Waste to Watts: Renewable Energy from Fish Industry Leftovers

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ABSTRACT

Fish processing generates large quantities of by-products, including heads, bones, skin, viscera, and scales, which pose environmental and economic challenges if discarded. These residues, rich in lipids and proteins, can be valorised for sustainable bioenergy production. Lipid-rich waste is converted into biodiesel, protein- and collagen-rich fractions into bioethanol, and mixed residues via anaerobic digestion produce methane-rich biogas. This integrated approach supports a circular economy, reduces carbon emissions, and provides additional income streams for the fisheries sector. Advances in microbial and pre-treatment technologies enhance energy yield and process efficiency, making fish waste a promising renewable energy resource.

INTRODUCTION

The global fish industry, which includes both capture fisheries and aquaculture, plays a critical role in ensuring food and nutrition security. In 2022, global production reached 223.2 million tonnes, marking a 4.4% increase compared to 2020 (FAO, 2024). While this expansion helps meet the protein needs of billions, it also generates substantial by-products, including fish heads, bones, scales, and offal. Studies estimate that around 35% of harvested fish and seafood is lost or wasted throughout the supply chain

(Fadeeva & Berkel, 2023). If not properly managed, this waste can lead to significant environmental problems, such as water pollution, greenhouse gas emissions, and economic losses. The vast volume of fish waste highlights the urgent need to view by-products not as mere residues, but as valuable raw materials. During processing—spanning bleeding, gutting, filleting, and trimming up to 60–70% of a fish's total weight can become by-products, including heads, fins, skin, viscera, and carcasses (Gill *et al*., 2025). These materials, rich in water and enzymes, are highly prone to rapid oxidation, making them potential environmental pollutants. Traditionally, they have been converted into lower-value products such as fishmeal, fertilizers, and animal feed. However, their modest economic returns have driven the industry to explore higher-value and more sustainable applications (Sarker & Kaparaju, 2024).

This shift is part of a broader paradigm of waste valorization within the circular economy, aiming to transform fish by-products into resources that enhance both economic and environmental sustainability (Vaishnav *et al*., 2025). Such initiatives are closely aligned with the Sustainable Development Goals (SDGs) 2030, particularly those related to responsible consumption, climate action, and innovation (Morton *et al*., 2017). Emerging research demonstrates diverse applications: collagen extracted from scales and bones for biomedical and cosmetic uses, gelatin from fish skin for edible films and coatings, and viscera yielding hydrolysates rich in peptides and enzymes with functional properties (Joy *et al*., 2024). Fish oil provides essential omega-3 fatty acids for nutraceutical and pharmaceutical sectors, while lipids serve as promising feedstock for biodiesel production (Otero *et al*., 2024). Recent advances in bioenergy technologies add another dimension transforming fish waste into renewable energy. Anaerobic digestion, for example, converts protein- and lipid-rich by-products into methane-rich biogas, offering both an energy solution and pollution mitigation (Lobanov, 2023; Pedullà *et al*., 2025). Fully harnessing this potential not only reduces environmental burdens but also creates new economic opportunities, fosters innovation, and contributes to a low-carbon future. Thus, fish waste valorization embodies the principle of turning "waste to watts" and beyond transforming a global disposal challenge into a pathway for sustainable energy, valuable biomaterials, and circular growth.

Types of Fish Waste and Their Energy Potential

Fish processing operations generate large amounts of waste such as heads, bones, guts, and scales, which can constitute 30–70% of the total fish mass (Shanthi *et al*., 2021). These byproducts are nutrient-rich, containing about 58% protein and 19% fat on a dry weight basis (Bhattacharya *et al*., 2022), making them highly suitable for bioenergy production. Proteins enhance biodegradability and support microbial activity in anaerobic digestion, yielding methane-rich biogas, while lipids, with their high calorific value, can be converted into biodiesel through transesterification or further contribute to biogas generation. Bones and scales, though more mineralized, provide collagen, chitin, and residual organic matter that can also be valorized alongside energy recovery. Studies indicate that one tonne of fish waste can produce over 200 m^3 of biogas with high methane content (Bücker *et al*., 2020), and fish oils extracted from processing residues have been successfully converted into biodiesel (Prasanna *et al*., 2023). Thus, utilizing fish waste through biorefinery approaches not only produces renewable energy in the form of biogas and biodiesel but also reduces environmental pollution, lowers disposal costs, and supports circular bioeconomy practices, transforming what was once considered an environmental burden into a sustainable energy opportunity. Some types of fish waste and their energy potential are presented in table 1.

Table 1 Types of fish waste and their energy potential

Type of Fish Waste	Main Composition	Energy Conversion Pathway	Potential Bioenergy Product
Heads & Bones (Tuna, Cod, Salmon)	Collagen, proteins, minerals	Hydrolysis + Fermentation	Bioethanol
Guts & Viscera (Mackerel, Sardine)	Proteins, enzymes, lipids	Anaerobic digestion	Biogas (methane)
Fish Scales (Tilapia, Carp)	Collagen, gelatin	Hydrolysis + Fermentation / AD	Bioethanol / Biogas
Fish Skin (Catfish, Pangasius, Salmon)	Collagen, fatty tissue	Hydrolysis + Fermentation / AD	Bioethanol / Biogas
Fish Oil Waste (Herring, Anchovy, Sardine)	High lipids, omega-3 fatty acids	Transesterification	Biodiesel
Shrimp & Prawn Shells	Chitin, protein, minerals	Anaerobic digestion / Fermentation	Biogas / Bioethanol
Squid & Cephalopod Waste	Proteins, enzymes, chitin	Anaerobic digestion / Hydrolysis	Biogas / Bioethanol
Processing Sludge (Mixed Fishery Waste)	Organic residues, fats, proteins	Anaerobic digestion / Co-digestion	Biogas

Biogas Production from Fish Waste

Biogas generation from fish waste is primarily achieved through **anaerobic digestion (AD),** a process in which microbial consortia break down organic matter in the absence of oxygen. Fish processing residues such as viscera, heads, and skin are rich in proteins and lipids, which serve as excellent substrates for methanogenic microbes (Choudhury *et al*., 2022). During AD, hydrolytic and fermentative bacteria degrade complex biomolecules into volatile fatty acids (Fig.1), which are then converted by methanogens into methane and carbon dioxide (Netshivhumbe *et al*., 2024). Fish waste has shown **high biogas yield potential** due to its nutrient density. For example, methane yields of **400–600 mL CH_4/g VS** have been reported, depending on waste type and pre-treatment methods. Co-digestion with carbohydrate-rich substrates (e.g., agricultural residues) is often employed to balance the high nitrogen content of fish waste, which otherwise leads to ammonia inhibition (Ivanovs *et al*., 2018). Thus, biogas production from fish waste not only offers **renewable energy generation** but also provides a sustainable waste management pathway for the fishery industry.

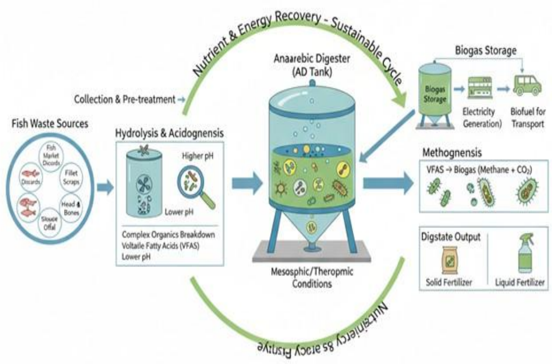

Fig. 1 A process flow diagram for biogas generation from fishery waste

Biofuel Production from Fish Waste

Fish waste, a major by-product of the fishing and aquaculture industries, offers significant potential for sustainable biofuel production due to its high content of lipids and proteins. Lipid-rich waste, including viscera, skin, and bones, can be converted into biodiesel through processes such as transesterification, pyrolysis, or enzymatic methods. Oil extraction methods vary depending on the type of waste and desired purity, and include solvent extraction (e.g., hexane), mechanical pressing, supercritical fluid extraction, or enzymatic extraction using lipases. Once extracted, fish oil undergoes transesterification with methanol or ethanol in the presence of a catalyst to produce fatty acid methyl esters (FAME), commonly known as biodiesel (Fig. 2). Optimizations such as the use of nanomagnetic catalysts have been shown to enhance yield and efficiency (Prasanna *et al*., 2023). Beyond biodiesel, fish waste is a valuable substrate for biogas production via anaerobic digestion, converting organic matter into methane-rich energy while mitigating waste disposal issues. Additionally, protein-rich by-products, such as skins, bones, and scales, are abundant in collagen. Collagen can be hydrolysed enzymatically or chemically into gelatin and peptide- or amino acid-rich hydrolysates, which contain fermentable sugars and nitrogenous compounds suitable for bioethanol production. These hydrolysates can be fermented by ethanol-producing microorganisms, such as Saccharomyces cerevisiae or engineered strains, under anaerobic conditions. The process involves hydrolysis of collagen, microbial fermentation of hydrolysates, and subsequent distillation to produce fuel- or industrial-grade ethanol. Studies indicate that bioethanol yields from collagen hydrolysates are comparable to conventional carbohydrate sources, offering an effective strategy for renewable energy generation while reducing environmental pollution from fish processing.

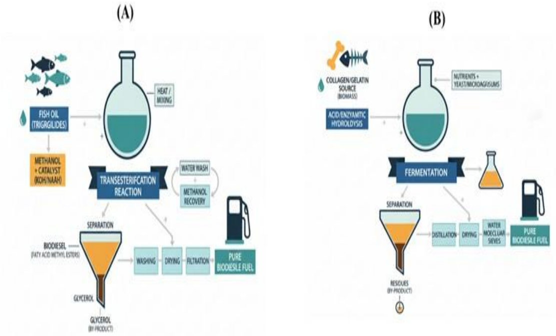

Fig. 2 The production of biofuel from fish oil (A) and collagen/gelatin hydrolysates (B)

Benefits of Bioenergy from Fish Waste

The utilization of fish waste for bioenergy production offers multiple environmental, economic, and social advantages. First, it provides an effective solution for waste management, as fish processing generates large quantities of by-products, including heads, bones, skin, and viscera, which otherwise contribute to environmental pollution if disposed of improperly. By converting these residues into biofuels such as biodiesel, bioethanol, and biogas, the environmental burden of organic waste is significantly reduced, mitigating water and soil contamination and lowering greenhouse gas emissions. Second, bioenergy from fish waste contributes to renewable energy generation. Lipid-rich fractions of fish waste can be converted into biodiesel, while protein-rich residues, including collagen, can be transformed into bioethanol, and anaerobic digestion of mixed waste produces methane-rich biogas. These energy carriers provide sustainable alternatives to fossil fuels, promoting energy security and reducing reliance on non-renewable resources. Finally, bioenergy production from fish waste can create additional income streams for the fisheries and aquaculture sector (Fig. 3). By valorizing by-products that would otherwise be discarded, fish processors can enhance profitability while contributing to a circular bioeconomy. Overall, fish waste-based bioenergy integrates environmental stewardship with economic benefits, supporting sustainable development and resource efficiency in the fisheries sector.

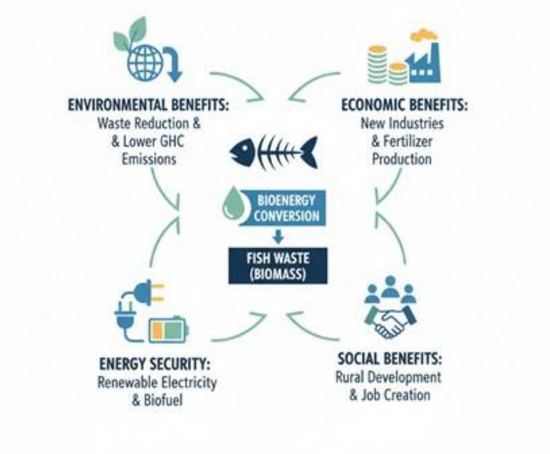

Fig. 3 Benefits of Bioenergy from Fish Waste

Challenges and Limitations

Despite its potential, bioenergy production from fish waste faces several challenges. One major limitation is the **seasonal and variable availability of fish waste**, which can affect the consistency of feedstock supply and, consequently, biofuel production. The quantity and composition of waste fluctuate with fishing seasons, species harvested, and processing practices, making continuous operation of bioenergy facilities challenging. Additionally, the **high lipid and protein content** of fish waste, while advantageous for energy yield, can create operational difficulties, particularly in anaerobic digestion. Excessive lipids may form scum layers and inhibit microbial activity, whereas high protein content can lead to ammonia accumulation, causing digestion imbalance and reduced biogas efficiency. Handling, storage, and transportation of fish waste also pose practical issues due to its rapid decomposition and odour generation, requiring careful management to prevent environmental and health hazards. Furthermore, technological and economic constraints, such as the need for specialized extraction and fermentation equipment, can limit scalability. Addressing these challenges through improved storage, pre-treatment methods, and optimized digestion protocols is crucial for realizing the full potential of fish waste as a sustainable bioenergy resource.

Future Prospects

Bioenergy from fish waste offers strong potential for a circular economy, turning processing by-products into valuable renewable energy. On-site conversion in aquaculture or seafood processing facilities can reduce waste, lower operational costs, and provide a steady energy supply. Wider adoption can also cut carbon emissions by replacing fossil fuels with biodiesel, bioethanol, or biogas. Advances in hydrolysis, fermentation, and microbial technologies are expected to improve efficiency and yield, making fish waste-based bioenergy a sustainable and economically viable solution for low-carbon, resource-efficient operations.

CONCLUSION

Converting fish processing waste into bioenergy exemplifies the "**waste to watts**" approach, transforming environmental liabilities into renewable energy resources. By producing biodiesel, bioethanol, and biogas from lipid- and protein-rich by-products, the fisheries and aquaculture sectors can enhance sustainability, reduce pollution, and generate additional revenue. Integrating these processes into existing operations not only supports a circular economy but also contributes to carbon footprint reduction and energy security. Overall, fish waste-based bioenergy represents a practical and eco-friendly solution for sustainable resource management.

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