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# Integrated Valorization of Fish–Processing Waste for Renewable Biofuel Production: From Lipid Recovery and Biodiesel to Anaerobic Digestion and Biogas within a Circular Bioeconomy

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## *Abstract*

*Fish-processing waste is a heterogeneous and underutilized biomass containing lipids, proteins, minerals, and biodegradable organic matter that can serve as feedstocks for the production of fuels, bioproducts, and recovered nutrients. However, conventional valorization approaches often focus on individual products, resulting in incomplete resource utilization and continued generation of residual waste. This review critically examines the potential of an integrated fish-waste biorefinery based on sequential fractionation and conversion of different waste components. Particular emphasis is placed on lipid recovery and biodiesel production, followed by utilization of the defatted biomass for anaerobic digestion and biogas or biomethane generation, with protein recovery and digestate-based nutrient recovery considered as complementary pathways. The review evaluates the biochemical basis, process parameters, pretreatment, and co-digestion strategies influencing anaerobic digestion, together with the effects of feedstock composition, free fatty acids, ammonia, long-chain fatty acids, and salinity on process performance. The environmental and techno-economic implications of integrated processing are also critically discussed, including energy consumption, greenhouse-gas emissions, logistics, product quality, process complexity, and the need for life-cycle and economic assessment. Particular attention is given to the trade-off between recovering energy-rich lipids for biodiesel and retaining them for methane production, highlighting the importance of evaluating total energy and resource recovery rather than individual product yields. The review identifies standardized feedstock characterization, low-energy extraction, reusable catalysts, inhibition control, optimized co-digestion, and pilot-scale validation as key research priorities. Overall, sequential valorization offers a promising pathway for transforming fish-processing residues from a disposal problem into a multi-product biorefinery, although its environmental and economic superiority must be demonstrated through integrated mass, energy, techno-economic, and life-cycle assessments.*

***Keywords:*** *fish-processing waste; biorefinery; biodiesel; anaerobic digestion; biogas; biomethane; lipid recovery; resource recovery; circular bioeconomy; life-cycle assessment.*

## 1. Introduction

### 1.1 Global Expansion of Fisheries and Aquaculture

The global fisheries and aquaculture sector has expanded considerably over the past several decades, driven by increasing demand for aquatic foods and the rapid development of aquaculture systems. According to the Food and Agriculture Organization (FAO), global fisheries and aquaculture production reached 223.2 million tonnes in 2022, including 185.4 million tonnes of aquatic animals and 37.8 million tonnes of algae. Aquaculture contributed 130.9 million tonnes, surpassing capture fisheries production of 92.3 million tonnes and highlighting its growing importance in the global aquatic food supply [1].

This expansion has been accompanied by increased fish-processing activities and the generation of substantial quantities of processing by-products. Depending on species and processing operations such as filleting, gutting, heading, and skinning, these by-products may include heads, viscera, skin, scales, bones, fins, frames, and trimmings, collectively accounting for approximately 30–75% of the original fish weight [2]. Rather than being viewed solely as waste, these residues represent heterogeneous biological resources containing valuable proteins, lipids, minerals, and collagen, offering significant potential for further valorization [3].

### 1.2 Fish Waste as an Environmental and Economic Challenge

The accumulation of fish-processing residues represents both an environmental challenge and a loss of potentially valuable biological resources. Fish waste contains substantial amounts of readily biodegradable organic matter, particularly proteins and lipids, making it highly susceptible to rapid autolysis and microbial decomposition when improperly preserved or managed. Such uncontrolled degradation can result in offensive odours, hydrogen sulfide formation, increased biological oxygen demand, and microbial proliferation, particularly in areas where large quantities of processing waste are generated within short periods [3]. Improper disposal may further contribute to nutrient release, deterioration of water quality, and greenhouse-gas emissions, while increasing the costs associated with collection, transportation, and waste treatment. At the same time, disposal results in the loss of valuable proteins, lipids, minerals, and other bioactive components that could otherwise be recovered. Therefore, fish-waste management should move beyond conventional disposal toward strategies that combine environmental protection with resource recovery [4]. The lipid- and organic-rich nature of these residues makes them particularly attractive for renewable-energy applications, where lipid fractions can be converted into biodiesel, while the remaining organic biomass can be processed through anaerobic digestion for biogas production, thereby transforming fish-processing residues from an environmental liability into a valuable feedstock for integrated energy recovery [5].

### 1.3 Fish Waste as a Renewable Feedstock

Fish-processing waste is a heterogeneous biomass whose composition varies with fish species, anatomical fraction, geographical origin, season, feeding conditions, and processing method. Its major constituents include proteins, lipids, moisture, and minerals, with reported compositions varying considerably among different fish-processing residues. For example, published data indicate approximately 49–58% protein, 22–3% ash, and 7–19% fat on a dry-weight basis, demonstrating that no single composition can represent all fish-processing waste [3]. This variability is important because the composition of a particular waste stream determines its most suitable valorization pathway. The lipid fraction is particularly relevant for renewable-fuel production because fish oils contain triglycerides that can be converted into fatty-acid alkyl esters through esterification and transesterification. Experimental studies have demonstrated biodiesel production from oils recovered from discarded fish parts, confirming the potential of fish-processing residues as non-edible lipid feedstocks [6]. However, the valorization potential extends beyond lipid recovery, as protein-rich fractions can be used for protein hydrolysates, while skin scales and bones provide potential sources of collagen, gelatin, and minerals [2]. Importantly, these fractions can be utilized sequentially rather than independently. Following lipid and other high-value component recovery, the remaining defatted biomass may still contain considerable biodegradable organic matter suitable for anaerobic digestion. Studies have demonstrated substantial biodegradability and methane-production potential from fish residues remaining after extraction of valuable components, supporting the concept of cascade or sequential valorization in which multiple products and energy carriers are recovered from a single fish-waste stream [7].

### 1.4 Circular Bioeconomy Approach to Fish-Waste Valorization

The increasing emphasis on resource efficiency has encouraged a shift from conventional waste management toward circular bioeconomy approaches, in which biological residues are treated as secondary resources rather than materials destined for disposal. Within this framework, fish-processing by-products can be fractionated and converted into multiple value-added products, thereby reducing the amount of material requiring disposal and improving overall resource utilization. Recent research has highlighted integrated biorefinery strategies in which different fractions of fish-processing residues are recovered and utilized rather than focusing on a single end product [8]. For renewable-energy production, fish-processing residues can be used through sequential valorization, with lipid-rich fractions recovered for biodiesel production and the remaining defatted biomass subsequently utilized for anaerobic digestion and biogas generation. The resulting digestate may further provide opportunities for nutrient recovery and other downstream applications, allowing greater value to be recovered from the original biomass while reducing residual waste and dependence on fossil-derived energy resources [9]. Experimental studies have also demonstrated the potential of fish-processing waste for anaerobic mono-digestion and methane production. However, the high protein and lipid content, salinity, and relatively low carbon-to-nitrogen ratio of certain fish-waste streams can influence process stability and methane yield, highlighting the importance of appropriate feedstock characterization, pretreatment, and process optimization [5]. Overall, this approach supports a transition from fish-waste disposal toward integrated recovery of fuels, energy and nutrients, providing a promising framework for applying circular-bioeconomy principles to fish-processing residues.

### 1.5 Scope and Objectives of the Review

Although fish waste has been widely investigated for biodiesel and biogas production, these pathways are often studied independently. This review therefore focuses on the integrated valorization of fish-processing waste within a circular bioeconomy framework, covering feedstock characteristics, lipid recovery, biodiesel production, utilization of residual biomass through anaerobic digestion, and biogas generation. It further examines the major technological, environmental, and economic challenges, including feedstock variability, extraction efficiency, free fatty acids, process stability, transportation, energy requirements, and scale-up. Particular emphasis is placed on sequential utilization of different biomass fractions to maximize resource and energy recovery while minimizing residual waste. The review also identifies current research gaps and future opportunities in process integration, life-cycle sustainability, techno-economic optimization, and development of scalable fish-waste biorefineries.

This approach aims to establish fish-processing residues not merely as a biodiesel feedstock, but as a multipurpose renewable resource for integrated fuel, energy and nutrient recovery.

## 2. Fish-Processing Waste: Sources, Composition and Characteristics

### 2.1 Major Sources of Fish-Processing Waste

Fish-processing by-products, also referred to as rest raw materials when they retain recovery potential, are generated during operations such as heading, gutting, scaling, filleting, deboning, and cutting. Major fractions include heads, viscera, skin, bones, scales, fins, frames, tails, and trimming residues, with their quantity and composition varying according to fish species and processing methods. These by-products may account for up to 70% of processed fish, highlighting their importance as potential biological resources rather than simply disposal materials [10]. Different processing operations generate distinct waste streams; for example, heading produces heads, gutting generates viscera, filleting produces frames and trimmings, while skinning and deboning generate skin and bone residues. Processing facilities also generate wastewater containing suspended solids, proteins, lipids, and nutrients, making fish-processing waste a combination of solid, semi-solid, and liquid streams requiring appropriate recovery strategies [11]. Among the solid fractions, heads, viscera, and trimmings are particularly relevant for resource recovery because they may contain substantial proteins and lipids, while skin and bones provide valuable collagen, gelatin, and minerals [10]. Rejected or low-value fish may also contribute to the waste stream and, despite limited commercial value, can retain proteins, lipids and minerals suitable for applications such as oil recovery, biodiesel production, protein products and anaerobic digestion [12]. Thus, the diverse composition of fish-processing residues provides opportunities for fraction-specific and integrated valorization within a circular bioeconomy framework.

### 2.2 Chemical composition of fish-processing waste

Fish-processing waste is a chemically heterogeneous biomass comprising proteins, lipids, moisture, minerals and other organic compounds, with considerable variation depending on fish species, processing practices and anatomical fractions. Viscera and liver are often rich in lipids, whereas skin, muscle residues, and other solid fractions contain substantial proteins; bones and scales are particularly rich in calcium, phosphorus, and other minerals [13]. Proteins present in these residues can be recovered as protein hydrolysates, peptides, and amino acids with potential nutritional and functional applications [14]. The lipid fraction represents an important source of triglycerides and fatty acids that can be recovered and converted into biodiesel through suitable pretreatment, esterification, and transesterification processes [15]. Following lipid recovery, the remaining biodegradable organic matter can be utilized as a substrate for anaerobic digestion and biogas generation, while mineral-rich fractions and processing wastewater provide opportunities for nitrogen, phosphorus, and other nutrient recovery [16]. Therefore, the diverse composition of fish-processing waste supports an integrated biorefinery approach in which different fractions are selectively converted into biofuels, bioproducts, biogas and nutrient resources, enhancing overall resource utilization and reducing the environmental burden associated with conventional disposal.

### 2.3 Factors affecting the composition of fish-processing waste

The chemical composition of fish-processing waste is highly variable and is influenced by several biological, anatomical, and processing-related factors. Fish species are a major determinant because differences in body composition, lipid reserves, muscle-to-bone ratio, and fat distribution affect the proportions of proteins, lipids, and minerals present in the residues [17]. Seasonal changes, age, sex, nutritional status, and reproductive condition can further modify the accumulation and distribution of proteins and lipids within different tissues, which may subsequently influence lipid recovery, biodiesel yield, and biological conversion efficiency [18,19]. The anatomical fraction generated during processing is also important, as viscera and liver are generally valuable lipid sources, skin contains proteins and collagen, while bones and scales are richer in minerals such as calcium and phosphorus [10]. Processing operations, including filleting, de-heading, skinning, deboning, drying, and smoking, determine both the quantity and characteristics of the resulting waste, while geographical origin and processing practices can introduce additional variability [20]. Storage conditions and duration are particularly critical because the high moisture content and endogenous microbial and enzymatic activities of fish residues can promote lipid oxidation, hydrolysis, and protein degradation, potentially reducing the quality of recoverable products [10]. Therefore, proper characterization of fish-processing waste considering species, season, anatomical fraction, processing method and storage conditions is essential for selecting suitable valorization technologies and achieving consistent recovery of biofuels, bioproducts and nutrients.

### 2.4 Environmental consequences of improper disposal

Improper disposal of fish-processing waste can cause significant environmental problems because of its high moisture content, nutrient concentration, and biodegradability. Rapid microbial and enzymatic decomposition of untreated residues can generate unpleasant odours and accelerate the deterioration of valuable proteins and lipids [10]. Discharge of fish-processing wastewater containing suspended solids, dissolved organic matter, nitrogen, and phosphorus can increase the organic load of receiving water bodies, resulting in increased microbial oxygen consumption and potential oxygen depletion, which may adversely affect aquatic ecosystems [16]. Excessive nitrogen and phosphorus inputs can further contribute to nutrient enrichment and eutrophication, making fish-processing effluents an important source of both organic and nutrient pollution [21]. On land, uncontrolled accumulation of fish residues may attract insects and other organisms, promote microbial degradation, and create localized sanitation problems. Moreover, disposal without recovery results in the loss of potentially valuable proteins, lipids, minerals, and other bioactive components.

These environmental and resource-related concerns highlight the need to shift from conventional disposal towards integrated valorization strategies, where lipid-rich fractions can be converted into biodiesel, residual biodegradable biomass into biogas, and mineral-rich fractions into nutrient products, thereby reducing environmental impacts while recovering energy and valuable resources.

## 3. Lipids in Fish Waste: Recovery and Characterization

### 3.1 Lipid-rich fractions in fish-processing waste

Lipids are among the most valuable components of fish-processing residues because they contain triglycerides and fatty acids that can serve as feedstocks for biodiesel production. However, lipid distribution varies considerably with fish species, tissue type, physiological condition, and feeding status. Viscera and liver are commonly important lipid-rich fractions, while heads, skin, frames,s and fatty trimmings may also contain recoverable oil [10]. The liver can act as a major lipid-storage tissue in several fish species, whereas viscera may provide substantial quantities of oil depending on species and processing conditions. Therefore, actual compositional characterization is essential for identifying suitable feedstocks rather than assuming uniform lipid yields across different fish wastes.

The distribution of lipids among anatomical fractions directly influences the efficiency of downstream extraction and biodiesel production. Processing lipid-rich fractions separately can improve oil recovery and reduce the amount of non-lipid material entering the extraction process, whereas combining different residues may increase feedstock availability but also introduce greater variation in moisture, protein, mineral, and lipid content. Thus, fraction-specific or appropriately integrated processing strategies should be considered when designing fish-waste-to-biodiesel systems.

### 3.2 Lipid extraction methods

Lipid extraction is a critical step in fish-waste biodiesel production because extraction efficiency and oil quality directly influence subsequent conversion. Conventional approaches include mechanical pressing, thermal treatment, and solvent extraction, while enzymatic, ultrasound-assisted, microwave-assisted, and supercritical-fluid extraction have emerged as alternative technologies [22]. Solvent extraction can provide efficient lipid recovery but may require substantial solvent use, recovery systems, and appropriate safety measures [22]. Mechanical and thermal methods are comparatively simple and can facilitate oil release from lipid-rich tissues, although excessive heating may promote lipid oxidation and affect oil quality [23]. Enzyme-assisted extraction can improve lipid release by hydrolyzing proteinaceous tissue structures and may simultaneously facilitate recovery of protein hydrolysates, supporting integrated utilization of the feedstock [24]. Ultrasound- and microwave-assisted techniques can enhance mass transfer and tissue disruption, potentially reducing extraction time and solvent requirements [25]. Supercritical $CO_2$ extraction offers solvent-free oil recovery and good control over extraction conditions, but its application may be limited by high-pressure equipment and capital requirements. Therefore, the selection of an extraction method should consider not only lipid yield but also energy consumption, solvent use, oil quality, environmental impact, scalability, and compatibility with subsequent biodiesel conversion [26].

### 3.3 Factors influencing lipid recovery

Lipid recovery from fish-processing residues is influenced by several feedstock and processing parameters, including solvent characteristics, temperature, extraction time, solvent-to-solid ratio, particle size, and moisture content. Solvent polarity and its ability to penetrate the biological matrix determine the extent and type of lipids extracted, while solvent mixtures may improve recovery of different lipid classes. Increasing temperature can enhance lipid solubility, reduce viscosity and improve mass transfer; however, excessive heating may promote lipid oxidation and hydrolysis, particularly in polyunsaturated fish oils [27]. Extraction time and solvent-to-solid ratio also affect recovery, although excessive extraction duration or solvent use can increase energy, solvent-recovery, and operational costs without proportional improvements in yield. Reduction of particle size can enhance surface area and facilitate matrix disruption, whereas excessive milling increases energy requirements. Moisture content is particularly important because water can affect solvent polarity, penetration, and oil separation. Pretreatment methods such as drying, grinding, thermal treatment, and enzymatic hydrolysis can further improve lipid release by disrupting tissue structures, but their energy requirements and effects on oil quality must also be considered. Therefore, optimization of these parameters according to the characteristics of the specific fish-waste fraction is essential for achieving efficient, economical, and scalable lipid recovery [28].

### 3.4 Characterization of recovered fish oil

Lipid yield is an important measure of extraction efficiency, but high oil recovery alone does not necessarily indicate suitability for biodiesel production. Recovered fish oil should therefore be characterized for free fatty acid (FFA) content, acid value, saponification value, iodine value, moisture, impurities, and fatty-acid composition. FFA content is particularly important because high levels can react with alkaline catalysts to form soaps, reducing transesterification efficiency and complicating product separation; such oils may require acid esterification before alkaline transesterification [29]. Acid value provides an indication of FFA levels and oil deterioration, while saponification and iodine values provide information on fatty-acid characteristics and degree of unsaturation. The fatty-acid profile is especially important for fish oil because the presence of highly unsaturated and polyunsaturated fatty acids can influence biodiesel properties such as oxidative stability and low-temperature performance [30]. Thus, comprehensive characterization is essential for determining the appropriate pretreatment and conversion strategy and for comparing oils obtained from different fish species and processing fractions.

### 3.5 Challenges associated with crude fish oil as a biodiesel feedstock

Despite its potential as a renewable biodiesel feedstock, crude fish oil presents several challenges related to its composition and quality. High FFA content can promote soap formation during alkaline transesterification and may therefore require an additional esterification step before biodiesel synthesis [31]. Residual moisture and non-lipid impurities such as proteins, phospholipids, pigments and salts can further interfere with catalyst activity, triglyceride conversion and biodiesel purification. Another important limitation is the high degree of polyunsaturation often present in fish oils, which can increase susceptibility to lipid oxidation and reduce the oxidative stability of the resulting biodiesel [32]. Consequently, biodiesel quality depends strongly on the fatty-acid composition of the feedstock, with a balance required between oxidative stability and low-temperature properties. In addition, drying, pretreatment, extraction, catalyst consumption, purification, and transportation contribute to the overall cost and environmental footprint of fish-oil biodiesel. Therefore, process evaluation should extend beyond biodiesel yield to include feedstock quality, energy consumption, economic feasibility, life-cycle impacts,s and integration with downstream utilization of the defatted biomass [33].

## 4. Biodiesel Production from Fish-Waste Lipids

Fish-processing waste-derived lipids represent a promising non-edible feedstock for biodiesel production because their triglycerides can be converted into fatty acid methyl or ethyl esters through transesterification. Unlike conventional edible oil feedstocks, fish-waste lipids utilize an existing processing residue, offering simultaneous waste-management and renewable-energy benefits [34]. However, variations in moisture, impurities, and free fatty acid (FFA) content necessitate appropriate feedstock characterization and pretreatment. Initial treatment may include filtration, centrifugation, drying, and degumming to remove water and non-lipid materials. High-FFA oils generally require acid-catalyzed esterification before alkaline transesterification to minimize soap formation, whereas low-FFA oils may be directly transesterified. Methanol and ethanol are commonly used alcohols, with NaOH and KOH among the widely employed catalysts [35]. Heterogeneous and enzymatic catalysts have also received attention because of their potential for catalyst recovery, reduced downstream processing, and milder reaction conditions. In addition, catalysts prepared from residual fish biomass offer an attractive route for further waste utilization. Biodiesel conversion is influenced by temperature, alcohol-to-oil ratio, catalyst concentration, reaction time, FFA content, and moisture, and optimization of these parameters is essential for achieving high conversion while minimizing chemical and energy requirements [36].

The quality of fish-waste biodiesel depends strongly on the fatty-acid composition of the recovered oil and the efficiency of the conversion process. Important fuel properties include viscosity, density, cetane number, acid value, iodine value, oxidation stability, flash point, and cold-flow characteristics.

The relatively high proportion of unsaturated and polyunsaturated fatty acids found in many fish oils can provide favourable low-temperature properties but may increase susceptibility to oxidation, making oxidative stability an important consideration during storage and use [37]. Compared with soybean, palm, used cooking oil, and terrestrial animal fats, fish waste offers the advantage of utilizing an existing residual biomass without requiring dedicated agricultural land, although feedstock variability, high moisture, rapid deterioration, elevated FFA levels and collection logistics remain important challenges. Therefore, the potential of fish-waste biodiesel should be evaluated beyond biodiesel yield alone, considering energy consumption, pretreatment requirements, fuel quality, process economics, and environmental impacts. Integration with downstream utilization of the defatted biomass for biogas, protein, and nutrient recovery can further enhance the overall resource efficiency and sustainability of fish-waste biorefineries [38].

## 5. Valorization of Defatted Fish Waste

Lipid extraction should be considered not as the endpoint of fish-waste utilization but as the first fractionation step in an integrated biorefinery. The defatted residue can retain substantial amounts of proteins, peptides, minerals,s and biodegradable organic matter, depending on the original fish species, anatomical fraction, and extraction conditions. Protein-rich residues can therefore be subjected to protein recovery or enzymatic hydrolysis to produce protein concentrates, peptides, and fish protein hydrolysates with potential nutritional, functional, and bioactive applications [39]. Enzymatic hydrolysis is particularly attractive because controlled degradation of proteins can generate peptides with antioxidant, antimicrobial, and other biological activities, although their application requires appropriate characterization, purification, and safety assessment. Mineral-rich fractions containing calcium and phosphorus can also contribute to nutrient recovery and fertilizer production following suitable stabilization and quality assessment. Thus, removing lipids for biodiesel production does not eliminate the value of the remaining biomass; rather, it creates a secondary feedstock that can be further fractionated into higher-value products [40].

The residual biodegradable fraction remaining after protein and mineral recovery can subsequently be directed towards anaerobic digestion for biogas production, with the resulting digestate providing an additional source of recoverable nutrients. This sequential approach enables multiple products to be generated from the same fish-processing waste stream: lipids can be converted into biodiesel, proteins into concentrates or hydrolysates, residual organic matter into biogas, and nutrients into fertilizer or soil-amendment products. Such cascading utilization can improve overall resource recovery and reduce the environmental burden associated with conventional disposal [41]. However, each processing step alters the composition and characteristics of the remaining biomass; therefore, conditions that maximize lipid or protein recovery may not necessarily be optimal for subsequent anaerobic digestion. Future research should consequently evaluate the complete process through mass and energy balances, techno-economic assessment, and life-cycle analysis rather than optimizing individual products independently. The central objective of fish-waste valorization should therefore shift from maximizing a single product, particularly biodiesel, toward maximizing the overall recovery of energy, materials and nutrients from the complete biomass [42].

## 6. Anaerobic Digestion of Fish-Processing Waste

Anaerobic digestion (AD) provides an important energy-recovery pathway for the biodegradable fraction of fish-processing waste and can complement lipid recovery and biodiesel production within an integrated biorefinery. In the absence of oxygen, a diverse microbial consortium converts complex organic matter into biogas, mainly methane and carbon dioxide, along with a nutrient-containing digestate. The process occurs through four interconnected stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During hydrolysis, proteins, lipids, and carbohydrates are broken down into soluble peptides, amino acids, fatty acids, glycerol, and sugars. These products are subsequently fermented during acidogenesis to form volatile fatty acids (VFAs), alcohols, hydrogen, and carbon dioxide [43]. During acetogenesis, suitable intermediates are further converted mainly into acetate, hydrogen, and carbon dioxide, which are finally utilized by methanogenic archaea to produce methane. The efficiency of these interconnected microbial pathways depends on maintaining suitable physicochemical conditions and a balanced microbial community [44]. Fish-processing waste therefore represents a promising substrate for biogas production, although its high protein, nitrogen, and lipid contents can create specific challenges for stable digestion.

Biogas production from fish-processing waste is influenced by several factors, including substrate composition, pH, temperature, organic loading rate, retention time, moisture, carbon-to-nitrogen ratio, ammonia concentration, and salinity. The high nitrogen content of protein-rich fish residues is particularly important because microbial degradation of proteins can result in ammonia accumulation, which may inhibit methanogenic activity at elevated concentrations [45]. Similarly, degradation of residual lipids can generate long-chain fatty acids that may interfere with microbial activity when they accumulate beyond tolerable levels. Excessive organic loading can accelerate VFA formation, leading to acidification and inhibition of methanogens, whereas insufficient loading may reduce reactor productivity. Salinity originating from marine tissues or processing operations can also impose osmotic stress on anaerobic microorganisms. Therefore, appropriate control of substrate loading, pH, temperature, and retention time, together with strategies such as dilution or co-digestion with complementary substrates, is important for maintaining process stability and improving methane recovery [46].

Within the proposed fish-waste biorefinery, anaerobic digestion is particularly valuable when applied to the biomass remaining after lipid and, where feasible, protein recovery. Lipid extraction first converts the energy-rich fraction into biodiesel, while the remaining biodegradable biomass can subsequently be utilized as a substrate for methane production. This sequential strategy provides the potential to recover energy in two forms: biodiesel from the lipid fraction and biogas from the residual biomass w, while the resulting digestate may provide an additional pathway for nutrient recovery [47]. However, lipid removal should not automatically be assumed to improve methane production, because its effect will depend on the composition, biodegradability, and residual nutrient content of the defatted biomass. The key research opportunity is therefore to determine whether sequential lipid recovery followed by anaerobic digestion can provide greater overall energy recovery, process stability, and environmental benefits than biodiesel production or anaerobic digestion conducted independently. Such integration shifts anaerobic digestion from a conventional waste-treatment approach toward a complementary energy-recovery stage within a circular fish-waste biorefinery [48].

## 7. Biogas Production from Fish-Processing Waste

Biogas production from fish-processing waste occurs through a coordinated anaerobic microbial process in which biodegradable organic matter is progressively converted into methane and carbon dioxide. The process involves four interconnected stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During hydrolysis, proteins, lipids, and carbohydrates are broken down into peptides, amino acids, fatty acids, glycerol, and soluble sugars. These products are subsequently fermented during acidogenesis to form volatile fatty acids (VFAs), alcohols, hydrogen, and carbon dioxide, followed by acetogenesis, where suitable intermediates are converted mainly into acetate, hydrogen, and carbon dioxide. Methanogenic archaea then convert these compounds into methane. The methane potential of fish-processing waste depends on its biochemical composition, biodegradability, and the efficiency of microbial conversion. Although fish residues contain readily biodegradable proteins and lipids with considerable energy potential, their degradation can also generate inhibitory compounds such as ammonia and long-chain fatty acids. Therefore, efficient biogas production requires a balance between substrate availability and the tolerance of the microbial community [45] [46].

Methane yield from fish-processing waste can vary substantially according to fish species, anatomical fraction, moisture content, lipid and protein concentration, pretreatment, temperature, organic loading rate, retention time, and reactor configuration. Protein-rich residues may provide considerable methane potential but can release ammonia during degradation, while lipid-rich fractions can generate long-chain fatty acids that may inhibit microbial activity at elevated concentrations. Salinity can impose additional osmotic stress, particularly in wastes originating from marine or salted processing streams [47]. The C/N ratio is also important because fish waste may be relatively nitrogen-rich; co-digestion with carbon-rich substrates such as food waste or selected agricultural residues may therefore improve nutrient balance and digestion stability. Pretreatment techniques such as grinding, thermal treatment, or biological treatment may improve substrate accessibility, but their energy requirements and possible formation of inhibitory compounds must also be considered. Importantly, lipid extraction before digestion should not automatically be assumed to increase methane production, because removal of lipids also removes a fraction with high theoretical energy potential.

The effect of defatting on methane yield, process stability and total energy recovery therefore requires direct experimental evaluation [48].

Co-digestion and biogas upgrading can further improve the practical potential of fish-waste digestion. Co-digestion with complementary substrates may dilute inhibitor compounds, improve the C/N ratio, and provide a more balanced substrate for the anaerobic microbial community, although the optimum combination and mixing ratio must be determined for each feedstock. The resulting raw biogas contains methane together with carbon dioxide, hydrogen sulfide, water vapour, and other impurities. After appropriate cleaning, biogas can be used directly for heat or electricity generation, while further upgrading through technologies such as water scrubbing, chemical absorption, pressure swing adsorption, or membrane separation can produce methane-rich biomethane. Anaerobic digestion also generates digestate containing residual organic matter and nutrients such as nitrogen and phosphorus. After suitable stabilization and quality assessment, this material may provide opportunities for nutrient recovery and agricultural applications. Thus, biogas production should be considered not merely as a waste-treatment option but as an important resource- and energy-recovery stage within an integrated fish-processing waste biorefinery [49] [50] [51].

## 8. Integrated Fish-Waste Biorefinery: Sequential Recovery of Fuels, Bioproducts and Nutrients

An integrated fish-waste biorefinery can recover multiple products from different fractions of the same processing residue instead of relying on a single conversion pathway. In the proposed approach, lipid-rich fractions are extracted and converted into biodiesel, while the remaining defatted biomass can be used for protein recovery or hydrolysis, followed by anaerobic digestion of the residual biodegradable fraction. This produces biogas that can be upgraded to biomethane, while the digestate may provide an opportunity for nutrient recovery. Such sequential processing treats fish-processing waste as a resource rather than a disposal burden and can increase overall material and energy recovery. However, each processing step alters the composition of the remaining biomass, so the entire cascade must be optimized as an integrated system [52].

The major advantage of this approach is the possibility of recovering value from different biochemical fractions. Lipids can provide biodiesel, proteins can be converted into protein concentrates or hydrolysates, residual organic matter can generate biogas, and nutrients in the digestate can potentially be recovered for agricultural use. However, individual product yields should not be considered independently. For example, lipid removal may reduce the methane potential of the remaining biomass while simultaneously producing biodiesel and potentially reducing lipid-related inhibition during digestion. Therefore, the key question is whether sequential processing provides greater overall energy recovery, resource utilization, and economic value than biodiesel production or anaerobic digestion alone [53].

From a circular-bioeconomy perspective, the integrated biorefinery can maintain carbon, nutrients, and other resources within productive cycles while reducing residual waste. Nevertheless, additional extraction, separation, and conversion steps can increase energy consumption, capital requirements, and process complexity. Its sustainability and commercial feasibility therefore depend on feedstock composition, logistics, processing efficiency and product markets. Mass and energy balances, techno-economic assessment (TEA), and life-cycle assessment (LCA) are essential to determine whether the benefits of multiple products and resource recovery justify the additional processing requirements. The overall objective should therefore be maximum resource recovery rather than maximum production of any single product, with biodiesel, protein products, biogas/biomethane,e and recovered nutrients considered as interconnected outputs of one integrated system [54].

## 9. Environmental Sustainability and Life-Cycle Considerations

Fish-waste valorization can provide environmental benefits by reducing the quantity of organic residues requiring disposal while recovering energy and materials from the same feedstock. Lipid extraction followed by biodiesel production converts the oil fraction into a renewable fuel, while anaerobic digestion of the remaining biodegradable biomass provides biogas or biomethane. Protein and nutrient recovery can further reduce the need for virgin resources and conventional fertilizer production. However, these benefits should not be assumed automatically. Collection, transportation, drying, extraction, chemical use, heating, wastewater treatment, and downstream processing all require energy and resources. Therefore, the environmental advantage of fish-waste valorization depends on whether the impacts associated with processing are lower than those avoided through waste disposal and the production of conventional fuels and materials [55].

From a climate perspective, the integrated biorefinery has the potential to reduce dependence on fossil resources by producing biodiesel and biomethane from an existing biological residue rather than dedicated energy crops. It may also reduce greenhouse-gas emissions associated with uncontrolled decomposition of fish-processing residues and avoid some impacts associated with producing equivalent products from virgin resources. Nevertheless, the overall greenhouse-gas benefit depends on the complete process chain. Energy consumption during extraction and conversion, transportation, chemical and catalyst production, wastewater treatment, and particularly methane leakage during anaerobic digestion and biogas upgrading can reduce the climate advantage. Therefore, renewable-energy production should be distinguished from net greenhouse-gas mitigation, which can only be established through a complete life-cycle assessment [56].

Life-cycle assessment (LCA) is therefore essential for determining whether the proposed fish-waste biorefinery provides a genuine environmental advantage over conventional waste-management or single-product systems. The assessment should consider the complete pathway from waste collection and transportation through lipid extraction, biodiesel production, protein recovery, anaerobic digestion, biogas upgrading, and digestate management.

Important indicators include global warming potential, cumulative energy demand, fossil-resource use, water consumption, eutrophication, acidification, and toxicity. At the same time, environmental trade-offs must be considered because additional processing stages can increase energy, chemical, and water requirements. The key question is therefore not whether fish-waste valorization is inherently sustainable, but under which feedstock processes and energy conditions sequential valorization provides a net environmental benefit while maximizing resource and energy recovery. This life-cycle perspective is particularly important when comparing biodiesel-only, anaerobic-digestion-only, and integrated biorefinery pathways [57] [58].

## 10. Techno-Economic Considerations

The techno-economic feasibility of fish-waste valorization depends strongly on feedstock availability, composition, logistics, and processing requirements. Fish-processing residues are often highly moist, geographically dispersed, and variable in lipid and protein content, making collection, transportation, and storage important cost factors [59]. Lipid extraction costs are influenced by extraction efficiency, energy and solvent requirements, equipment, and downstream purification, while biodiesel production additionally depends on catalyst requirements, reaction conditions, purification, and oil quality. Similarly, anaerobic digestion requires investment in reactors, feeding, heating, gas collection and digestate management, with its economic performance largely determined by methane yield, operating conditions and energy consumption. Therefore, maximizing individual product yield does not necessarily result in the most economical process [60].

The integrated biorefinery can potentially improve economic feasibility by generating multiple revenue streams, including biodiesel, biogas or biomethane, protein-derived products, recovered nutrients and glycerol. However, these benefits must be balanced against the additional capital and operating costs associated with multiple processing stages [61]. A complete assessment should therefore include mass and energy balances, CAPEX, OPEX, feedstock and transportation costs, energy consumption, product revenues, payback period, NPV, IRR, and minimum selling price. Energy inputs from extraction, heating, pumping, drying, chemical processing, and transportation should be compared with energy recovered as biodiesel, biogas, and useful heat [62].

Ultimately, the economic potential of an integrated fish-waste biorefinery should not be assumed simply because it produces several products. Its feasibility depends on consistent feedstock supply, efficient process integration, product quality, market demand, and regulatory requirements. Future studies should therefore compare conventional disposal, single-product conversion, and integrated valorization using combined techno-economic and life-cycle assessments. Such system-level evaluation can identify whether sequential recovery of lipids, proteins, bio, and nutrients provides sufficient economic and environmental benefits to justify the additional processing complexity [63].

## 11. Current Challenges and Research Gaps

The valorization of fish-processing waste into biodiesel, biogas and value-added products is promising, but commercial implementation is limited by feedstock variability, process complexity, logistics and economic constraints. Fish residues differ in species, anatomical fraction, season, processing method, and storage conditions, affecting lipid, protein, moisture, nitrogen,n and methane potential. High moisture and rapid deterioration further complicate transportation and storage. Therefore, standardized feedstock characterization and reporting are essential for reliable comparison between studies [64].

Technical challenges occur at both the biodiesel and anaerobic-digestion stages. High free fatty acid levels can complicate biodiesel production, while polyunsaturated fatty acids may affect fuel stability. During anaerobic digestion, ammonia, long-chain fatty acids, salinity, and unsuitable C/N ratios can inhibit microbial activity. Controlled feeding, co-digestion, suitable pretreatment, and process optimization may help overcome these limitations. At larger scales, transportation, solvent recovery, reactor operation, energy requirements, and integration of multiple processing stages become additional challenges [65]. A major research gap is the limited experimental validation of the complete sequential pathway linking lipid extraction with subsequent anaerobic digestion of the defatted biomass. Future studies should directly compare conventional anaerobic digestion with sequential lipid recovery followed by digestion using mass and energy balances. Key priorities include low-energy extraction, reusable catalysts, ammonia and long-chain-fatty-acid control, optimized co-digestion and pilot-scale validation. Finally, techno-economic assessment and life-cycle assessment are required to determine whether the integrated system genuinely improves resource recovery, energy efficiency, environmental performance, and economic feasibility [66].

## 12. Future Perspectives

Future research on fish-waste valorization should focus on the development of integrated cascade biorefineries in which different fractions are directed toward the most suitable high-value, energy, and nutrient-recovery applications rather than converting the entire biomass into a single low-value product. Advanced lipid-extraction technologies such as ultrasound-assisted, microwave-assisted, enzymatic, and supercritical-fluid extraction could improve lipid recovery, but their evaluation should consider not only extraction yield but also energy consumption, solvent requirements, scalability, cost,t and environmental impact [67]. The development of low-cost, reusable heterogeneous catalysts and immobilized or stabilized lipases may further improve the feasibility of biodiesel production, particularly from high-FFA fish oils, while biological and enzymatic pretreatment could enhance subsequent lipid, protein, or methane recovery under milder processing conditions. Anaerobic co-digestion with food waste or agricultural residues also offers potential for improving C/N balance and reducing inhibition, although optimum substrate ratios and operating conditions require further investigation [68]. In parallel, artificial intelligence and machine-learning approaches could support multi-parameter optimization by linking feedstock characteristics with extraction efficiency, biodiesel and methane yields, energy consumption, and environmental performance.

Future process development should therefore combine life-cycle assessment and techno-economic analysis to evaluate technical, economic, and environmental performance simultaneously rather than optimizing individual processes in isolation [69]. Decentralized or modular fish-waste biorefineries located near processing facilities may further reduce transportation requirements and rapid deterioration of residues, although their economic feasibility must be compared with centralized systems. Ultimately, greater integration with fisheries and aquaculture industries could establish closed-loop systems in which processing residues are converted into biodiesel, biogas or biomethane and recovered nutrients are returned to agricultural or aquaculture systems, strengthening resource efficiency and advancing the transition toward a circular fish-processing bioeconomy [70].

## 13. Conclusion

Fish-processing waste should no longer be considered solely as a disposal problem; its substantial lipid, protein, and biodegradable organic fractions make it a potentially valuable feedstock for integrated resource recovery. The literature demonstrates the feasibility of converting fish-derived lipids into biodiesel and organic residues into biogas, while protein and mineral fractions provide additional opportunities for value-added products and nutrient recovery. However, the environmental and economic performance of these pathways is strongly influenced by feedstock variability, transportation, moisture, free fatty acid content, catalyst requirements, ammonia inhibition, salinity, energy consumption, and downstream processing requirements. The most promising direction is therefore a sequential fish-waste biorefinery, in which lipid-rich fractions are first recovered and converted into biodiesel, while the remaining biomass is further valorized through anaerobic digestion to produce biogas or upgraded biomethane. Subsequent digestate management can provide an additional pathway for nutrient recovery. Such a cascade has the potential to increase overall resource and energy recovery while reducing the quantity of residual waste. However, the superiority of this approach over single-product systems cannot be assumed and must be demonstrated through integrated mass balance, energy balance, techno-economic assessment, and life-cycle assessment.

Ultimately, the transition from fish waste to a circular bioeconomy will require a shift from single-product conversion toward integrated, multi-output and location-specific biorefinery systems. Future research should therefore prioritize pilot-scale validation, standardized feedstock characterization, sequential process optimization, co-digestion strategies, low-cost catalysts, advanced extraction technologies and AI-assisted process control. The central opportunity lies not simply in producing biodiesel or biogas from fish waste, but in developing a system capable of maximizing the recovery of carbon, energy, proteins, and nutrients from every fraction of the original biomass while minimizing environmental burden and economic cost.

## AI-Assisted Writing and Language Editing Disclosure

The authors used Grammarly to assist with grammar, spelling, punctuation, readability, and language refinement during manuscript preparation. Generative artificial intelligence (AI) tools were used only to support language editing, organization, and refinement of the manuscript where applicable. The authors independently verified the scientific content, interpretation of the literature, accuracy of citations, and factual statements and retained full responsibility for the originality, integrity, and final content of the manuscript. AI tools were not used to generate, fabricate, or manipulate scientific data, results, references, or conclusions.

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