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REVIEW

Fish as a functional food: a comprehensive review of bioactive components and their therapeutic potential for human health

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Abstract Fish is widely known as a highly nutritious food, rich in high-quality proteins, lipids (including omega-3 fatty acids), vitamins, minerals, and essential amino acids that contribute to human health and disease prevention. However, fish processing generates a substantial amount of waste, including scales, skin, skeleton, head, liver, viscera, and eyeballs, which are often discarded. These by-products serve as a potent source of bioactive compounds like collagen, chitin, hyaluronic acid, enzymes, peptides, and unsaturated fatty acids, which possess significant nutritional, therapeutic, and commercial potential. Improper disposal of fish waste not only leads to environmental pollution but also represents a major loss of valuable biomaterials. To address this issue, green extraction technologies such as Ultrasound-Assisted Extraction (UAE) and Supercritical Fluid Extraction (SFE) have emerged as sustainable and efficient solutions. UAE makes it easier to release bioactive compounds by creating cavitation bubbles that rupture cells, while SFE uses eco-friendly solvents like supercritical CO_2 to extract heat-sensitive compounds without degradation. The recovered bioactive compounds can be utilized in a wide range of sectors, including nutraceuticals, pharmaceuticals, food and animal feed, cosmetics, and industrial products. Valorizing fish waste through such innovative, eco-friendly techniques not only mitigates environmental impacts but also enhances the circular bio economy. This integrated approach supports sustainable food systems by converting waste into value-added products, thereby promoting both environmental conservation and human health.

Keywords Fish . Fish by product . Bioactive compound . Therapeutic potential . Green extraction technologies

Introduction

Fish is widely valued as an affordable and reliable source of nutrition, offering high-quality protein, a well-balanced mix of essential amino acids, healthy fats, important vitamins and minerals (Sedyaaw et al. 2024). Fish and other marine organisms, which comprises almost half of the global biodiversity, possess significant amount of novel bioactive compounds that holds great potential for improving human health (Saba et al. 2023). Bioactive compounds—a term derived from the Greek and Latin words for "life" and "activity" are substances that have beneficial effects on living organisms. Fish are an abundant and valuable source of these compounds. They contain a wide range of bioactive nutrients, including long-chain polyunsaturated fatty acids (PUFAs) like eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), omega-3 fatty acids, bioactive peptides, protein hydrolysates, amino acids, vitamins, minerals, gelatin, collagen, fish oil, and nutrients extracted from fish bones. This complex profile makes fish and their by-products important raw materials for the development of nutraceuticals and functional foods (Kundam et al. 2018). There

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is currently consumer demand for functional foods that provide health benefits beyond adequate nutrition and could potentially prevent diseases (Afzaal et al. 2022).

Since the 1980s, fish has been increasingly recognized as a functional food, due to its content of omega-3 fatty acids, high-quality proteins, essential vitamins, and minerals—offering health benefits that extend beyond basic nutritional needs. These components promote brain health and the immune system while reducing the risk of heart disease. Recently, it has been examined how bioactive compounds in fish can be utilized for therapeutic purposes. Functional foods, such as fish, provide additional health benefits and can help reduce the risks of chronic diseases. As the saying goes, "Eat fish, live longer," highlighting its value as a health-promoting food (Sarojnalini and Hei 2019). The use of seafood, which includes finfish and shellfish, has a significant impact on the world's food security (Azra et al. 2021). Approximately 820 million people, or about 11% of the global population, are suffering from poverty and lack access to nutritious food, hindering proper growth and health (Afsana et al. 2022). Despite significant progress in recent decades, the world is struggling to produce enough food to meet the requirements for its upcoming population (Giller et al. 2021).

The chemical composition of raw fish typically includes 0%–0.5% carbohydrates, 16%–21% protein, 1.2%–1.5% minerals, 0.2%–25% fat, and 66%–81% water (Noreen et al. 2025). The term "proximate composition" refers to the assessment of composition of fish, which can be different depending on species, sex, and other factors. Notably, the therapeutic potential of fish consumption is largely attributed to high levels of long-chain omega-3 polyunsaturated fatty acids (PUFAs). Additionally, various bioactive components in fish have also been shown to positively impact human health (Afzaal et al. 2021). The World Health Organization recommends consuming fish 1–2 times per week to obtain 200–500 mg of EPA and DHA, particularly from salmon or trout, to help prevent coronary heart diseases and strokes (Ashraf et al. 2020). Many people are affected by lack of awareness in different ways, and these effects are due to individual behaviors in dietary habits or a change in lifestyle (Ikram et al. 2023).

Fish consumption has been widely proven to have health-promoting effects through both observational and clinical research (Zang et al. 2020). Aquatic foods provide over 20% of the animal protein intake for over 3 billion people worldwide, and approximately 600 million individuals depend on fisheries for their livelihoods (Alsaleh 2023). Over the past 50 years, the consumption of aquatic food has doubled and is expected to increase further by 2050 due to population increases (Islam et al. 2021). Food waste refers to foods that are acceptable for consumption but eventually end up being discarded (Ijaz et al. 2024).

Seafood waste is surprisingly rich in valuable nutraceutical compounds, including omega-3 fatty acids, carotenoids, proteins such as myosin and collagen, enzymes, amino acids, and chitosan. These bioactive components have been associated with a range of health benefits, including antioxidant, anti-inflammatory, and antimicrobial effects. Marine biotechnology offers innovative methods to extract and utilize these compounds from seafood and its by-products, turning waste into a valuable resource (Saba et al. 2023). Carotenoids are plant based component but are also extracted from fish skin as a byproduct. Carotenoids are well documented to reduce the human specific diseases, cancers and fortifying the immune system while safeguarding against age-related weakness of the eyes (Ikram et al. 2024).

Fish provides about 17% of the animal protein consumed worldwide (Ashraf et al. 2020). In 2022, global fish production reached approximately 184.1 million tons, reflecting a 1.2% increase compared to previous years. While aquaculture continues to expand rapidly at an annual growth rate of around 7%, other sources of fish production have shown only modest growth since 2015 and 2020. Notably, fisheries and aquaculture remain vital to the livelihoods of over 500 million people, particularly in developing countries (Bhujel 2024).

Approximately 32,000 fish species have been recorded globally, highlighting the diversity and importance of fish in global ecosystems. The production of fish plays a significant part in the global provision of food, aquaculture, and livestock industries. Due to its high volume and organic content, seafood waste is a major environmental and economic issue (Chen et al. 2022).

A bibliometric analysis of 1,109 publications (2010-2024) shows a significant rise in seafood waste valorization research, mainly from China, Japan, and European nations. Key extraction methods like supercritical fluid extraction (SFE) yield valuable compounds such as omega-3 fatty acids and collagen for health and cosmetic uses. This study emphasizes challenges of scaling and cost, suggests hybrid methods for improved recovery, and highlight a gap between publication volume and impact, which suggests opportunities for innovation in sustainable seafood waste utilization (Baarimah et al. 2024).

The global fishery industry generates an enormous amount of waste over 20 million tons annually, largely comprising of non-target species, heads, fins, skins, and viscera, much of which is either discarded or used for low-value applications (Coppola et al. 2021). Traditional extraction methods like maceration and Soxhlet are inefficient and environmentally harmful, leading to the loss of valuable bioactive compounds. In contrast, green technologies such as Ultrasound-Assisted Extraction (UAE) and Supercritical Fluid Extraction (SFE) offer sustainable and effective alternatives for recovering these health-promoting components (Martins et al. 2023). However, despite the known nutritional benefits of fish rich in omega-3 fatty acids, high-quality proteins, vitamins, and antioxidants there is a clear research gap in fully exploring and standardizing environmentally friendly methods for utilizing fish and its by-products as functional foods. Many studies have not thoroughly examined the therapeutic properties of fish-derived bioactive compounds in various industries, and consumers are not well-informed about fish-based functional foods. This review is therefore significant as it aims to consolidate existing knowledge on the nutritional and therapeutic benefits of fish, highlight innovative green extraction techniques, and promote sustainable utilization of fish by-products. The core aim of this review is to provide a comprehensive overview of fish as a functional food, identify current challenges in waste valorization, and support future research and industrial applications for health and sustainability.

Nutritional composition of fish flesh

Fish is globally one of the most important nutritional sources, providing a wide range of micronutrients, macronutrients, bioactive compounds, and antimicrobial elements that are essential for human health (Karadaş 2024). Fish contain proteins (essential amino acids and non-essential amino acids), minerals (magnesium, zinc, potassium, selenium, sodium, iodine, phosphorus, iron, and iodine), dietary vitamins (A, D, E, B3, B6, B12 and H), fatty acids (monosa turated fatty acids (MUFAs), saturated fatty acids (SFA), polyunsaturated fatty acids (PUFAs), sterols, pigments, polyphenols, and many more micronutrients (Lall and Kaushik 2021; Phogat et al. 2022). The proximate composition of some important freshwater species is shown in Table 2.

Fish protein is a superior animal protein source because of its complete amino acid profile, which is essential for muscle repair, immune function, and growth (Mondal et al. 2021). The ability of fish protein to be used by the human body is quite easy due to its high bioavailability (Moya Moreira et al. 2023). Fish also contains a broad spectrum of fatty acids, such as omega-3 polyunsaturated fatty acids (PUFAs) that are the most critical for human health. Omega-3s not only affect eicosatetraenoic acid (EPA) and docosahexaenoic acid (DHA), but they also support cell membrane structure, regulate anti-inflammatory responses, and enhance memory (Djuricic and Calder 2021). Oil rich fish, such as salmon, mackerel, and sardines, are

Table 1 The world fish production in 2018

Category	Quantity / Value	References
Total Fish Production (2018)	179 million tons	Bartley (2022)
Total Value	$401 billion	FAO (2020)
Aquaculture Contribution	82 million tons ($250 billion)	Same as above
Fish for Human Consumption	156 million tons (~20.5 kg per person)	Lichna et al. (2023)
Fish for Non-Food Uses	22 million tons (Fishmeal, Fish Oil)	Thiao and Bunting (2022)
Asia's Share in Fish Farming	89% of global production	Garlock et al. (2020)
Countries with Rising Fish Farming	Bangladesh, Chile, Egypt, India, Indonesia, Norway, Vietnam	Jolly et al. (2023)
Largest Producer	China	Crona et al. (2020)

Table 2 The proximate composition of some freshwater fish species

Scientific name	Common name	Protein (%)	Moisture (%)	Fats (%)	Ash (%)	References
Labeo rohita	Rohu	15.90	75.60	2.70	2.60	He et al. (2024)
Oreochromis niloticus	Nile tilapia	17.60	76.40	1.89	3.84	Ayanda et al. (2019)
Trachysurus spp.	Catfish	16.02	74.15	5.31	3.86	Prabhakar et al. (2020)
Lates calcalifer	Asian sea bass	21.10	72.80	2.60	1.60	Mohanty et al. (2016a)
Tor putitora	Mahseer	17.90	74.90	4.30	1.50	Same as above
Belone belone	Gar fish	20.26	73.97	3.64	1.25	Kocatepe and Turan (2012)
Cyprinus carpio	Common carp	17.25	77.24	1.26	0.94	Teame et al. (2016)
Piaractus mesopotamicus	Pacu	25.00	73.75	4.34	1.28	Rodrigues et al. (2020)
Cirrhinus Mrigala	Mrigal	15.15	75.73	4.19	4.87	Hussain et al. (2016)
Clarias Batrachus	Walking catfish	16.40	75.90	3.70	2.30	Mohanty et al. (2016a)

especially enriched with useful fats, making them the leading dietary option to promote better cardiovascular health and reduce inflammation (Ashraf et al. 2020).

Fish flesh is beneficial due to its high protein and omega-3 content, low saturated fat, and the absence of trans fats, which, are all linked to its remarkable impact on heart health (Singh et al. 2025). According to the recent studies, eating fish on a regular basis is likely to protect against cardiovascular disease (CVD) as omega-3s can serve as antimicrobial agents (Ali et al. 2022; Kwasek et al. 2020).

Fish-based nutrients and their role in human health

Protein and amino acids

Proteins possess multiple functions as biomolecules. The peptide bond is responsible for bonding amino acids to form proteins, making them the most versatile biomolecules. (Prabhakar et al. 2020). Fish proteins are easy to digest and contain a very high number of amino acids (Awuchi et al. 2022; Ullah et al. 2022).The fish muscle contains three different types of proteins, which are myofibrillar or contractile proteins (actin, myosin, tropomyosin, and actomyosin), and these are about 60%–65% of the total protein content; sarcoplasmic or enzymatic proteins (albumin, globulin, and enzymes), which are about 30%–35% of the total proteins; and stroma or connective tissue proteins (collagen), which are about 3%–5% of the total proteins (Ochiai and Ozawa 2020). Freshwater fish proteins are more abundant in all essential amino acids (e.g., methionine and lysine) than other plant proteins. In general, this is the primary difference, as proteins from plant sources frequently lack sufficient essential amino acids (Jia et al. 2021). The amino acid composition of freshwater and marine fish is almost the same. The nutritional content of fish proteins is similar to that of red meat, and they are very easy to digest, with more than 90% of the material being digestible. The general water content in nature allows freshwater fish to be slightly more hydrated and contain a bit less protein than marine fish because these fish obtain more water and consume less salt, which in turn influences their body composition (Fitri et al. 2022). Fish flesh consistency depends on cellularity, i.e., the amount of muscle fibers and their size. Fish live immersed in water, and therefore, they don't need to push their skeletons forcibly, which corresponds to decreased muscle fiber density and a smaller diameter of muscle fiber (Horton 2020). Plant sources such as Buckwheat contain all essential amino acids and are also a good source of protein (Saeed et al. 2021). Fish flesh is always softer than the meat of land animals. This is one of the main aspects that affect the texture and quality of fish meat. When comparing the essential amino acid profiles of chicken, eggs, and fish (*Clarias gariepinus*), fish is source of higher quantity of all essential amino acids (B AS 2015). A recent study assessed the crude protein and amino acid composition of 30 food fish species col-

Table 3 The essential amino acid components in different fish species

Essential Amino Acids (EAAs)	Composition	Health benefits	EAAs Rich in fish species
Arginine	Precursor of nitric oxide	Controlled and maintained neurotransmitters, blood clotting, blood pressure, immune regulation, wound healing hormones, and regulation.	*Eleotris Fusca* (4.90 ± 0.36g /100g) *Securicula gora* (3.17 ± 0.34 g/100 g) *Mystus cavasius* (2.28 ± 0.18 g/100 g)
Leucine	Alpha amino acids, alpha carboxylic acids	Help in protein synthesis, blood sugar regulation, muscle growth, and human metabolism Helpful during injuries, trauma, sepsis, and burn	*Macrobracium malcolmsonii* (3.08 ± 0.32 g/100 g)
Isoleucine	Isomer of leucine	Build and recover muscle strength Improve muscles' pain	*Eleotris Fusca* (3.10 ± 0.24 g/100 g)
Valine	Alpha amino acids, alpha carboxylic acids	Regulate metabolic pathways Maintain immune systems Smooth the nervous system	*Eleotris Fusca* (3.10 ± 0.24 g/100 g)
Lysine	Alpha amino group $-NH^{+3}$	Maintain optimal growth and immune system	*Eleotris Fusca* (4.06 ± 0.33 g/100 g)
Methionine	sulfur-containing EAA and acetaminophen	Boosts the flexibility and nature of the skin as well as the hair Helpful in liver damage, Parkinson's disease, allergies, and depression	*Eleotris Fusca* (1.92 ± 0.18 g/100 g) *Securicula gora* (1.45 ± 0.11 g/100 g) *Macrobracium malcolmsonii* (1.26 ± 0.12 g/100 g)
Phenylalanine	Precursor of tyrosine	Help to treat chronic pain, Parkinson's disease, depression, and speech difficulties	Seabreems (0.7 ± 1.4 g/100 g)
Histidine	Precursor of histamine	Remove heavy metals from the body Recover cell tissues and myelin sheaths	*Eleostric fusca* (1.77 ± 0.021 g / 100g)
Threonine	Natural supplement	Helps in the maintenance of nervous disorders	*Securicula gora* (a.7 ± 0.21g/100g)

lected from various landing stations along the Ganga River. Crude protein content was determined using the Kjeldahl method, while amino acid profiling was conducted through high-performance liquid chromatography (HPLC). The findings revealed that species such as *Eleotris fusca, Macrobrachium malcomsonii*, and *Mystus cavasius* contained higher levels of essential amino acids including glycine, glutamic acid, cysteine, threonine, phenylalanine, methionine, lysine, leucine, isoleucine, histidine, and valine. It is remarkable that consuming around 50 grams of these fish daily can fulfill the daily amino acid requirements of a 60 kg adult. These results suggest that such fish species may be recommended by healthcare professionals as natural dietary supplements to address specific amino acid deficiencies (Das et al. 2024) Table 3.

Lipids, bioactive compounds, and their health benefits

Fish are rich in monounsaturated and polyunsaturated fatty acids (PUFAs), particularly omega-3 fatty acids like DHA and EPA. These beneficial fatty acids promote energy metabolism and support various biological processes, including the prevention of chronic illnesses (Mititelu et al. 2024).

Alpha-linolenic acid (ALA) is an important omega-3 fatty acid that precedes EPA and DHA. Consuming fish increases levels of these fatty acids, which help reduce the risk of coronary heart disease by lowering triglycerides, improving heart function, and decreasing blood pressure and inflammation (Gormley 2013). The anti-inflammatory property of EPA and DHA occurs through the modulation of prostaglandin synthesis (Reimers and Ljung 2019). Fatty acids help reduce platelet build-up in the blood by narrowing the blood vessels and reducing the risk of blood clot formation (Kundam et al. 2018). Since human cannot produce PUFAs longer than 18 carbon atoms outside of diets, fish lipid fractions are reliable source of these PUFAs, which are crucial for human health (Zheng et al. 2013). Omega-3 fatty acids in fatty fish are important for children's growth. DHA supports brain function and neurodevelopment, while EPA boosts cardiovascular health. These fatty acids also play roles in osmoregulation, nutrient assimilation, and transport (AlAmmar et al. 2021). The U.S. Departments of Agriculture, Health and Human Services recommended a daily intake of 250 mg of EPA and DHA types of omega-3 polyunsaturated fatty acids (PUFAs) to help reduce the risk of heart disease. (Banaszak et al. 2024).

Vitamins

In addition to lipids, fish based products and fish oils like cod liver oil are the biggest source of vitamins A,

Table 4 The vitamins found in fish species and their role in human health

Vitamins	Fish Species	Functional Properties	References
Vitamin A (Retinol or Retinoic acid)	Atlantic Herring *(Clupea harengus)*, Atlantic Cod *(Gadus morhua)*	Has antioxidant properties Help to maintain sustainable growth, promote eyesight, build cells.Biosynthesis of many protein that enhance the development of cell and regulate cell sensitivity to hormones	Oruch and Pryme (2012)
Vitamin B	Channel Catfish *(Ictalurus punctatus)*	Regulate the body metabolism and maintenance Necessary for DNA synthesis Helps to maintain nerve and healthy blood	Shadyeva et al. (2022)
Vitamin D	*Tenualosa ilisha*	Help in prevention from major diseases including rickets,osteoporosis, osteomalacia	Goswami et al.(2022)
Vitamin E	*Sardinella longiceps*	Has antioxidant activity that helps to maintain cell antioxidant defense system Prevent body from major diseases including cancer, aging, arthritis and cataracts.	Phogat et al. (2022)

Table 5 Minerals found in fish species and their role in human health

Minerals	Fish Species	Properties	References
Calcium	Atlantic Salmon *(Salmon salar)*	Bone formation, Strong dental tissues in children, adults and pregnant women	Aas et al. (2022)
Magnesium		Support memory and learning	
Phosphorus		Bones and teeth formation, increase metabolic function	
Sodium		Help in nerve impulse transmission, maintain electrolyte balance	
Iron		Transport oxygen in the body due to the presence of hemoglobin	
Zinc	*Stolephorus waitei, Stolephorus commersonii*	Act as a cofactor important for metabolism, digestion, nerve function, cell growth and development, immune system, DNA and protein synthesis	Kawarazuka and Béné (2011)
Potassium	Atlantic Salmon *(Salmon salar),* Tilapia (*Oreochromis spp.*) Sardines(*Sardina pilchardus*)	Help in nerve impulse transmission, maintain electrolyte balance in the body	Ali et al. (2022)
Iodine	Atlantic Cod *(Gadus morhua)*	Help in disability, pregnancy and cretinism	
Copper	Grass carp *(Ctenopharyngodon idella)*	Growth, metabolism	Abbas et al. (2022)
Selenium	*Clarias batrachus*	antioxidant property, lower the risk of cancer, boosts fertility	Mohanty et al. (2016b)

B, D and E which are essential for maintenance of biological effects in human body (Phogat et al. 2022). Vitamins are bioavailable in fish species like mackerel, lake trout, salmon, and sardine (Badoni et al. 2021). The vitamins found in fish species and their role in human health are shown in Table 4.

Minerals

Aquatic foods consist of larger amounts of essential minerals and trace elements than terrestrial foods (Mitra et al. 2022). Due to the presence of minerals and trace elements, fish can produce inorganic atoms. These minerals are essential for human health and also found in greater concentration in sea food (Nag et al. 2022).Some important minerals are calcium, iron, potassium, iodine, sodium, magnesium phosphorus, copper, selenium and zinc that necessary for human biochemical responses given in Table 6**.**

Carbohydrates

Fish flesh contains very little carbohydrate, and glycogen is primarily stored in the liver. In live fish, glycogen serves as an energy reserve but is rapidly broken down into lactic acid after the fish dies. Fish protein without carbohydrates does not raise the glucose levels in body which is important for diabetics to maintain dietary balance (Saba and Rana 2023).

Bioactive compounds and their extraction methods

Fish processing generates byproducts, which account for about 45% of total production and include heads, skin, and bones. Despite being rich in bioactive compounds, improper disposal leads to economic losses and environmental issues, such as greenhouse gas emissions. Notably, 30% to 50% of the fish meat remains unutilized during filleting, highlighting the potential waste (Ghalamara et al. 2024). Bioactive compounds can be extracted from seafood by-products, transforming them into valuable products that benefit both the economy and the environment. Components like collagen, omega-3 fatty acids, and antioxidants hold potential for pharmaceuticals and cosmetics. Efficient extraction requires advanced technologies tailored to seafood waste. Circular economy principles are becoming increasingly important in food production, highlighted by the adoption of new techniques that minimize waste and optimize resource use (Pizzone 2023).

Green extraction technologies

Ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction (UAE) is an eco-friendly method gaining popularity for extracting bioactive compounds from fish tissues and other sources (Garcia-Larez et al. 2025).UAE uses ultrasound waves to improve the extraction of target compounds from solid matrices into liquid solvents, and is effective for extracting bioactive compounds from sources like fish and aquatic resources (Jinadasa et al. 2023). Ultrasound-assisted extraction (UAE) of bioactive compounds from fish utilizes acoustic cavitation, where ultrasound waves create and collapse cavitation bubbles in the solvent. This collapse generates high-energy conditions—high temperatures and pressures—that break down cell walls and membranes, allowing bioactive compounds to be released into the solvent (Linares and Rojas 2022).

Several key parameters influence the efficiency of UAE, including the solvent type, solid-to-solvent

Table 6 Fish protein residual ratios

Fish by-products	Residue (%) proteins	References
Viscera	12-18	Estiasih et al. (2021)
Carcass	9-15	Zatta Cassol et al. (2025)
Bones	9-15	Coppola et al. (2021)
Head	9-12	Kong et al. (2022)
Scale	5	Zatta Cassol et al. (2025)
Skin	1-2	Zatta Cassol et al. (2025)

ratio, extraction time, temperature, and ultrasound power or amplitude. Optimizing these parameters is crucial for maximizing the yield and preserving the integrity of the extracted bioactive compounds (Myo and Khat-Udomkiri 2022).

Mechanism of ultrasound-assisted extraction

The UAE technique uses high-frequency ultrasound (over 20 kHz, up to 100 MHz) to enhance extraction (Santos-Zea et al. 2021). Hypotheses for this enhancement include disruption of cell walls, increased penetration and swelling, and hydration. Ultrasound vibrates and accelerates solid and liquid particles, allowing solutes to quickly move from solid to solvent. This process, known as cavitation, involves the formation, growth, and collapse of bubbles, which disrupt cell membranes, facilitating the release of compounds and improving solvent penetration and mass transfer (MS et al. 2018).The mechanism of the UAE method is shown in Figure 1. The choice of solvent is crucial for the efficiency of ultrasound-assisted extraction (UAE) of bioactive compounds from fish. Common solvents include ethanol, methanol, and water, often enhanced with acids or bases. The solvent should dissolve target compounds while being compatible with the fish matrix. Process optimization involves adjusting ultrasound intensity, extraction time, temperature, and the solvent-to-solid ratio to maximize yield. A key advantage of UAE is its non-thermal nature, preserving heat-sensitive compounds. After extraction, the bioactive-rich solvent is separated from the solid residue, and further purification like filtration, evaporation, or chromatography may follow. Overall, UAE is a rapid, efficient, and environmentally friendly method for extracting valuable bioactive compound from fish tissues (Rathod et al. 2023).

Various fishery and marine by-products have demonstrated significant potential for the extraction of high-value bioactive compounds using green and efficient extraction technologies. For example, the whole body of *Diadema setosum* (sea urchin) was found to be rich in compounds like cholest-5-en-3-ol (3β), palmitic acid, oleic acid, stearic acid, flavonoids, phenols, batilol, and steroids. Extraction via ultra-sonication using ethyl acetate for 30 minutes yielded the highest antioxidant, antibacterial, anti-inflammatory, and anticancer activities. Similarly, flesh from *Channa striata* (snakehead fish) was used to produce high-quality fish protein concentrate (FPC) containing up to 73.17% protein, with peptides ranging between 4–174 kilodalton (kDa), making it a valuable ingredient for functional food applications. The skin of Japanese sea bass (*Lateolabrax japonicus*) was used to extract collagen through UAE, which preserved its native structure, including α1 and α2 chains (basic protein subunits that make up collagen**)**.Additionally, gelatin extracted from the scales of *Hypophthalmichthys nobilis* (bighead carp) showed improved technological properties, with a high storage modulus (5000 Pa), and favorable gelation (22.94 °C) and melting points (29.54 °C), indicating its potential in food and pharmaceutical formulations. Chondroitin sulfate (ChS) was efficiently extracted from *Dosidicus gigas* cartilage using ultrasound-assisted extraction (UAE). The optimized process yielded high-purity ChS in the 4S and 6S forms, confirmed by FTIR and NMR. Collagen hydrolysate was extracted from *Theragra chalcogramma* skin using enzymatic and ultrasound-assisted methods. The ≤3 kDa fraction from UAE and control showed the highest antioxidant activity. Combined EAE+UAE treatment enhanced collagen breakdown, producing bioactive peptides suitable for functional and pharmaceutical uses. In one study Ultrasound-assisted extraction significantly increased collagen yield from *Chitala ornata* skin, especially at 80% amplitude for 10 min and ultrasound-assisted process (UAP-80/10-C). The triple-helical structure and amino acid profile were maintained, indicating good molecular integrity. This study supports the valorization of fish skin waste as a high-quality collagen source. These UAE application is given in the Table 7.

Supercritical fluid extraction (SFE)

Supercritical Fluid Extraction (SFE) is a green technology that extracts bioactive compounds from fish using supercritical carbon dioxide (CO2). This method is environmentally friendly because CO2 is non-toxic, readily available, and easily recyclable, minimizing environmental impact (Martins et al. 2023).

Mechanism

Supercritical Fluid Extraction (SFE) is an environmentally friendly technology used for extracting bioactive compounds from fish using supercritical carbon dioxide (CO_2). This method leverages CO_2's unique properties—non-toxic, abundant, and recyclable. The SFE process begins with sample preparation, where fish tissue is ground and dried through techniques like freeze-drying or vacuum drying to reduce moisture. Optionally, enzymatic hydrolysis can be applied to enhance compound release. During extraction, CO_2 is converted to its supercritical state under high pressure (7.38-33.0 MPa) and temperature (above 31.1°C). The supercritical CO_2 permeates the fish sample, selectively dissolving target compounds. After extraction, the CO_2 is depressurized in a separator, reverting it to gas and leaving behind the desired bioactive materials. The gas is then cooled, recompressed, and recycled, promoting sustainability. Schematic representation of the supercritical fluid extraction process is shown in Figure 2.

Post-extraction, further purification may be necessary using solvents like ethanol or methanol, along with techniques such as high-performance liquid chromatography (HPLC) for high-purity fractions. Analyzing the extracts is conducted via HPLC or mass spectrometry to assess purity and properties. SFE has notable advantages, including the absence of harmful solvents, high selectivity for specific compounds, and preservation of heat-sensitive nutrients. The resulting extracts are often purer than those from traditional methods, making SFE ideal for nutraceuticals, functional foods, and pharmaceuticals (Luksta et al. 2024; Martins et al. 2023).

Several studies have explored the extraction of valuable bioactive compounds from fish and seafood by-products using sustainable methods such as supercritical fluid extraction (SFE) and solvent extraction (SE). Canned by-products of *Tuna* have been utilized to extract volatile oils, which demonstrated improved

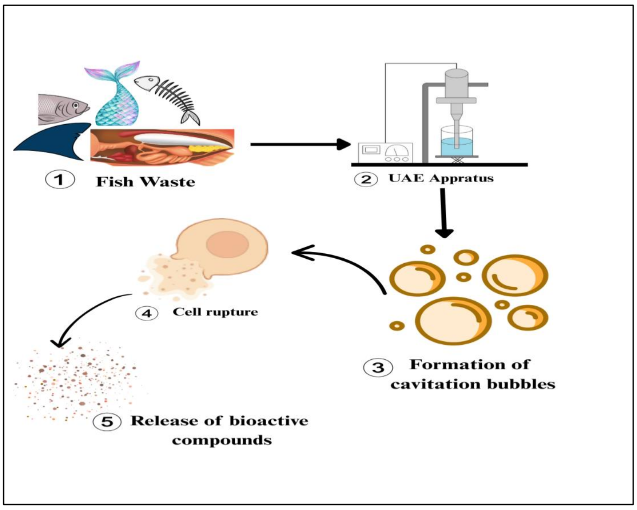

Fig. 1 Schematic representation of the ultrasound-assisted extraction (UAE)

Table 7 Ultrasound-assisted extraction (UAE) of bioactive compounds from aquatic sources

By-Product Source	Species	Bioactive Compound / Product	Main Effects / Bioactivities	References
Whole body	*Diadema setosum* (sea urchin)	Cholest-5-en-3-ol (3β), palmitic acid, oleic acid, stearic acid, flavonoids, phenols, batilol, steroids	UAE (ethyl acetate, 30 min) gave highest antioxidant, antibacterial, anti-inflammatory, anti-cancer activity	Yusuf et al. (2020)
Flesh	*Channa striata* (snakehead fish)	Fish Protein Concentrate (FPC)	High-quality Type A FPC (73.17% protein); peptides 4–174 kDa; ideal for functional foods	Kumoro et al. (2024)
Skin	Japanese sea bass *(Lateolabrax japonicus)*	Collagen	UAE did not alter the major components of collagen (1, 2 and chains)	Kim et al. (2013)
Scales	Bighead carp (*Hypophthalmichthys nobilis*)	Gelatin	Improved technological properties: highest storage modulus (5000 Pa), gelation point (22.94 C), and melting point (29.54 C)	Huang et al. (2017)
Cartilage	Jumbo squid *(Dosidicus gigas)*	Chondroitin sulfate (ChS)	UAE combined with Box–Behnken design optimized ChS yield (23.7%) and purity (82.3%); confirmed 4S/6S forms (ratio 1.62); promising for nutraceutical and pharma use	Yang et al. (2021)
Skin	Alaska pollock *(Theragra chalcogramma)*	Collagen hydrolysate	UAE and EAE+UAE enhanced antioxidant activity in ≤3 kDa fractions; rich in glycine and proline; promising bioactive peptides	Lee et al. (2022)
Skin	*Chitala ornata* (Clown featherback)	Collagen	UAP (80% amplitude, 10 min) improved yield while maintaining triple-helical integrity and amino acid content; valorizes fish skin waste	(Petcharat et al. (2020)

oil yield, oxidative stability, and better compound profiles. Similarly, *Common carp* viscera were found to yield high levels of polyunsaturated fatty acids (PUFAs), particularly DHA and EPA, with yields exceeding 50 g/100 g—comparable to petroleum ether extraction—and resulting in omega-enriched oils. Tuna liver has also proven to be a rich source of fatty acids, with studies reporting a notable high oil yield of 98.45%. In another study, the muscle, bone, and skin of *Salmon* were processed to obtain PUFA-rich oil, achieving yields ranging from 76.12% to 86.99% and showing excellent biochemical and biological properties . The viscera of *Todarodes pacificus* (squid) produced lecithin rich in EPA and DHA with high oxidative stability and enzyme extracts from squid viscera showed superior thermal stability compared to conventional n-hexane extracts without causing protein denaturation.*Sardina pilchardus* (sardine) waste provided omega-3 fatty acids and protein hydrolysates, with SFE at 250 bar yielding 20.3 g oil/100 g. The use of seawater (SW) in the process further enhanced protein recovery and antioxidant properties. Similarly, by-products from *Mullet* roe were used to extract EPA- and DHA-rich oils, with solvent extraction achieving the highest yield and SFE ensuring low oxidation and high PUFA content.

Finally, *Northern shrimp* (*Pandalus borealis*) by-products, including head, shell, and tail, have been effectively utilized to extract ω-3 PUFAs (EPA and DHA). Supercritical fluid extraction at 35 MPa and 40 °C produced deep red oil, with EPA and DHA concentrations of 7.8 ± 0.06% and 8.0 ± 0.07%, respectively. Furthermore, SFE at 400 bar and 55 °C extracted 23 mg/k of astaxanthin (ASX), and the inclusion of supercritical methyl ester as a co-solvent improved the yield to 35 mg/kg dry weight. The SFE application given in Table 8.

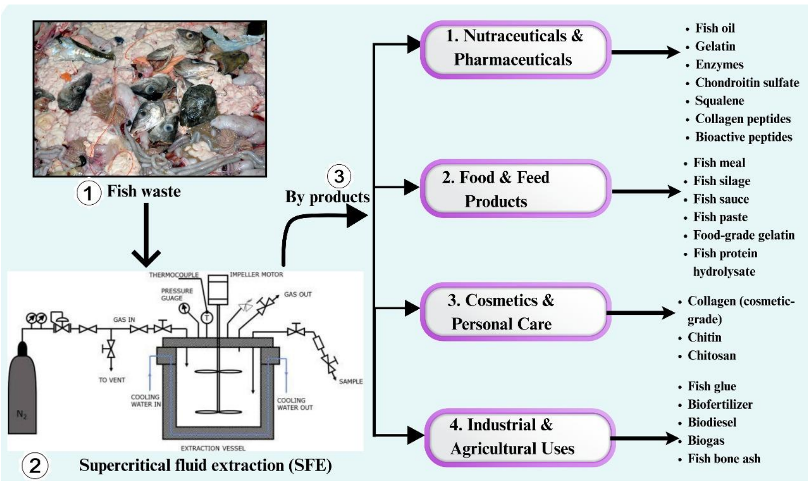

Fig. 2 Schematic representation of the supercritical fluid extraction (SFE) process

Table 8 Bioactive compound obtained from fish and fish by-products by SFE

Fish Species (By-product)	Bioactive Compound	Key Outcome	References
Tuna (Canned by-product)	Oils (volatiles)	Improved oil yield and oxidative ability; better compound profiles	Taati et al. (2017)
Common Carp (viscera)	PUFA (DHA & EPA)	High yield (>50 g/100 g); similar to petroleum ether; omega-enriched oils	Kuvendziev et al. (2018)
Tuna (Liver)	Fatty acids	Excellent oil quality and high yield (98.45%)	Fang et al. (2019)
Salmon (muscle, bone, skin)	PUFA-rich Oil	High yield (76.12%–86.99%); premium biochemical and biological properties	Haq et al. (2017)
Squid (*Todarodes pacificus*, viscera)	Lecithin (with EPA & DHA)	Lecithin contained PUFAs with high oxidative stability	Uddin et al. (2011)
Squid (Viscera)	Enzymes	Enzymes thermally more stable than n-hexane extract; no protein denaturation	Uddin et al. (2009)
Sardine (*Sardina pilchardus* waste)	Omega-3 fatty acids, protein hydrolysates	20.3 g oil/100 g at 250 bar; SW improved protein yield and antioxidant effects	Melgosa et al. (2020)
Mullet roe by-products	EPA, DHA-rich oil	SE gave highest yield; SFE showed low oxidation and high PUFA content	Kalogianni et al. (2023)
Northern Shrimp (*Pandalus borealis*) (head, shell, tail)	ω-3 PUFAs (EPA & DHA)	Deep red oil via SFE (35 MPa, 40 °C); EPA: 7.8 ± 0.06%, DHA: 8.0 ± 0.07%	Amiguet et al. (2012)
Northern Shrimp (Pandalus borealis) (head,shell,tail)	Astaxanthin (ASX)	SCFE at 400 bar, 55 °C yielded 23 mg/kg ASX; SF methyl ester improved yield to 35 mg/kg DW	Parjikolaei et al. (2015)

Industrial application of fish waste

Various high-value products obtained from fish by-products are summarized in Table 9. These include fish oil, collagen, gelatin, enzymes, chondroitin sulfate, squalene, probiotics, and bioactive peptides, sourced from fish eye, head, liver, skin, skeleton, scales, and viscera. These compounds are widely used in nutraceuticals, pharmaceuticals, cosmetics, food, and agriculture. They offer multiple health benefits such as antioxidant, anti-inflammatory, joint support, immune enhancement, and skin repair. These valuable compounds can be extracted using both conventional and green extraction technologies. Green extraction technology allows for the extraction of bioactive compounds that are environmentally friendly and preserve their functional properties. From an industrial and agricultural perspective, fish waste is further valorized into bio

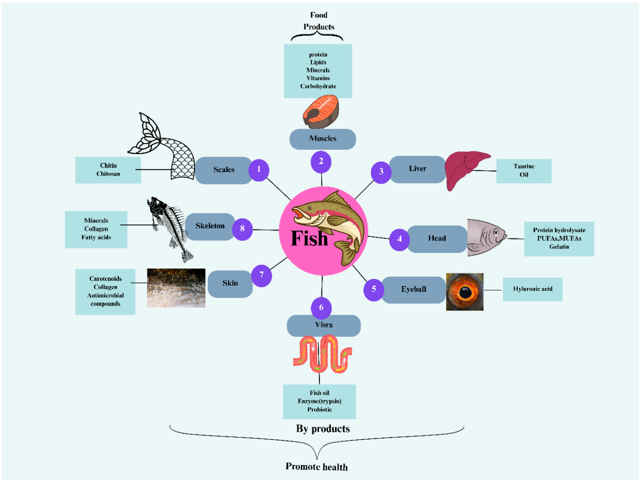

Fig. 3 Fish parts and their functional products

Table 9 Industrial application of fish by product

Industry	Product	What It Is	Source	Application	Reference
Nutraceutical & Pharma	Fish Oil	Omega-3 rich oil	Liver, fatty tissues	Heart, brain health, anti-inflammation	da Silva Batista et al. (2024)
	Gelatin	Collagen protein	Skin, bones, fins	Capsules, joint/skin supplements	Nurilmala et al. (2022)
	Enzymes (e.g., Trypsin)	Digestive proteins	Stomach, pancreas	Digestive aids, wound cleaning	Klomklao et al. (2024)
	Chondroitin Sulfate	Cartilage compound	Cartilage	Joint and arthritis treatment	Rekalov et al. (2024)
	Squalene	Antioxidant oil	Fish liver (shark, deep-sea)	Skincare, vaccines, disease prevention	Kumar et al. (2023)
	Collagen Peptides	Hydrolyzed collagen	Skin, bones	Anti-aging, tissue repair	Geahchan et al. (2022)
	Bioactive Peptides	Functional protein fragments	Muscle, skin proteins	Antioxidant, immune-boosting, antihypertensive	Nurdiani et al. (2017)
	Probiotics	Beneficial live microbes	Fish gut (e.g., *Lactobacillus*)	Gut health, immune support in humans and fish	Martínez Cruz et al. (2012)
	Hyaluronic Acid	Moisture-retaining sugar molecule	Fish skin, eyeballs	Skin hydration, joint lubrication, eye care	Alcântara et al. (2023)
Food & Feed	Fish Meal	Protein-rich powder	Whole fish, by-products	aquaculture feed	Afreen and Ucak (2020)
	Fish Silage	Fermented liquid protein feed	Fish waste	Feed for pigs and fish	Same as above
	Fish Sauce	Umami-rich fermented liquid	Fish in brine	Food seasoning	Han et al. (2023)
	Fish Paste	Ground fermented fish	Low-value fish	Flavor enhancer in foods	Yang et al. (2025)
	Gelatin (food-grade)	Gelling agent	Skin, bones	Desserts, jellies	Usman et al. (2022)
	Protein Hydrolysate	Pre-digested protein	Hydrolyzed fish waste	Elderly, infant, nutrition	Desai et al. (2022)
Cosmetics & Personal Care	Collagen	Anti-aging protein	Skin, scales	Creams, serums	Amnuaikit et al. (2022)
	Chitin	Shell-derived fiber	Scales, shells	Cleansers, films, wound dressing	Aranaz et al. (2018)
	Chitosan	Water-soluble fiber from chitin	From chitin	Moisturizers, oral care, hair products	Same as above
Industrial & Agriculture	Fish Glue	Natural protein-based adhesive	Collagen-rich tissues	Wood, paper, bookbinding	Arvanitoyannis and Kassaveti (2008)
	Bio fertilizer	Organic compost	Fish waste	Soil nutrient enhancer	Same as above
	Biodiesel	Renewable biofuel	Fish oil	Clean energy (fuel)	Same as above
	Biogas	Methane-rich renewable gas	Digested fish waste	Heating and electricity	Same as above
	Fish Bone Ash	Calcium/phosphorus-rich residue	Bones	Fertilizers, ceramics, glass	Same as above

fertilizers, biodiesel, biogas, fish glue, and fish bone ash, contributing to circular bio economy models and environmental sustainability. The use of such sustainable approaches supports waste valorization, reduces environmental impact, and promotes a circular bio economy. Fish parts and their functional products are shown in Figure 3.

Critical challenges and key drivers in fish and waste valorization

Fish and seafood waste valorization faces numerous challenges and is influenced by several key factors. A lack of infrastructure, technical limitations, and high processing costs are major barriers, particularly in regions without proper collection systems or cold chains. Seafood by-products are highly perishable; delays in processing lead to decomposition, nutrient loss, and unpleasant odors. Improper disposal of seafood waste causes serious environmental issues, including the release of methane—a potent greenhouse gas—through anaerobic decomposition, and oxygen depletion in water bodies, resulting in hypoxia that harms marine biodiversity. Nutrient runoff can trigger eutrophication and harmful algal blooms, deteriorating water quality, and threatening aquatic ecosystems and human livelihoods. In addition to the environmental impacts, the transporting and handling of these bulky by-products has a significant impact on operational costs, resulting in a decrease in profitability. The underutilization of valuable nutrients, proteins, and bioactive compounds like omega-3 fatty acids, enzymes, and collagen results in missed opportunities for high-value product development in the nutraceutical, pharmaceutical, and cosmetic sectors. Conventional disposal methods, such as landfilling and incineration, not only cost money but also fail to capitalize on this economic potential. Regulatory challenges further complicate management; compliance often requires investment in infrastructure and technology, but many policies prioritize disposal over resource recovery. Food safety is another crucial issue improper handling can lead to contamination and disease, posing risks to both human and environmental health. Sustainable valorization requires strict hygiene practices, quality control, and advanced recycling methods to ensure consumer safety and prevent pollution. In addition, valorization techniques must consider the emissions, energy use, and environmental impact to remain truly sustainable. On the other hand, several influencing factors can promote successful valorization. These include the type of fish species, processing methods, proper time and temperature control, supportive government policies, proximity of processing facilities, and adoption of green technologies like enzymatic hydrolysis and supercritical fluid extraction. Growing market demand for sustainable and functional food products further drives the need to utilize seafood by-products. Integrating circular bio economy principles and sustainable practices can transform waste into valuable resources. Graphical representation of fish waste valorization is shown in (Sultan et al. 2023) Figure 4. By overcoming the major challenges and leveraging key enablers, the seafood industry can reduce environmental harm, enhance economic returns, and promote a resilient and sustainable seafood supply chain.

Concluding remarks and future outlooks

Fish and its by-products are abundant in essential nutrients and bioactive compounds such as omega-3 fatty acids (EPA and DHA), high-quality proteins, peptides, collagen, gelatin, chitosan, vitamins, and minerals. These compounds exhibit various health-promoting properties, including antioxidant, anti-inflamma-

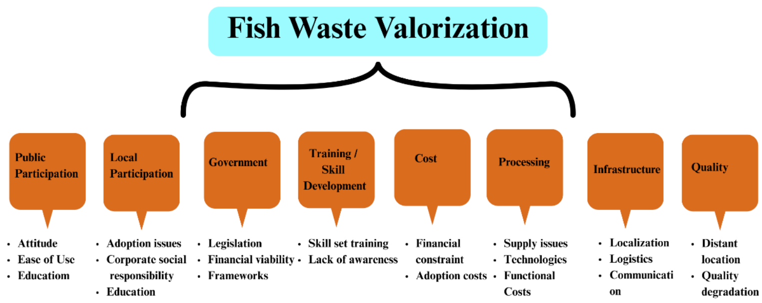

Fig. 4 Fish waste valorization

tory, antimicrobial, antihypertensive, and cardio-protective effects, making fish an excellent resource for developing functional foods and nutraceuticals. The sustainable valorization of fish waste through green extraction technologies, such as supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction, and microwave-assisted extraction, not only improves the yield, purity, and stability of bioactive compounds but also aligns with environmental goals by minimizing solvent use and waste. Despite these advancements, commercial applications still face challenges such as raw material variability, regulatory constraints, limited consumer awareness, and technological costs. Future research should prioritize the optimization of extraction processes by using green extraction technology, the development of bioactive-rich functional products with enhanced delivery systems (e.g., Nano encapsulation), and extensive clinical validation to support health claims. The promotion of increasing fish consumption is crucial, particularly in developing countries where food security is a major concern. It's also important to raise awareness about the valuable nutrients found in fish—such as high-quality proteins, omega-3 fatty acids, and other beneficial compounds—that can play a vital role in improving nutrition and overall human health. Furthermore, supportive policies and cross-sector collaboration are critical to scale up sustainable technologies and encourage full utilization of fishery resources. Overall, fish-based functional foods hold great promise for improving public health, reducing waste, and promoting sustainable and intelligent food systems.

Conflicts of interest The authors declare no conflicts of interest

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