SCIENTIA REVIEW

Scientia Review

Website: www.scientiafoundation.in

REVIEW ARTICLE

Transforming Fish Waste for Economic and Environmental Gains

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Abstract

India is a global leader in fish production, with fisheries contributing 1.07% to the national GDP and supporting livelihoods for over 28 million people. However, 30–50% of fish biomass is discarded as processing waste, creating environmental and public health challenges. Recent advancements in biotechnology and waste management have unlocked opportunities to transform this waste into valuable products such as fish meal, fish oil, collagen, gelatin, biofertilizers, biodiesel and bioactive peptides. These innovations align with India's Swachh Bharat Mission and circular economy principles while supporting Sustainable Development Goals (SDGs) related to responsible consumption, climate action and economic growth. Fish waste-derived products offer diverse applications across industries. Fish meal and oil serve as nutrient-rich inputs for aquaculture and agriculture, while collagen and gelatin find use in food, pharmaceuticals and cosmetics. Biofertilizers enhance soil health and crop yields and biodiesel production from fish oil contributes to renewable energy solutions. Additionally, bioactive peptides and enzymes extracted from fish waste exhibit antioxidant, antimicrobial and therapeutic properties. Despite these opportunities, challenges such as inadequate infrastructure, informal waste disposal practices and limited awareness among small-scale fishers hinder widespread adoption. Government initiatives like the Pradhan Mantri Matsya Sampada Yojana (PMMSY) and research efforts by institutions such as ICAR-CIFT are driving progress in fish waste valorization. Successful case studies demonstrate the economic viability of converting waste into wealth, creating income opportunities for coastal communities and reducing environmental pollution. To fully realize this potential, scaling up technologies, strengthening policy frameworks and fostering stakeholder collaboration are essential. By integrating sustainable waste management practices, India can position itself as a leader in fisheries-based circular economies, promoting both environmental conservation and socio-economic development.

Keywords: *Fish, Waste, Value-Added Products, Sustainable, Bioeconomy*

Received: 18 June 2025
Revised: 30 June 2025
Accepted: 2 July 2025
Published online: 5 July 2025

Article ID: SR01001

Citation: Hussain, I. A. & Yasmin, R. (2025) Transforming Fish Waste for Economic and Environmental Gains. *Scientia Review*, **1**(1), 1-12

Introduction

India ranks among the top fish-producing nations globally, with fisheries contributing about 1.07% to the national GDP and providing livelihoods to over 28 million people (NFDB, 2023). However, with increasing fish production, there is a corresponding rise in fish processing waste, estimated to be 30–50% of total fish biomass (Ghaly *et al.*, 2013). This waste, if not managed properly, contributes to environmental pollution, bad odor and disease transmission.

Historically, fish waste has been underutilized or discarded. But with advancements in biotechnology, waste management and circular economy principles, these by-products are being transformed into value-added commodities (ICAR-CIFT, 2022). Turning fish waste into wealth not only boosts economic value but also aligns with India's Swachh Bharat and waste-to-wealth missions. Moreover, the approach contributes to the Sustainable Development Goals (SDGs), especially those related to responsible consumption, climate action and economic growth (FAO, 2020).

Types and Sources of Fish Waste

Fish waste is generated at multiple points across the value chain:

- Capture Fisheries and Aquaculture: Mortality during harvesting and handling.
- Processing Units: Trimmings, skin, bones, viscera, heads.
- Retail and Household Consumption: Spoiled or unused parts.

Fish waste is rich in proteins, lipids, minerals and bioactive compounds, making it a potent raw material for secondary processing (Ghaly *et al.*, 2013).

Value-Added Products from Fish Waste

Fish Meal and Fish Oil

Fish meal and fish oil are valuable marine-derived products widely used in aquaculture, agriculture and human nutrition. They are rich in high-quality proteins, essential amino acids, omega-3 fatty acids (EPA and DHA), vitamins and minerals. These products are primarily obtained from small, oily fish species such as anchovies, sardines, mackerel and menhaden, as well as from by-products of fish processing.

Production and Composition of Fish Meal

Fish meal is a nutrient-dense powder produced from whole fish or fish processing by-products, primarily small pelagic species like anchovies, sardines and menhaden. The manufacturing process involves cooking, pressing, drying and grinding the fish to create a stable, high-protein product. During production, the fish are first cooked to coagulate proteins, then pressed to separate solids (press cake) from liquids (press liquor). The press cake is dried to reduce moisture content below 10%, preventing microbial spoilage and then ground into a fine powder. The press liquor undergoes centrifugation to extract fish oil, while the remaining water (stick water) is evaporated to produce fish solubles, which may be reincorporated into the meal to enhance nutritional value (FAO, 2020).

Fish meal is prized for its high protein content (60–72%) and balanced amino acid profile, particularly lysine and methionine, which are essential for animal growth. It also contains 8–12% lipids, including beneficial omega-3 fatty acids (EPA and DHA), along with essential minerals (calcium, phosphorus) and B vitamins (B12, riboflavin) (Tacon and Metian 2008).

Uses of Fish Meal in Animal and Aquaculture Feeds

The primary application of fish meal is in aquaculture, where it serves as a key protein source in feeds for species like shrimp, salmon, trout and tilapia. Its high digestibility and amino acid profile promote rapid growth and improve feed conversion ratios. In poultry farming, fish meal enhances egg production and chick development, while in swine nutrition, it boosts growth performance and immune function (Hardy 2010). Additionally, it is used in premium pet foods for dogs and cats due to its palatability and nutrient density. Beyond animal feed, fish meal is utilized as an organic fertilizer, providing nitrogen and phosphorus to crops. However, concerns over overfishing and ecological sustainability have prompted research into alternative protein sources, such as plant-based meals (soy, pea protein) and insect meal (Barange*et al.* 2018).

Extraction and Nutritional Properties of Fish Oil

Fish oil is derived from the tissues of oily fish or as a by-product of fish meal production. The most common extraction method is wet pressing, where fish are cooked, pressed and centrifuged to separate oil from water and solids. Advanced techniques like enzymatic extraction improve yield but are costlier. Fish oil is rich in long-chain omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are crucial for human and animal health (Tocher 2015).

In addition to omega-3s, fish oil contains fat-soluble vitamins (A and D) and antioxidants like astaxanthin, which prevent oxidation and prolong shelf life. The quality of fish oil depends on factors such as fish species, freshness and processing methods, with anchovy and sardine oils being among the most valued (Rubio-Rodríguez *et al.* 2010).

Applications of Fish Oil in Health and Industry

In aquaculture, fish oil is a vital ingredient in feeds for carnivorous fish species, supporting growth, reproduction and immune function. For human consumption, it is widely used in dietary supplements to promote cardiovascular health, cognitive function and anti-inflammatory responses. Clinical studies have shown that EPA and DHA reduce triglycerides, lower blood pressure and decrease the risk of heart disease (Mozaffarian and Wu 2011).

Pharmaceutical industries use fish oil in capsules to treat conditions like rheumatoid arthritis and hyperlipidemia. Industrially, it serves as a component in lubricants, paints and cosmetics. However, sustainability concerns have led to increased use of algal oil as a plant-based alternative for omega-3 supplementation (Sprague *et al.* 2016).

Collagen and Gelatin

Collagen is the most abundant structural protein in animals, constituting about 25–35% of total body protein in mammals. It is a key component of connective tissues such as skin, bones, tendons, cartilage and blood vessels. Structurally, collagen consists of three polypeptide chains wound into a triple helix, primarily composed of glycine, proline and hydroxyproline (Shoulders and Raines 2009). There are at least 28 types of collagen, with Type I (found in skin, tendons and bones) being the most prevalent. Collagen provides tensile strength, elasticity and structural integrity to tissues (Ricard-Blum 2011).

Whereas gelatin is partially hydrolyzed form of collagen, obtained through the controlled breakdown of collagen's triple-helix structure. The production process involves acid (Type A gelatin) or alkali (Type B gelatin) pretreatment of collagen-rich tissues (e.g., bovine hides, porcine skin, fish scales), followed by hot water extraction (Gómez-Guillén *et al.* 2011). Gelatin retains many of collagen's amino acids but loses its fibrous structure, making it soluble in water and capable of forming thermo-reversible gels.

Production Methods of Collagen and Gelatin

Collagen Extraction

Acid-soluble collagen (ASC) is typically extracted using mild organic acids, such as acetic acid, which help dissolve collagen fibers while preserving their native triple-helical structure. This method is particularly suitable for tissues with low cross-linking, as it maintains the structural integrity of the collagen molecules.

For tissues with stronger cross-linking, such as tendons or skin, pepsin-soluble collagen (PSC) extraction is often employed. In this method, the enzyme pepsin is used to cleave the telopeptide regions of collagen, enhancing solubility and yield. This approach is especially useful for obtaining higher amounts of collagen from densely structured tissues (Zhang *et al.* 2009).

Advanced extraction techniques, such as ultrasound-assisted extraction, have been developed to improve efficiency while minimizing collagen degradation. Ultrasound waves disrupt the collagen matrix, facilitating faster and more effective solubilization without compromising molecular integrity (Li *et al.* 2013).

Gelatin Manufacturing

The production of gelatin begins with a pretreatment step, where raw collagen tissues are soaked in either acid (for Type A gelatin) or alkali (for Type B gelatin). Acid treatment is typically used for porcine-derived gelatin, while alkaline treatment is common for bovine sources. These processes help break intermolecular cross-links, making the collagen more soluble for subsequent extraction.

During extraction, the pretreated tissues are heated in water at temperatures ranging from 50–100°C. This thermal hydrolysis solubilizes the collagen, converting it into gelatin. The resulting solution is then purified through filtration to remove impurities, concentrated and dried into either powder or sheet forms (Karim and Bhat 2009).

In recent years, fish-derived gelatin has gained popularity due to religious dietary restrictions (e.g., halal and kosher requirements) and safety concerns, such as avoiding bovine spongiform encephalopathy (BSE). However, fish gelatin generally has a lower melting point and weaker gel strength compared to mammalian gelatin, limiting its use in certain applications (Boran and Regenstein 2010).

Functional Properties and Applications of Collagen and Gelatin

Functional Properties

Collagen, the most abundant structural protein in animals, exhibits unique functional properties that make it valuable in various industries. Its triple-helical structure provides high tensile strength, elasticity and biocompatibility (Gómez-Guillén *et al.* 2011). Collagen is also hydrophilic, allowing it to retain moisture, which is beneficial in cosmetics and wound dressings. Additionally, its ability to form thermo-reversible gels makes it useful in food and pharmaceutical applications (Shoulders and Raines 2009).

Gelatin, derived from the partial hydrolysis of collagen, possesses distinct functional properties. It forms thermally reversible gels upon cooling, a key feature in food industries for gelling, thickening and stabilizing products (Karim and Bhat 2009). Gelatin also acts as an emulsifier and foaming agent, improving texture in confectionery and dairy products. Furthermore, its film-forming ability makes it useful in biodegradable packaging and pharmaceutical capsules (Boran and Regenstein 2010).

Applications:

Applications in the Food Industry: Collagen and gelatin are widely used in food products due to their gelling, binding and stabilizing properties. Gelatin is essential in marshmallows, gummy candies and yogurts, while collagen hydrolysates are used as protein supplements in sports nutrition (Schrieber and Gareis 2007). Marine-derived gelatin is gaining popularity as a halal/kosher alternative in Muslim and Jewish dietary markets (Boran and Regenstein 2010).

Biomedical and Pharmaceutical Applications: Due to its biocompatibility and biodegradability, collagen is extensively used in wound healing, tissue engineering and drug delivery systems (Lee *et al.* 2001). Collagen-based scaffolds support cell growth and regeneration in skin grafts and bone repair. Gelatin, being non-immunogenic, is used in capsule coatings, vaccine stabilizers andhemostatic sponges (Gómez-Guillén *et al.* 2011).

Cosmetic and Nutraceutical Uses: In cosmetics, collagen's moisture-retention and anti-aging properties make it a key ingredient in skincare creams, serums and hair treatments (Avila Rodríguez *et al.* 2018). Hydrolyzed collagen peptides are consumed as nutraceuticals to improve skin elasticity and joint health (Proksch *et al.* 2014).

Emerging Applications: Recent advancements include 3D bioprinting of collagen scaffolds for artificial organs and gelatin-based edible films for sustainable food packaging (Li *et al.* 2020). Additionally, fish collagen peptides are being explored for their antioxidant and antihypertensive benefits (Nalinanon*et al.* 2011).

Health Benefits and Nutritional Aspects of Collagen and Gelatin

Collagen Supplementation for Skin Health

Oral supplementation with hydrolyzed collagen has been shown to improve skin elasticity and reduce wrinkles. Clinical studies indicate that a daily intake of 10 grams of hydrolyzed collagen significantly enhances skin hydration and reduces signs of aging by stimulating collagen synthesis in the dermis (Proksch *et al.* 2014). This makes collagen peptides a popular ingredient in nutraceuticals and beauty supplements.

Collagen for Joint Pain Relief

Collagen peptides have demonstrated efficacy in alleviating symptoms of osteoarthritis and joint discomfort. Research suggests that a daily dosage of 8–12 grams of collagen peptides can reduce joint pain and improve mobility in individuals with degenerative joint conditions (Clark *et al.* 2008). The bioactive peptides in collagen help regenerate cartilage and reduce inflammation, making it a natural therapeutic option.

Collagen for Bone Density Improvement

Postmenopausal women are at higher risk of bone loss, but studies indicate that collagen peptides, when combined with calcium, can enhance bone mineral density (BMD). A clinical trial found that long-term supplementation with collagen hydrolysates significantly improved BMD and bone strength, reducing the risk of osteoporosis (König *et al.* 2018).

Nutritional Benefits of Gelatin

Gelatin is a rich source of glycine and proline, amino acids that play a crucial role in gut health, muscle repair and inflammation regulation (Wang *et al.* 2019). These amino acids support digestion by maintaining the intestinal lining and promoting protein synthesis in muscle tissues, making gelatin beneficial for athletes and individuals with digestive disorders.

Biofertilizers and Fish Hydrolysates

Fish hydrolysates, made through enzymatic digestion of fish waste, are rich in nitrogen, phosphorus and trace minerals. They serve as effective biofertilizers, especially in organic and sustainable farming practices (Ravishankar, 2021).

Production of Biofertilizers

Biofertilizers are produced through composting or anaerobic digestion, where fish offal is mixed with carbon-rich materials (e.g., rice husks) and inoculated with beneficial microbes (Ghaly *et al.* 2013). Key microorganisms include:

Nitrogen-fixing bacteria (Azotobacter, Bacillus), which convert fish protein into plant-available ammonium (Bhardwaj *et al.* 2014).

Phosphate-solubilizing fungi (Aspergillus), which release phosphorus from fish bones (Sharma *et al.* 2013).

Chitin-degrading bacteria (Serratia), which break down crustacean shells into soil-enhancing compounds (Sharp, 2013).

These biofertilizers improve soil structure, increase organic matter (up to 30%) and enhance crop yields by 15–25% in field trials (Aranconet *al.* 2017).

Production of Fish Hydrolysates

Fish hydrolysates are produced through:

Enzymatic Hydrolysis: Proteases (e.g., alcalase) break down proteins into peptides at controlled temperatures (Tahergorabi*et al.* 2012).

Fermentation: Lactobacillus cultures reduce odor while boosting nutrient availability (Halimatussadiah*et al.* 2021).

Chemical Hydrolysis: Acid/alkali treatment is cost-effective but may leave residues (Ferreira *et al.* 2020).

The resulting hydrolysates contain 8–12% nitrogen, 4–6% phosphorus and omega-3 fatty acids, making them effective as foliar sprays or soil amendments (Du Jardin 2015). Studies show they can increase tomato yields by 20% and enhance plant stress resistance (Rouphael*et al.* 2018).

Applications in Sustainable Agriculture

The utilization of fish waste-derived fertilizers and hydrolysates has emerged as a game-changing approach in sustainable agriculture, offering multifaceted benefits that address soil health, resource efficiency and plant protection. These applications demonstrate how circular economy principles can be effectively implemented in agricultural systems.

Soil Health Enhancement

Fish waste fertilizers significantly improve soil biological and physical properties through several mechanisms:

Microbial Biomass Stimulation: Fish-based fertilizers increase microbial populations by 30-50% compared to untreated soils (Mahanty*et al.* 2017). The high protein content provides organic nitrogen that fuels microbial growth, while fishbone-derived phosphorus (5-8% P_2O_5) serves as a slow-release nutrient source.

Key Study: Field trials with fish waste compost showed a 45% increase in dehydrogenase activity (indicator of microbial activity) in maize rhizospheres (Bhardwaj *et al.* 2021).

Water Retention Improvement: The colloidal nature of fish hydrolysates enhances soil aggregation, increasing water-holding capacity by 15-20% in sandy soils (Arancon*et al.* 2017). This is particularly valuable in drought-prone regions, where fish emulsion applications reduced irrigation needs by 25% (Rouphael*et al.* 2018).

Organic Matter Enrichment: Fish waste contains 12-18% organic carbon, which builds stable humus complexes when composted. Long-term use (3+ years) can increase soil organic matter by 2.5 percentage points (from 1.5% to 4.0%) (Olsen *et al.* 2022).

Aquaponics Integration

Fish hydrolysates enable efficient nutrient recycling in closed-loop aquaponic systems:

Nutrient Recovery Efficiency: Goddek*et al.* (2019) demonstrated that integrating fish sludge hydrolysates into hydroponic subsystems recovered 92% of nitrogen and 88% of phosphorus that would otherwise be wasted. This reduced dependence on synthetic fertilizers by 40% in lettuce production systems.

System Optimization: Recent designs use two-stage mineralization:

- Anaerobic digestion of fish solids produces volatile fatty acids
- Aerobic biofilters convert these to plant-available nitrates

This approach achieves 30% higher nutrient uptake than traditional single-loop systems (Delaide*et al.* 2022).

Economic Viability: Commercial aquaponic farms using fish waste fertilizers report 18-22% lower input costs compared to conventional hydroponics (Love *et al.* 2021).

Plant Disease Resistance

Fish waste components trigger sophisticated plant defense mechanisms:

Chitin-Induced Immunity: Crustacean-derived chitin (2-5% in shrimp waste fertilizers) acts as a pathogen-associated molecular pattern

(PAMP). At concentrations as low as 0.1%, it upregulates:

- Pathogenesis-related (PR) proteins (chitinases, β-1,3-glucanases)
- Salicylic acid biosynthesis (Kumar *et al.* 2021)

Field trials with chitin-rich fish fertilizers reduced Fusarium wilt incidence in tomatoes by 65% (Sharp *et al.* 2023).

Antimicrobial Peptides: Fish protein hydrolysates contain bioactive peptides (e.g., pleurocidin-like compounds) that directly inhibit Pythium and Phytophthora zoospores at 50-100 ppm concentrations (Halimatussadiah*et al.* 2023).

Systemic Acquired Resistance (SAR): Fish emulsion foliar sprays (5% v/v) induced SAR in cucumbers, reducing powdery mildew severity by 72% through jasmonic acid pathway activation (du Jardin *et al.* 2022).

Chitin and Chitosan

Traditionally discarded or underutilized, fish biowaste presents an opportunity for sustainable valorization through the extraction of high-value biopolymers such as chitin and its deacetylated derivative, chitosan. Chitin is a linear β-(1→4)-linked polymer of N-acetyl-D-glucosamine and is second only to cellulose in natural abundance (Kumar 2000). Chitosan, obtained by partial deacetylation of chitin, offers improved solubility and functional versatility, making it highly attractive for a variety of industrial and biomedical applications.

Sources of Chitin in Fish Waste

While crustaceans like shrimp and crabs are the traditional commercial sources of chitin, certain fish species, particularly those with mineralized scales and skins (e.g., tilapia, carp), also contain significant quantities of chitin in their exoskeletal structures (Arbia *et al.* 2013). Fish scales are structurally composed of collagenous and mineral matrices, but they also include chitin fibrils interwoven with proteins and calcium compounds (Rinaudo 2006). Fish skins and bones, although lower in chitin content compared to crustacean shells, still provide a viable alternative, especially when considering their abundance in processing waste streams.

Extraction of Chitin and Chitosan

The conventional extraction of chitin from fish waste typically involves three key steps: demineralization, deproteinization anddeacetylation. Demineralization is achieved using dilute hydrochloric acid (HCl) to remove calcium carbonate and other minerals. Deproteinization uses sodium hydroxide (NaOH) to eliminate proteins. Subsequent deacetylation of chitin to chitosan is conducted using concentrated NaOH at elevated temperatures (Kurita 2006). Recent advancements include enzymatic and microbial methods that aim to reduce environmental pollution associated with chemical treatments (Synowiecki and Al-Khateeb 2003). Fermentation using lactic acid bacteria (LAB) has emerged as a promising green alternative that simultaneously achieves deproteinization and partial demineralization.

Physicochemical Properties

The functional properties of chitin and chitosan are greatly influenced by their degree of deacetylation (DD), molecular weight, crystallinity and solubility. Chitosan with a higher DD (>70%) exhibits increased solubility in acidic media, enabling its use in a wide range of applications (Ravi Kumar 2000). Fish-derived chitosan is often characterized by lower ash content and higher purity due to the softer mineral content in fish scales compared to crustacean shells. The physicochemical properties can be tailored by adjusting extraction conditions, which impacts the polymer's film-forming ability, water-binding capacity and antimicrobial efficacy (No *et al.* 2000).

Applications of Chitin and Chitosan

Biomedical Applications: Chitosan exhibits excellent biocompatibility, wound healing properties andhemostatic activity, making it suitable for drug delivery, tissue engineering and wound dressing materials (Jayakumar *et al.* 2010). Fish-derived chitosan has shown promising results in the preparation of nanocarriers for controlled drug delivery due to its lower immunogenicity and biodegradability.

Food Industry: Chitosan is widely used as a natural food preservative due to its antimicrobial and antifungal activities. It can be incorporated into edible films and coatings to extend the shelf life of perishable foods (Dutta *et al.* 2009). Fish-waste-derived chitosan has been used in active food packaging materials due to its non-toxicity and ability to inhibit pathogenic microorganisms such as Listeria monocytogenes and Escherichia coli.

Agriculture: In agriculture, chitosan acts as a biostimulant and biopesticide. It enhances plant growth, induces resistance to pathogens andimproves nutrient uptake (El Hadrami *et al.* 2010). Foliar sprays and soil conditioners containing fish-derived chitosan improve crop productivity while reducing the dependence on synthetic agrochemicals.

Wastewater Treatment: Chitosan's high cationic nature allows it to bind with negatively charged pollutants including dyes, heavy metals and phosphates. It has been effectively used in flocculation and removal of contaminants from industrial effluents (Gupta and Nayak 2012). Fish-waste-derived chitosan is gaining attention as an eco-friendly and cost-effective adsorbent material for environmental remediation.

Environmental and Economic Benefits

Utilizing fish waste for chitin and chitosan production aligns with the principles of circular economy and zero-waste biorefinery models. It reduces environmental pollution caused by fish processing discards and adds economic value to underutilized resources (Zargar *et al.* 2015). The integration of green extraction technologies can further enhance sustainability while creating local employment opportunities in coastal and fishing communities.

Biodiesel and Biogas

Fish waste, a byproduct of the fishing and aquaculture industries, offers untapped potential for bioenergy generation in the form of biodiesel and biogas. The abundance of fish processing waste comprising viscera, heads, skins, bones and oily residues makes it a promising feedstock for circular bioeconomy initiatives, particularly in coastal and fishery-dependent nations like India (Ravishankar 2021; FAO 2022).

Fish Oil-Based Biodiesel Production

Fish oil, a lipid-rich component extracted from waste tissues such as viscera and liver, is an excellent raw material for biodiesel production. The biodiesel conversion process involves transesterification, wherein triglycerides in fish oil react with short-chain alcohols (usually methanol) in the presence of a catalyst (typically sodium or potassium hydroxide) to produce fatty acid methyl esters (FAMEs) and glycerol (Hossain *et al.* 2008). The properties of fish oil biodiesel such as high cetane number, good lubricity and acceptable viscosity—are comparable to conventional diesel and meet ASTM D6751 and EN 14214 standards (Demirbas 2009).

One of the unique features of fish oil biodiesel is its relatively high proportion of unsaturated fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). While these enhance cold flow properties, they may reduce oxidative stability, which can be improved through antioxidant additives or blending with other biofuels (Sivaramakrishnan and Ravikumar 2012). Studies from Indian research institutions have demonstrated the feasibility of converting waste fish oil from processing plants and markets into high-yield biodiesel with conversion efficiencies ranging from 80% to 95% (Ravishankar 2021; Ghosh *et al.* 2020).

Anaerobic Digestion of Fish Waste for Biogas

Anaerobic digestion (AD) is another environmentally sound approach to valorize fish waste by converting it into biogas, a combustible mixture of methane (CH_4), carbon dioxide (CO_2) and trace gases. This microbial process occurs in the absence of oxygen and involves four sequential stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Appels *et al.* 2008). Fish waste, being rich in proteins and lipids, serves as a potent substrate but also poses challenges such as ammonia inhibition and foam formation due to high nitrogen content and rapid degradation rates (Salminen and Rintala 2002).

In India, pilot-scale anaerobic digesters have been implemented in coastal states like Kerala, Tamil Nadu and Andhra Pradesh to process market fish waste into usable biogas for cooking and electricity generation (Ravishankar 2021; Bhuvaneswari *et al.* 2019). Co-digestion strategies where fish waste is combined with carbohydrate-rich materials such as food waste, cow dung, or agricultural residues have proven effective in enhancing methane yields and stabilizing the digestion process (Yusof *et al.* 2011). Typically, biogas yields from fish waste range between 300 to 600 L CH_4/kg VS (volatile solids), depending on pre-treatment and digester design (Siles *et al.* 2010).

Energy Potential and Environmental Benefits

The conversion of fish waste to biodiesel and biogas contributes significantly to energy recovery, waste minimization and climate change mitigation. For every tonne of fish waste, up to 100–150 liters of biodiesel and 60–80 cubic meters of biogas can be recovered under optimized conditions (Kumar and Sharma 2016). These renewable fuels can replace fossil-based alternatives, thereby reducing greenhouse gas emissions and dependency on imported crude oil. Additionally, the residues from anaerobic digestion (digestate) can be used as nutrient-rich organic fertilizer, closing the nutrient loop and supporting sustainable agriculture.

Enzymes and Peptides

Fish waste, particularly from viscera, heads, skins and internal organs, is not only rich in macronutrients like proteins and lipids but also a valuable source of bioactive compounds, notably enzymes and peptides. These biologically active substances have gained increasing attention for their applications in various industries, including pharmaceuticals, food processing, leather and textiles. In recent years, the biochemical valorization of fish processing waste has emerged as a sustainable approach for waste reduction and the production of high-value biochemicals, aligning with the goals of a circular bioeconomy (Ghaly *et al.* 2013; Shahidi and Kamil 2001).

Fish Viscera as a Source of Industrial Enzymes

Fish viscera the digestive organs such as stomach, intestine and pancreas are particularly rich in digestive enzymes including proteases, lipases, amylases and nucleases. Among these, proteases such as trypsin, chymotrypsin and pepsin are of paramount importance in the commercial enzyme market due to their protein hydrolyzing capability. These enzymes can be extracted using simple aqueous buffer systems followed by precipitation and purification steps like ammonium sulfate precipitation, dialysis and chromatography (Kristinsson and Rasco 2000).

Studies have demonstrated the effective recovery of trypsin from cod, tuna and salmon viscera, which shows comparable activity to bovine trypsin, but with distinct properties such as higher activity at lower temperatures and varying pH optima, making them suitable for cold-water detergent applications (Klomklao*et al.* 2006). Similarly, lipases obtained from fish pancreas and intestines play a significant role in the hydrolysis of triglycerides and are useful in biocatalysis, biodiesel production andflavor development in food processing (Gupta *et al.* 2004). The production of alkaline proteases from fish waste has been optimized in several studies for use in detergent formulations and dehairing processes in the leather industry (Simões *et al.* 2008).

Applications

Fish-derived enzymes have versatile applications across multiple industries. In the food sector, proteases are used for the tenderization of meat, production of protein hydrolysates and the preparation of fermented products. Lipases are employed in flavor enhancement and the modification of fats and oils. In the pharmaceutical industry, proteolytic enzymes from fish are being explored for their anti-inflammatory, thrombolytic and antimicrobial properties (Kim and Mendis 2006).

Enzymes like trypsin and pepsin derived from fish viscera are also used in peptide synthesis and biotechnological research. Moreover, marine enzymes are often preferred due to their activity at extreme pH and temperature ranges, making them suitable for industrial processes that require robust catalysts (Gildberg 2004). The textile industry also utilizes proteases for de-sizing and bio-polishing processes, replacing harsh chemical treatments and thereby reducing environmental impact (Ghorbel *et al.* 2003).

Bioactive Peptides from Fish Waste

In addition to enzymes, bioactive peptides can be obtained from fish waste through enzymatic hydrolysis using endogenous or exogenous proteases. These peptides, typically consisting of 2–20 amino acid residues, exhibit antioxidant, antimicrobial, antihypertensive, immunomodulatory and anticancer properties (Kim and Wijesekara 2010). The enzymatic hydrolysis of fish by-products such as heads, bones and skins generates protein hydrolysates rich in low molecular weight peptides, which can be further purified and characterized using ultrafiltration and chromatography techniques.

Numerous studies have reported the identification of antioxidant peptides from fish waste hydrolysates, capable of scavenging free radicals and protecting against oxidative stress in food systems and biological tissues (Samaranayaka and Li-Chan 2011). Such peptides are increasingly being incorporated into functional foods and nutraceuticals. The production of antihypertensive peptides, particularly those inhibiting angiotensin-I converting enzyme (ACE), has been reported from salmon and tuna viscera hydrolysates (Wu *et al.* 2003). These health-promoting peptides offer immense potential for the development of marine-derived therapeutic agents.

Indian Scenario: Initiatives and Case Studies

India is seeing growing interest in fish waste utilization:

- Research institutes like ICAR-CIFT and CUSAT have successfully developed technologies to produce protein hydrolysates and organic fertilizers (ICAR-CIFT, 2022).

- Startups like Sea6 Energy are working on marine biomass valorization and waste-derived bio-products (Sea6 Energy, 2023).
- Under the Pradhan Mantri Matsya Sampada Yojana (PMMSY), government schemes support fish waste processing infrastructure (NFDB, 2023).

Challenges:

- Lack of infrastructure and cold chains for waste handling.
- Informal and unhygienic waste disposal in local markets.
- Limited awareness among small-scale fishers and processors (Kurian, 2020).

Environmental and Economic Impact

Environmental Benefits:

- Significant reduction of organic pollutants in land and water.
- Lower methane and greenhouse gas emissions.
- Support for India's goals under the UN SDGs and climate action plans (FAO, 2020).

Economic Benefits:

- Value-added income opportunities for coastal communities and SHGs.
- Export potential for high-demand products like collagen and omega-3 oil.
- Creation of decentralized waste-to-wealth hubs in rural and coastal belts (Ravishankar, 2021).

Conclusion

Fish waste, long considered a disposal problem, is now a valuable resource waiting to be tapped. With the right mix of technology, policy support and stakeholder awareness, India has the opportunity to lead the way in sustainable fisheries waste management. Converting fish waste into wealth not only reduces environmental harm but also contributes to rural employment, blue economy growth and global health through high-value bio-products. The future lies in scaling up innovations, promoting community-led initiatives and embedding waste valorization into India's fisheries development agenda.

Conflict of Interest

The authors declare no conflict of interest.

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