous fish species, abundant in several African Great Lakes, are especially valuable, as studies in Zambia demonstrate their significant contribution to improving children's nutritional status through micronutrients such as zinc, calcium, iodine, and iron (Marinda *et al.,* 2018).

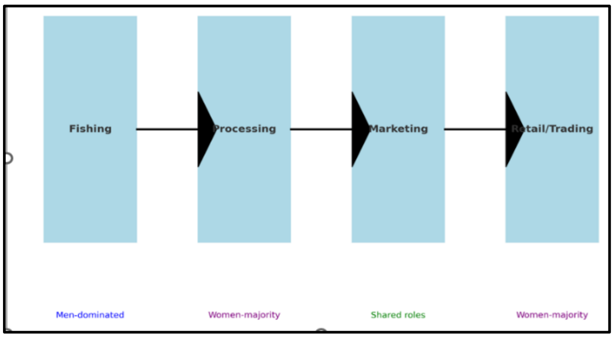
Developing policies that increase access to fisheries and aquaculture resources, provide extension services, and raise public awareness can promote fish consumption and reduce undernutrition. Simultaneously, policies must ensure sustainable management and conservation of fish resources to safeguard both livelihoods and food security. In sub-Saharan Africa, where undernutrition is widespread and fisheries face threats from climate change, overexploitation, and illegal, unregulated fishing, the protection of fish stocks is crucial. For instance, declining catches in Zimbabwe's Lake Kariba negatively affected fishermen's incomes, limiting household food access and diversity (Boah *et al.,* 2019; Muringai *et al.,* 2021). Therefore, effective policies should balance resource conservation with the socio-economic needs of communities dependent on fisheries.

3.6 Invisibility of Social and Gender Dimensions in Fish Value Chains

Women and marginalised communities play crucial roles in fish processing and by-product utilisation, particularly in artisanal and small-scale fisheries. Despite their contributions, these groups are often poorly documented and excluded from technological advancements and value-added opportunities. Few studies address the social equity and gender inclusivity aspects of fish nutrition and by-product utilisation, yet these factors are essential for holistic well-being and livelihood security.

Although men occupy the majority of positions in the fishing industry, women constitute over 25% of the workforce, with most (69.2%) employed as processors in inland fisheries (de Graaf & Garibaldi, 2014; Funge-Smith *et al.*, 2019). Women are frequently engaged in post-harvest activities, including small-scale fish processing (Fig. 6), local market retail, fish selling, fishing gear supply, and credit provision, thereby generating critical income for their families (Muringai *et al., 2021;* Gul *et al.,* 2024). For example, in Msaka (Lake Malawi) and Kachulu (Lake Chilwa), women dominate as local brokers, processors (51% and 81% of processors, respectively), and exporters (100% and 83%, respectively) (Manyungwa-Pasani *et al.,* 2017).

Figure 6
Gendered Value Chain in Fisheries and By-Product Utilisation



3.7 Challenges and Future Directions

Unlocking the full potential of seafood resources requires overcoming key challenges while charting a clear path for future progress. One of the most pressing challenges is sustainable harvesting, which calls for strategies to protect marine ecosystems from overfishing and depletion. Only evidence-based laws, such as science-based catch quotas, fishing effort limitations, seasonal fishing closures, marine protected areas, minimum size limits, bycatch reduction strategies, and ecosystem-based fisheries management, can do this effectively. To guarantee sustainable exploitation while preserving biodiversity and sustaining long-term seafood productivity, these laws should be based on frequent fish stock assessments, ecosystem monitoring, and fisheries-dependent data (Hilborn *et al.,* 2020; UN, 2022: FAO, 2024). Measures such as fishing quotas, seasonal closures, and marine protected areas are essential for reducing environmental impacts and supporting species recovery. Equally important is fostering collaboration among governments, industry stakeholders, and conservation organisations to harmonise efforts toward sustainable fisheries management.

3.7.1 Three Areas of Focus for Future Action Plans

Research: Create cost-effective processing technologies, conduct nutritional profiling of fish and byproducts, and improve safety assessments.

Policy: Incorporate fish-based meals into national nutrition initiatives (e.g., school feeding, maternal health programmes) and promote sustainable aquaculture and responsible fishing. Encourage circular use of fish waste, empower small-scale fisheries and women's groups, and educate consumers on the nutritional and environmental benefits of fish products.

These actions directly contribute to various Sustainable Development Goals (SDGs):

SDG 2 (Zero Hunger) suggests that fish and by-products can address protein, energy, and micronutrient deficits in vulnerable people. According to SDG 3 (Good Health and Well-Being), fish include bioactive components that support cardiovascular, cognitive, and immunological health. SDG 12 (Responsible Consumption and Production) recommends valuing fish waste to promote circular food systems and reduce environmental impacts. SDG 13 (Climate Action) promotes sustainable aquaculture practices to reduce greenhouse gas emissions and improve climate resilience. SDG 14 (Life Below Water) promotes responsible fisheries management to protect biodiversity and aquatic ecosystems. Regional priorities, particularly in Africa, should focus on improving fish utilisation where consumption lags behind global averages, scaling aquaculture to meet population growth, and investing in innovations that are affordable, safe, and culturally relevant. By aligning research, policy, and practice with these frameworks, fisheries and aquaculture can evolve into powerful drivers of environmental stewardship, economic development, and improved human nutrition.

4.0 Conclusion

More than just a traditional source of animal protein, fish and fishery resources are an important part of sustainable food systems that can enhance nutrition, provide jobs, and promote environmental sustainability. By utilising fish products and processing by-products creatively, waste may be significantly reduced, resource efficiency can be increased, and high-value ingredients for culinary, nutraceutical, pharmaceutical, and industrial uses can be produced. However, achieving these advantages will require more funding for infrastructure, supportive legislation, technology advancement, and research, especially in developing nations where these resources' potential is yet underutilised.

To develop the fisheries and aquaculture industry sustainably, inclusive strategies that increase participation along the value chain, including that of women and other marginalised groups, are also necessary. By encouraging better nutrition, resource conservation, environmental stewardship, and resilient livelihoods, these initiatives will hasten the achievement of the Sustainable Development Goals.

In the future, research and development should concentrate on scalable technology for recovering and using bioactive chemicals produced from fish, creating functional and fortified foods, enhancing waste valorisation systems, and guaranteeing the safety and quality of the products. To convert scientific discoveries into workable solutions that optimise the nutritional, economic, and environmental advantages of fish and fishery resources, cooperation between researchers, legislators, businesses, and local people will be crucial.

5.0 Acknowledgements

The authors are grateful to Mbeya University of Science and Technology for the opportunity to conduct this study.

6.0 Funding Statement

The authors received no financial support for this study, authorship, and/or publication of this article.

7.0 Conflict of Interest

The authors declare no potential conflicts of interest.

8.0 References

Adegbola, I. P., Aborisade, B. A., & Adetutu, A. (2021). Health risk assessment and heavy metal accumulation in fish species (Clarias gariepinus and Sarotherodon melanotheron) from industrially polluted Ogun and Eleyele Rivers, Nigeria. Toxicology reports, 8, 1445-1460. https://doi.org/10.1016/j.toxrep.2021.07.007

Agriculture Organization of the United Nations. Fisheries Department. (2018). The state of world fisheries and aquaculture. Food and Agriculture Organization of the United Nations.

Ahern, M. B., Thilsted, S. H., Kjellevold, M., Overå, R., Toppe, J., Doura, M., ... & Franz, N. (2021). Locally-procured fish is essential in school feeding programmes in sub-saharan Africa. *Foods,* 10(9), 2080. https://doi.org/10.3390/foods10092080

Akram, S., Muzaffar, A., & Farooq, Q. (2023). Persistent organic pollutant fragile effects, their sources, transportation and state-of-the-art technologies. International *Journal of Agriculture and Environment,* 2(2), 26-45.

Arvanitoyannis, I. S., & Kassaveti, A. (2008). Fish industry waste: treatments, environmental impacts, current and potential uses. *International Journal of Food Science and Technology,* 43(4), 726-745.

Bellinger, D. C. (2013). Prenatal exposures to environmental chemicals and children's neurodevelopment: an update. Safety and health at work, 4(1), 1-11.

Bellinger, D. C., Devleesschauwer, B., O'Leary, K., & Gibb, H. J. (2019). Global burden of intellectual disability resulting from prenatal exposure to methylmercury, 2015. *Environmental research,* 170, 416-421. https://www.sciencedirect.com/science/article/pii/S0013935118306777.

Béné, C., Barange, M., Subasinghe, R., *et al.* (2015). Feeding 9 billion by 2050 – Putting fish back on the menu. *Food Security*, 7, 261-274. https://doi.org/10.1007/s12571-015-0427-z

Benjakul, S., & Regenstein, J. M. (2019). Fish protein hydrolysates: Production, bioactivities, and applications. *Food Chemistry,* 276, 173-188. In Food Chemistry, DOI works: 10.1016/j.foodchem.2018.09.005.

Bennett, A., Basurto, X., Virdin, J., Lin, X., Betances, S. J., Smith, M. D., ... & Zoubek, S. (2021). Recognize fish as food in policy discourse and development funding. *Ambio*, 50(5), 981-989. https://doi.org/10.1007/s13280-020-01451-4

Boah, M., Azupogo, F., Amporfro, D. A., & Abada, L. A. (2019). The epidemiology of undernutrition and its determinants in children under five years in Ghana*. Plos one,* 14(7), e0219665. https://doi.org/10.1371/journal.pone.0219665

Cai, J., Huang, H., & Leung, P. (2016). Understanding the Contribution of Aquaculture and Fisheries to GDP. FAO Fisheries and Aquaculture Technical Paper No. 606; FAO: Rome, Italy, 2019; 80p.

Caruso, G. (2016). Fishery wastes and by-products: A resource to be valorised. Journal of Fisheries Sciences.com, 10(1), 12–15.

Chan, C. Y., Tran, N., Pethiyagoda, S., Crissman, C. C., Sulser, T. B., & Phillips, M. J. (2019). Prospects and challenges of fish for food security in Africa. Global food security, 20, 17-25. https://10.1016/j.gfs.2018.12.002

Codex Alimentarius Commission. (2023). *Code of Practice for Fish and Fishery Products (CXC 52-2003).*

de Bruyn, J., Wesana, J., Bunting, S. W., Thilsted, S. H., & Cohen, P. J. (2021). Fish acquisition and consumption in the African Great Lakes Region through a food environment lens: A scoping review. Nutrients, 13(7), 2408. https://doi.org/10.3390/nu13072408 de Graaf, G., & Garibaldi, L. (2014). The value of African fisheries. FAO Fisheries and Aquaculture Circular No. 1093. Rome: Food and Agriculture Organization of the United Nations.

Domínguez, R., Pateiro, M., Gagaoua, M., Barba, F. J., Zhang, W., & Lorenzo, J. M. (2019). A comprehensive review on lipid oxidation in meat and meat products. *Antioxidants,* 8(9), 429.Antioxidants, DOI: 10.3390/antiox8090429.

EFSA. (2023). Scientific Opinion on Polycyclic Aromatic Hydrocarbons in Food.

Elavarasan, K. (2018). Importance of fish in human nutrition. Training Manual On Seafood Value Addition. ICAR Central Institute of Fisheries Technology. Available online: https://krishi.icar.gov.in/jspui/bitstream/123456789/20327/1/1_Importance%20of%fish%20in%20 human%20health.pdf

European Commission. (2020). *A New Circular Economy Action Plan: For a Cleaner and More Competitive Europe*. Brussels, Belgium.

FAO. (2024). The State of World Fisheries and Aquaculture 2024.

FAO. (2024). *The State of World Fisheries and Aquaculture 2024*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2024). *The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*. Rome: Food and Agriculture Organization of the United Nations.

Food and Agriculture Organization of the United Nations (FAO). FAO Working for SDG 14: The Special Role of Fish in Human Nutrition; FAO: Rome, Italy, 2017; Available online: http://www.fao.org/3/a-i7298e.pdf

Food and Agriculture Organization of the United Nations. (2026). *The State of World Fisheries and Aquaculture 2026: Blue Transformation in Action*. FAO. https://doi.org/10.4060/cd8357en

FoodStruct. (n.d.). *Sardine, Atlantic, canned in oil, drained solids with bone: Nutrition facts*. Retrieved September 15, 2025, from https://foodstruct.com/food/fish-sardine-atlantic-cannedinoil-drainedsolidswithbone

Funge-Smith, S., & Bennett, A. (2019). A fresh look at inland fisheries and their role in food security and livelihoods. Fish and Fisheries, 20(6), 1176-1195. https://doi.org/10.1111/faf.12403

Ghalamara, S., Brazinha, C., Silva, S., & Pintado, M. (2024). *Exploring Fish Processing By-Products as an Alternative Source of Bioactive Peptides: A Review on Extraction and Food Applications*. *Current Food Science and Technology Reports*, 2, 377–391. https://doi.org/10.1007/s43555-024-00041-9

Ghaly, A. E., Ramakrishnan, V. V., Brooks, M. S., Budge, S. M., & Dave, D. (2013). Fish processing wastes as a potential source of proteins. *Amino acids and oils: A critical review. J. Microb. Biochem. Technol*, *5*(4), 107-129.

Glencross, B. D., Booth, M., & Allan, G. L. (2007). A feed is only as good as its ingredients–a review of ingredient evaluation strategies for aquaculture feeds. *Aquaculture nutrition*, *13* (1), 17-34.

Government of Canada. (2008). *Canadian nutrient file: Nutrient value of some common foods – Table 8 (Fish and shellfish)*. Ottawa, ON: Health Canada. Retrieved September 15, 2025, from https://www.canada.ca/en/health-canada/services/food-nutrition/healthy-eating/nutrient-data/table-8-fish-shellfish-nutrient-value-some-common-foods-2008.html

Guerard, F. (2010). Fish by-products: Processing, nutritional and functional aspects. In Functional Ingredients from Fish (pp. 1–35).

Gul, S., Shafiq, U., Mir, S. A., Iqbal, G., & Lone, H. Q. (2024). Enhancing global food security through sustainable fisheries and aquaculture: a comprehensive review. Asian Journal of Agricultural Extension, Economics and Sociology, 42(10), 60-70. https://doi.org/10.9734/ajaees/2024/v42i102563.

Hilborn, R., Amoroso, R. O., Anderson, C. M., Baum, J. K., Branch, T. A., Costello, C., ... & Ye, Y. (2020). Effective fisheries management instrumental in improving fish stock status. *Proceedings of the National Academy of Sciences*, *117*(4), 2218-2224.https://doi.org/10.1073/pnas.1909726116

Claeys L, Romano C, De Ruyck K, *et al.* Mycotoxin exposure and human cancer risk: a systematic review of epidemiological studies. Compr Rev Food Sci Food Saf. 2020; 19: 1449–1464. https://doi.org/10.1111/1541-4337.12567

Khalili Tilami, S., & Sampels, S. (2018). Nutritional value of fish: lipids, proteins, vitamins, and minerals. Reviews in Fisheries Science& Aquaculture, 26(2), 243-253. https://doi.org/10.1080/23308249.2017.1399104

Kristinsson, H. G., & Rasco, B. A. (2000). Fish protein hydrolysates: Production, biochemical, and functional properties. Critical Reviews in Food Science and Nutrition, 40(1), 43–81. Critical Reviews in Food Science and Nutrition, 10.1080/10408690091189266.

Manjengwa, F., Nhiwatiwa, T., Nyakudya, E., & Banda, P. (2019). Fish from a polluted lake (Lake Chivero, Zimbabwe): a food safety issue of concern. Food Quality and Safety, 3(3), 157-167. https://doi.org/10.1093/fqsafe/fyz015

Manyungwa-Pasani, C. L., Hara, M., & Chimatiro, S. K. (2017). Women's participation in fish value chains and value chain governance in Malawi: A case of Msaka (Lake Malawi) and Kachulu (Lake Chilwa).

Marinda, P. A., Genschick, S., Khayeka-Wandabwa, C., Kiwanuka-Lubinda, R., & Thilsted, S. H. (2018). Dietary diversity determinants and contribution of fish to maternal and under-five nutritional status in Zambia. PloS one, 13(9), e0204009.https://doi.org/10.1371/journal. pone.0204009.

Maulu, S., Musuka, C. G., Molefe, M., Ngoepe, T. K., Gabriel, N. N., Mphande, J., ... & Zhang, L. (2024). Contribution of fish to food and nutrition security in Southern Africa: challenges and opportunities in fish production. Frontiers in Nutrition, 11, 1424740. https://doi.org/10.3389/fnut.2024.1424740

Mitra, A., Amulejoye, F. D., Barua, P., Odu-Onikosi, S. G., Mohanty, P., Khalil, H. S., &Maulu, S. (2025). Nano-enhanced diets: advancing sustainability in aquaculture - a review. *Cogent Food & Agriculture*, *11*(1). https://doi.org/10.1080/23311932.2025.2453900

Muringai, R. T., Mafongoya, P., Lottering, R. T., Mugandani, R., & Naidoo, D. (2021). Unlocking the potential of fish to improve food and nutrition security in sub-Saharan Africa. Sustainability, 14(1), 318. https://10.3390/su14010318

My Food Data. (2024, March 28). *Salmon nutrition facts & health benefits*. Retrieved September 15, 2025, from https://www.myfooddata.com/articles/salmon-nutrition.php

NutritionValue.org. (n.d.). *Fish, tilapia, raw, farmed: Nutrition facts*. Retrieved September 15, 2025, from https://www.nutritionvalue.org/Fish%2C_tilapia%2C_raw%2C_farmed_nutritional_value.html

Obiero, K., Meulenbroek, P., Drexler, S., Dagne, A., Akoll, P., Odong, R., Kaunda-Arara, B., & Waidbacher, H. (2019). The Contribution of Fish to Food and Nutrition Security in Eastern Africa: Emerging Trends and Future Outlooks. Sustainability, 11(6), 1636. https://doi.org/10.3390/su11061636

Ore Areche, F. R. A. N. K. L. I. N., Julcahuanga Dominguez, J. A., Ticsihua Huaman, J. O. V. E. N. C. I. O., Malpartida Yapias, R. J., Choque Rivera, T. J., Mamani Perales, L. D., ... & Yoshira Areche-Mansilla, D. E. N. I. S. S. (2024). Maximizing the Potential of Marine Resources: a Sustainable Approach to High-Value Product Development from Seafood by-Products and Waste. Current Research in Nutrition & Food Science, 12(3). https://doi.org/10.12944/CRNFSJ.12.3.7

Oregon State University, Seafood Network Information Center (SNIC). *Seafood nutrition overview: Omega-3 fatty acids (EPA & DHA) content in seafood*. Retrieved September 15, 2025, from https://www.seafoodhealthfacts.org/nutrition/seafood-nutrition-overview

Organisation for Economic Co-operation and Development (OECD); Food and Agriculture Organization of the United Nations (FAO). Chapter 8. Fish and seafood. In OECD/FAO Agricultural Outlook 2018–2027; FAO: Rome, Italy, 2018; pp. 175–190.

Oteri, M., Di Rosa, A. R., Lo Presti, V., Giarratana, F., Toscano, G., & Chiofalo, B. (2021). Black soldier fly larvae meal as alternative to fish meal for aquaculture feed. *Sustainability*, *13*(10), 5447. . https://doi.org/10.3390/ su13105447

Pal, J., Shukla, B. N., Maurya, A. K., Verma, H. O., Pandey, G., & Amitha, A. (2018). A review on role of fish in human nutrition with special emphasis to essential fatty acid. International journal of fisheries and aquatic studies, 6(2), 427-430.

Rana, R., Sayem, A. S. M., Sabuz, A. A., Rahman, T., & Hossain, A. (2021). Effect of Lablab Bean (Lablab purpureus L.) Seed Flour on the Physicochemical and Sensory Properties of Biscuits. *International Journal of Food Science and Agriculture*, 5(1), 52-57. https://doi: 10.26855/ijfsa.2021.03.008

Rombenso, A., Araujo, B., & Li, E. (2022). Recent Advances in Fish Nutrition: Insights on the Nutritional Implications of Modern Formulations. Animals, 12(13), 1705. https://doi.org/10.3390/ani12131705

Rustad, T., Storrø, I., & Slizyte, R. (2011). Possibilities for the utilisation of marine by-products. International journal of food science & technology, 46(10), 2001-2014.

Saba, A. O., Eyo, V. O., Elegbede, I. O., Fakoya, K. A., Ojewole, A. E., Dawodu, F. O., ... & Amal, M. N. A. (2024). Sustaining the blue bounty: Fish food and nutrition security in Nigeria's evolving blue economy. AIMS Agriculture and Food, 9(2), 500-530. https://doi.org/10.3934/agrfood.2024029

Santos, R., Oliveira, M., Monteiro, R., & Marques, C. (2020). Sardine (Sardina pilchardus): Nutritional composition and health benefits. *Foods, 9*(3), 306. https://doi.org/10.3390/foods9030306

Tacon, A. G., & Metian, M. (2015). Feed matters: Satisfying the feed demand of aquaculture. Reviews in Fisheries Science & Aquaculture, 23(1), 1–10. Reviews in Fisheries Science & Aquaculture, DOI works: 10.1080/23308249.2014.987209.

Tocher, D. R. (2015). Omega-3 long-chain polyunsaturated fatty acids and aquaculture in perspective. *Aquaculture*, *449*, 94-107.

Toor, M. D., & Ramzan, H. (2023). A brief description on the use of organo-mineral phosphorus in sustainable agriculture. International Journal of Agriculture and Environment, 2(2), 67-71. https://doi.org/10.62881/ijae.v2i2.37

UNEP. (2023). Turning Off the Tap: How the World Can End Plastic Pollution.

United Nations (UN). (2022). *The Sustainable Development Goals Report 2022*. United Nations, New York.

USDA/Food Struct (2026)*Catfish, channel, farmed, raw: Nutrition facts*. Retrieved May 15, 2026, from https://foodstruct.com/food/fish-catfish-channel-farmed-raw

USDA/FoodStruct (2026)*Mackerel, Atlantic, raw: Nutrition facts*. Retrieved May 15, 2026, from https://foodstruct.com/food/fish-mackerel-atlantic-raw

Välimaa, A. L., Mäkinen, S., Mattila, P., Marnila, P., Pihlanto, A., Mäki, M., & Hiidenhovi, J. (2019). Fish and fish side streams are valuable sources of high-value components. Food Quality and Safety, 3(4), 209-226. https://doi.org/10.1093/fqsafe/fyz024

Vianna, G. M., Zeller, D., & Pauly, D. (2020). Fisheries and policy implications for human nutrition. Current Environmental Health Reports, 7(3), 161-169. https://doi.org/10.1007/s40572-020-00286-1

WHO. (2023). Food Safety: Chemical Hazards in Food. World Health Organization & Food and Agriculture Organization of the United Nations (2023). Safety evaluation of certain contaminants in food: prepared by the ninetieth meeting of the Joint FAO/WHO Expert Committee on Food Additives (JECFA). World Health Organization. Food and Agriculture Organization of the United

Nations. https://iris.who.int/handle/10665/371103. License: CC BY-NC-SA 3.0 IGO

World Health Organization (WHO). (2024). *Food Safety: Fish and Fishery Products*.