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# Technological solutions for processing fatty waste from the fishing industry to minimize environmental impact

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This paper presents an analytical review of fat-containing waste from fish processing enterprises as a promising secondary raw material for producing high-value products and reducing environmental burden. The study covers the main sources of waste generation in the fishing industry, in particular heads, entrails, skin, bone residues, and fat fractions, which are characterized by lipid content of 8–30%, free fatty acids of 5–25%, and moisture of 40–75%. It was established that these wastes have significant resource potential for the production of diesel biofuel, feed products, fatty acids, and biologically active compounds, particularly ω-3 polyunsaturated fatty acids. The chemical composition of fat-containing waste was studied, and the main groups of impurities were identified, including phospholipids, protein components, water, mineral salts, and oxidation products that affect the efficiency of technological processing. A comparative analysis of technological processing methods was carried out, including thermal, chemical, biotechnological, and methods of intensification of technological processes (ultrasound, cavitation, vibromechanical effects). It was established that under optimal conditions (temperature 50–65 °C, alcohol: fat ratio 6:1–9:1, humidity < 0.5%), the yield of biodiesel can reach 90–96%, while the use of methods of intensification of technological processes increases the degree of fat extraction by 10–25%. Approaches to complex waste processing using anaerobic digestion have been standardized, enabling the production of biogas with 55–70% methane content, as well as feed and protein products. A critical analysis of international and Ukrainian experience has been conducted, showing that waste utilization in EU countries reaches 90–98%, while in Ukraine it is 50–60%, indicating a significant reserve for increasing efficiency. The environmental assessment confirmed that implementing processing technologies can reduce greenhouse gas emissions by 60–85% and significantly reduce the volume of organic waste. The practical significance of the study lies in substantiating the selection of optimal technological solutions for processing fatty waste from the fishing industry, thereby increasing production resource efficiency, reducing environmental load, and advancing bioenergy technologies in Ukraine.

*Keywords*: biofuels; secondary resources; fish oil; intensification; environmental efficiency; waste processing; energy use.

## Introduction

Increased production volumes and a significant accumulation of organic by-products characterize the modern development of the fish processing industry. According to estimates by international industry organizations, the share of waste in the fish processing process is on average 40–60%, and for certain technological schemes, up to 70% of the mass of the starting raw material (Kovalenko et al., 2021). At the same time, fish waste has a high resource potential, as it contains 20–45% lipids, 15–25% proteins, and over 80% organic matter on a dry-mass basis, making it a promising raw material for producing energy and bioactive products (Statkevych et al., 2024).

At the same time, the lack of effectively organized, technologically advanced waste processing systems leads to their accumulation in the environment, thereby increasing the environmental load. This is manifested in the pollution of soils, water resources, and air, the deterioration of the sanitary condition of territories, and the loss of valuable secondary resources that could be reused in economic activities. The value of the biochemical oxygen demand (BOD5) for wastewater generated during fish processing can exceed 30,000 mg $O_2/dm^3$, which is 50–100 times the permissible standard (Bal-Prylypko et al., 2024). This leads to the intensive development of anaerobic microflora, the formation of toxic gases ($NH_3$, $H_2S$), disruption of the oxygen regime in aquatic ecosystems, and degradation of the natural environment.

World practice demonstrates a high level of integration of waste into production cycles. In the EU, Norway, and Japan, the level of fish waste recycling exceeds 90%, with up to 80% of the waste mass being converted into valuable products (fats, hydrolysates, feed) (Holembovska et al., 2021). Bioenergy technologies, in particular anaerobic digestion, provide an output of about 550 $m^3$ of biogas from 1 t of raw material, and the use of modern technologies for the production of biofuel diesel allows achievement of 90% conversion of lipids into fatty acid methyl esters (Archana et al., 2024; Sher et al., 2024).

In Ukraine, the level of reuse of fish waste remains significantly lower at 25%, underscoring the underutilized potential of this resource and the need to implement innovative processing technologies (Bal-Prylypko et al., 2022). Existing approaches are mainly focused on the production of feed meal and technical fat, which do not ensure the full extraction of valuable components and fail to comply with the principles of the circular economy.

Similar to other types of secondary raw materials from the food industry, in particular plant waste (apple pomace, oilseed meal), which are successfully used to produce pectins, antioxidants, and biofuels, fatty waste from fish processing plants can be integrated into multi-component technological schemes (Mushtruk, 2025). This is consistent with modern trends in sustainable development and resource conservation, which involve the maximum use of biomass.

One of the most promising areas is the production of biodiesel from fish oil via transesterification. Under rational process conditions (50–65 °C, alcohol-to-fat molar ratio 6:1–12:1, use of alkaline or heterogeneous catalysts), a high degree of conversion is achieved (Mushtruk et al., 2024). Improved environmental characteristics distinguish the resulting biodiesel compared to traditional petroleum diesel fuel.

In particular, its use reduces carbon monoxide (CO) emissions by up to 50%, thereby lowering the toxic burden on the atmosphere. In addition, the fuel contains practically no sulfur compounds; therefore, sulfur dioxide ($SO_2$), which is a key factor in acid rain, is not formed during combustion. Another important advantage is its high biodegradability: under natural conditions, this fuel degrades within approximately 20–30 days, significantly reducing the risk of long-term environmental pollution if it enters ecosystems (Osman et al., 2024).

Along with this, promising areas of processing include anaerobic digestion, which allows conversion of organic raw materials into biogas with a methane content of 65%, making it suitable for energy use (Mushtruk et al., 2025). Biotechnological methods also play an important role, in particular enzymatic hydrolysis, which can be used to obtain valuable products – fatty acids and protein hydrolysates, which are widely used in the food industry.

At the same time, the efficiency of these processes largely depends on the properties of the starting material. It is characterized by high humidity (up to 60%), unstable chemical composition, and a tendency to rapid microbiological degradation. This complicates its storage and processing and necessitates the implementation of complex technological solutions that combine preliminary preparation, stabilization, and optimization of process parameters (Monika et al., 2023). Table 1 presents the general characteristics of fish waste and the effectiveness of the main processing areas. Analysis of the presented indicators indicates a high resource potential of fat-containing raw materials and the possibility of producing a wide range of target products under energy-efficient conditions.

**Table 1**
Generalized characteristics
of fish waste and directions of their processing

| Indicator | Value | Comment |
|---|---|---|
| Share of waste | 40–70% | from the mass of fish |
| Fat content | 20–45% | main raw materials for biofuels |
| Protein content | 15–25% | potential of feed products |
| Organic matter | > 80% | high bioenergetic value |
| $BSC_5$ | up to 3,000 mg $O_2/m^3$ | high environmental load |
| Biogas | 400–600 $m^3/t$ | anaerobic digestion |
| Methane in biogas | 60–70% | energy efficiency |
| Biodiesel yield | 85–95% | under optimal conditions |
| Disposal Level (EU) | 80–90% | high level |
| Disposal Level (Ukraine) | 20–30% | low level |

*Note*: developed by the authors based on research Monika et al. (2023), Archana et al. (2024), Osman et al. (2024), Sher et al. (2024), Mushtruk et al. (2025).

Despite the significant resource potential of fatty waste from the fish processing industry, Ukraine currently lacks comprehensive technological solutions that enable efficient, complete processing while simultaneously generating energy and functional products. This means that a significant portion of valuable raw materials is used inefficiently or lost altogether, reducing the industry's overall efficiency.

Existing approaches to processing are usually fragmented and not sufficiently coordinated. They do not fully account for the physicochemical properties of the raw material, in particular its high moisture content, variable composition, and tendency to rapid degradation. In addition, such approaches often fail to comply with the principles of the circular economy, which call for the maximum reuse of resources, waste minimization, and the creation of closed technological cycles. In this regard, the development of integrated technologies that enable the comprehensive use of fat-containing waste to produce high-value products is relevant.

The purpose of the work is to scientifically substantiate technological approaches to the complex processing of fatty fish waste to produce biofuel and related products, thereby increasing the rational use of resources and reducing the environmental burden.

At the same time, implementing these directions requires consideration of several specific features of fish waste. These include high humidity, rapid enzymatic and microbiological destruction, the presence of impurities that complicate the separation of the fat fraction, significant variability of the chemical composition depending on the type of raw material, as well as the need for prompt transportation and preliminary preservation. All this requires the development of scientifically sound technological schemes that combine mechanical, thermal, chemical, and biotechnological processing methods and ensure maximum extraction of useful components with minimal energy and environmental costs. The study is relevant because it aims to develop and implement effective technologies for processing fatty waste from the fish processing industry, focusing on the integrated use of raw materials, reducing environmental pollution, and increasing resource utilization. The scientific justification of such solutions is important for both the development of the domestic fish processing industry and the formulation of practical principles for a circular economy in the food industry. In this regard, the purpose of the work is to substantiate technological approaches to the processing of fatty waste from the fish industry with the production of valuable energy and functional products that ensure environmental safety and increase the complexity of the use of raw materials.

**Resource potential of fatty waste from the fish processing industry**

Analysis of scientific sources and industry statistics indicates that the fish processing industry generates significant amounts of fatty waste with high resource potential. During fish processing, 20–70% of the raw material mass is wasted, and in some cases up to 80%, including heads, entrails, skin, and trimmings, which contain a significant amount of lipids. These wastes are the main source of fish oil, which is characterized by a high biological value (particularly its ω-3 fatty acid content) and a wide range of applications (Shanina et al., 2020). An effective model for the use of fatty fish waste within the framework of a circular economy has been formed in the countries of the European Union. A significant proportion of the raw materials for the production of fish oil and fishmeal is formed precisely from processing by-products (Mamat et al., 2025). At the same time, the production volume of fish oil in the EU is about 110 thousand tons per year, and of fishmeal, 470 thousand tons, and an increasing share of this production is obtained from processing waste rather than from food raw materials. According to forecasts, by 2030, about 47% of global fish oil production will be derived from waste, underscoring the strategic role of secondary raw materials (Giosuè et al., 2025).

Ukraine is characterized by a specific structure of the fish processing industry: although the volumes of industrial catch and processing are relatively small, the share of waste remains high. This is primarily due to technological imperfections in production and to the insufficient implementation of integrated approaches to raw material processing. According to industry research, a significant portion of fish processing waste is either improperly disposed of or used inefficiently. In particular, it is often used as a feedstock without prior lipid extraction, resulting in the loss of valuable fats that could be used to produce biofuels or other high-value products. As a result, this not only reduces the industry's economic efficiency but also imposes additional environmental burdens due to the accumulation and improper management of waste (Santos et al., 2023).

It has been established that fat-containing fish processing waste has high potential for the following areas of use: production of fish oil (food, feed, pharmaceutical); production of biofuel (high triglyceride content ensures conversion efficiency); biogas and energy use; isolation of biologically active compounds (omega-3, phospholipids); production of feed and feed additives (Liu et al., 2021). From an energy perspective, fish oils have a high calorific value (at 37–39 MJ/kg), making them a competitive feedstock for biodiesel production. Furthermore, unlike vegetable oils, they do not compete with the food sector, which is consistent with the principles of sustainable development (Rathod et al., 2022).

An important feature of fish waste is its high moisture content and its rapid biodegradability. This means that such raw materials quickly deteriorate, lose their valuable components, and can cause sanitary and environmental problems. In this regard, there is a need for their prompt processing without long-term storage or the introduction of special methods to intensify technological processes.

These methods include hydrothermal treatment, enzymatic hydrolysis, and mechanical dehydration, which accelerate processing, stabilize raw materials, and increase the yield of valuable products. In the countries of the European Union, these technologies are already widely used in the industry and are part of complex processing systems. At the same time, in Ukraine, their implementation remains limited, hindering the increased efficiency of the aforementioned technological processing methods.

Therefore, the results indicate that fatty waste from the fish processing industry has significant resource potential, especially in the context of the transition to a bioeconomy. The European experience demonstrates an effective model of integrated processing, while in Ukraine, there is significant potential to increase utilization and incorporate this type of raw material into the production of biofuels and high-value products.

**Analysis of technological methods for processing fatty waste from the fish processing industry**

A summary of current research shows that the efficiency of processing fatty waste from the fish industry is largely determined by the choice of technological method and raw material parameters (humidity 40–75%, fat content 8–30%, free fatty acid content 5–25%) (Yari et al., 2019). Table 2 provides a comparative analysis of the main technological methods for processing fatty fish waste.

As the data show, different technological approaches to processing fatty waste differ significantly in efficiency, energy consumption, and process duration. This means that the choice of a specific technology should be based on a compromise between the yield of the target product, energy consumption, and the quality of the resulting product. In particular, thermal methods (rendering) provide a relatively stable fat yield of 70–85%. However, they are associated with significant energy consumption (up to 1200 MJ/t) and a partial reduction in the product's biological value (Yang et al., 2022). Chemical methods, such as esterification and transesterification, are the most effective for obtaining biodiesels and allow achieving a yield of up to 95%, especially if the acid number of the raw material is previously reduced to a level of less than 2 mg KOH/g. Biotechnological approaches, on the contrary, allow preservation of up to 90% of polyunsaturated fatty acids, which is important for obtaining functional products. However, their implementation requires much more time, 3–5 times longer than traditional methods (Heidari & Rezaei, 2022).

**Table 2**
Comparison of the main technological methods for processing fatty fish waste

| Method | Fat/product yield, % | Energy consumption, MJ/t | Process duration, hours | Advantages | Disadvantages |
|---|---|---|---|---|---|
| Thermal (rendering) | 70–85 (fat), 90–95 (general disposal) | 800–1200 | 1–3 | simplicity, high performance | degradation of ω-3, high energy consumption |
| Transesterification (biodiesel) | 85–95 (biodiesel) | 500–800 | 2–6 | high fuel yield, mature technology | sensitivity to water and acidity |
| Acid esterification (preliminary stage) | 80–90 (fatty acid conversion) | 400–600 | 1–2 | effective in fatty acid conversion >10% | need for post-processing |
| Enzymatic method | 80–92 | 200–400 | 6–24 | conservation ω-3, environmental friendliness | high cost of enzymes |
| Ultrasonic/cavitation intensification | +10–25% to the basic method | 300–500 | 0.5–2 | shorten the time, increase the extraction | optional equipment |
| Ultrasonic/cavitation intensification | 60–75 (by organic matter) | 150–300 | 10–20 | comprehensive disposal | slow process speed |

*Note*: developed by the authors based on research Yari et al. (2019), Heidari & Rezaei (2022), Loan et al. (2022), Yang et al. (2022).

Process intensification technologies play an important role, in particular the use of ultrasound, cavitation, and vibromechanical effects. Their use increases fat extraction by 10–25% and reduces processing time by 50%, thereby significantly increasing overall processing efficiency. For low-quality raw materials, it is advisable to use biogas technologies that produce methane at 0.45–0.65 m³/kg of organic matter and allow the disposal of residues after the main processes (Loan et al., 2022).

In the countries of the European Union, integrated technological schemes prevail, for example, rendering → fat purification → transesterification → processing of residues in biogas plants. This approach ensures the comprehensive use of raw materials with an efficiency of over 95%. In Ukraine, this indicator usually does not exceed 50–60%, indicating significant potential to improve technologies (Rajabimashhadi et al., 2023).

Analysis of literary sources shows that the most promising technological solutions for processing fat-containing waste from the fish processing industry are combined technological approaches that leverage rational technological influences, thereby increasing the yield of target products, reducing energy consumption, and ensuring comprehensive utilization of raw materials.

**Biodiesel production**

Analysis of experimental and literature data shows that the yield of biofuel from fish oils and fatty waste is determined by a set of technological parameters, among which the key ones are the process temperature, molar ratio of alcohol: fat, catalyst concentration, reaction time, free fatty acid (FFA) content, and moisture (Mushtruk et al., 2025). It has been established that the reaction temperature significantly affects the rate of transesterification. The optimal range is 50–65 °C, which is close to the boiling point of methanol. Increasing the temperature from 40 to 60 °C increases the biodiesel yield from 70–75% to 90–95%; however, further increases in temperature lead to alcohol losses and a decrease in process efficiency (Cheliadyn et al., 2020). The molar ratio of alcohol: fat is one of the most important factors. The theoretical ratio is 3:1, but in practice, the optimal ratio is 6:1–9:1, which shifts the reaction equilibrium towards the formation of methyl esters. At a 6:1 ratio, a yield of about 92–95% is achieved, whereas a 3:1 ratio limits yield to 75–80% (Chen et al., 2022).

A catalyst concentration (NaOH or KOH) of 0.5–1.0 wt.% is optimal for most fish oils after preliminary preparation. An increase in concentration above 1.5% leads to saponification and emulsion formation, reducing biodiesel yield by 10–20% (Dahiya, 2020).

The content of free fatty acids plays a special role. For effective alkaline transesterification, their level should not exceed 2–3%. For fish waste, this figure often ranges from 10–25%, requiring prior acid esterification. Reducing the FFA from 15% to 2% allows the biodiesel yield to be increased from 65–70% to 90–95%. The moisture content of the feedstock is a critical parameter: at water contents above 0.5%, triglyceride hydrolysis occurs, and the biodiesel yield decreases by 15–30%. For fish waste with an initial moisture content of 40–70%, preliminary dehydration (mechanical or thermal) is required (Eldiehy et al., 2022).

The reaction duration also affects the degree of conversion. The optimal time is 60–120 min, at which the maximum yield is achieved (up to 95%). Extending the process beyond 3 hours does not yield a significant increase; instead, it promotes side reactions. Table 3 presents the results of assessing the influence of transesterification technological parameters on the yield of biofuel diesel. The analysis shows that optimizing the temperature regime, catalyst concentration, and reagent ratio allows the maximum lipid conversion to fatty acid methyl esters. The results confirm that, for fatty waste from the fish processing industry, preliminary conditioning of the raw material (reducing moisture and acidity) is crucial. In EU countries, the use of two-stage technologies enables the stable production of biodiesel with a yield of 90–96%, whereas in Ukraine, due to variability in raw materials, this indicator often fluctuates between 70–85%.

The results of the study indicate that optimizing technological parameters is a key factor in increasing the efficiency of biodiesel production from fish waste, and the introduction of new technological solutions for process intensification further increases the yield of the final product and ensures its compliance with standards.

**Table 3**
Impact of technological transesterification on biodiesel yield

| Parameter | Range of values | Biodiesel yield, % | Features of influence |
|---|---|---|---|
| Temperature, °C | 40 → 60 → 70 | 75 → 92 → 88 | optimum 50–65 °C |
| Alcohol: fat ratio | 3:1 → 6:1 → 9:1 | 78 → 93 → 95 | excess alcohol improves conversion |
| Catalyst, % | 0.3 → 0.8 → 1.5 | 70 → 94 → 80 | excess causes saponification |
| Fatty acid conversion, % | 15 → 5 → 2 | 65 → 85 → 95 | pre-esterification required |
| Humidity, % | 0.1 → 0.5 → 1.0 | 95 → 85 → 70 | water reduces efficiency |
| Time, min | 30 → 90 → 180 | 70 → 95 → 96 | optimum 60–120 min |

*Note*: developed by the authors based on research (Cheliadyn et al., 2020; Dahiya, 2020; Eldiehy et al., 2022).

**Comparison of methods for processing fatty waste from the fish processing industry**

Given the growth in the processing volume of aquatic bioresources and the increasing need for the rational use of raw materials, such waste is increasingly viewed not as a by-product but as an important source of secondary materials and energy resources. Their composition, represented by lipids, proteins, and mineral components, provides significant potential for obtaining a wide range of products – from feed and food ingredients to biofuels and biologically active substances. At the same time, the specific physicochemical properties of this raw material, in particular high humidity, compositional instability, and a tendency to rapid biodegradation, necessitate specialized technological approaches to intensify processing (Jaiswal et al., 2024).

In this context, a comparison of existing technological solutions for processing fatty waste is particularly relevant to determine their efficiency, energy intensity, duration, and preservation of valuable components. Analysis of global experience indicates the dominance of integrated approaches combining thermal, chemical, and biotechnological methods, with consideration of the principles of the circular economy. In particular, in the countries of the European Union, a holistic model of the circular bioeconomy has been developed, in which fatty waste serves as a full-fledged secondary raw material, ensuring high levels of utilization and reuse (Rana et al., 2023).

The comparative analysis indicates significant differences between the countries of the European Union and Ukraine in the level of use of the resource potential of fatty waste from fish processing, technological development, and overall processing efficiency. An integrated model of the circular bioeconomy operates in the EU, where such waste is considered a valuable secondary raw material rather than a by-product. This provides a high level of resource efficiency, since a significant proportion of fish oil and fish meal is produced from processing waste. The high level of fish oil consumption (about 15% of the global volume) creates a sustainable demand and stimulates the implementation of innovative, resource-saving processing technologies (Pleissner et al., 2023). Table 4 provides a comparative description of international and Ukrainian experience.

Analysis of the results indicates that Ukraine is significantly lagging in key indicators, particularly in waste disposal, enterprise technical and technological equipment, and the structure of final products. This limits the effective use of available raw material potential and hinders the industry's development accordingly.

The efficiency with which available raw materials are used constrains the industry's development. In European countries, combined technological solutions are used that combine rendering, biodiesel, and biogas production, and are also characterized by a high level of automation and energy efficiency. This ensures almost complete utilization of raw materials (90–98%) and an orientation towards producing products with high added value, in particular ω-3 concentrates and pharmaceutical components (Desai et al., 2021).

In contrast, in Ukraine, the industry is characterized by fragmented production, a limited raw-material base, and a predominance of primary or partial processing. Waste is mostly used as a feed raw material without deep extraction of the fat fraction, due to the lower levels of technological equipment in enterprises.

**Table 4**
Comparative analysis of technological and resource-efficient indicators of processing of fat-containing fish waste in the EU countries and Ukraine

| Indicator | European Union | Ukraine |
|---|---|---|
| Waste disposal rate, % | 90–98 | 50–60 |
| Share of waste in fat production | 30–60% and growing | < 20% |
| Fish oil production | 90–140 thousand. t/year | limited, local |
| Technological level | high (integrated systems) | medium/low |
| Main Products | diesel biofuels, ω-3, pharmaceuticals | feed additives |
| Intensification methods | widely used | surveyed |
| Energy efficiency | high (recuperation, biogas) | low/partial |

*Note*: developed by the authors based on research Desai et al. (2021), Smaisim et al. (2022), Pleissner et al. (2023), Rana et al. (2023), Jaiswal et al. (2024).

As a result, the level of effective use of fat-containing waste in Ukraine is only 50–60%, whereas in the European Union it exceeds 90%. In addition, the concept of zero-waste processing is being actively implemented in the EU, which involves the full use of all raw material components. For example, waste from fat extraction is used to produce biogas or feed, ensuring a closed production cycle. In Ukraine, such approaches are only beginning to be implemented and are mainly experimental or local in nature (Smaisim et al., 2022).

Another important difference is regulatory policy: the EU has strict environmental requirements and incentives for waste recycling, which promote innovation and attract investment. In Ukraine, the regulatory framework is underdeveloped, hindering the industry's modernization.

The results of the comparative analysis indicate that international experience demonstrates a high level of technological maturity and integrated use of fatty fish processing waste. Ukraine has significant potential for development in this area, particularly through the implementation of integrated technologies, the application of technological approaches to intensify processing, and the adoption of European circular-economy principles.

**Environmental aspects of processing fatty waste from the fish processing industry**

A summary of current research shows that processing fatty waste from the fish processing industry is an important tool for reducing environmental burdens and transitioning to a circular bioeconomy. The greatest environmental effect is achieved by reducing the volume of organic waste, reducing greenhouse gas emissions, and replacing fossil fuels.

It has been established that, when stored in uncontrolled conditions, fish waste quickly biodegrades, producing methane ($CH^4$), ammonia, and hydrogen sulfide, leading to significant environmental deterioration. Processing this waste reduces greenhouse gas emissions by 60–85% compared to traditional landfilling. This is especially true for biodiesel and biogas production technologies (Bhattacharya et al., 2022). The production of biodiesel from fish oil results in a 50–78% reduction in $CO_2$ emissions compared to petroleum diesel, accounting for the entire life cycle. In addition, sulfur oxides (SOX) emissions are reduced to almost zero, and particulate matter is reduced by 30–50% (Rigueto et al., 2023).

Anaerobic digestion of fatty waste produces biogas with 55–70% methane content, preventing uncontrolled $CH_4$ emissions. The environmental effect is a reduction in the global warming potential (GWP) by 65–80% (Elvines et al., 2024).

At the same time, it has been established that thermal methods (rendering) have a double environmental impact: on the one hand, they facilitate waste disposal, and on the other hand, they entail high energy consumption (up to 1200 MJ/t) and associated $CO_2$ emissions. In EU countries, this disadvantage is compensated by heat recovery and the use of renewable energy sources (Reza et al., 2022).

**Table 5**
Comparative analysis of the environmental efficiency of the main technological methods for processing fatty fish waste

| Technology | Reduction of $CO_2$ emissions, % | GWP decrease, % | Additional effect |
|---|---|---|---|
| Biodiesel from fish oil | 50–78 | 55–75 | $SO_x \approx 100\%$ reduction |
| Anaerobic digestion | 40–65 | 65–80 | disposal of organic matter, biogas |
| Rendering | 20–40 | 25–45 | waste disposal |
| Complex processing (EU) | 70–90 | 75–90 | almost waste-free production |

*Note*: developed by the authors based on research Bhattacharya et al. (2022), Reza et al. (2022), Rigueto et al. (2023), Elvines et al. (2024).

Comparative analysis shows that in European Union countries, a high level of environmental efficiency is achieved through the implementation of closed technological cycles, the use of residual biomass for energy production, effective treatment of wastewater and gas emissions, and the implementation of zero-waste principles.

In Ukraine, however, the environmental impact of processing fatty waste is significantly lower. This is due to insufficient development of processing infrastructure, the lack of comprehensive technological schemes, and limited implementation of biogas and energy-efficient technologies. At the same time, the potential for environmental impact in Ukraine is high: if modern technologies are implemented, it is possible to reduce industry greenhouse gas emissions by 30–50% and significantly reduce organic waste volumes.

Thus, the study's results confirm that processing fatty waste from the fish processing industry is an effective environmental solution that combines waste disposal with the production of renewable energy and high-value-added products. The most promising direction is the implementation of integrated technologies that ensure maximum resource conservation and minimize environmental impact.

## Discussion

The study's results confirm that fatty waste from fish processing enterprises is a valuable secondary raw material with high potential for complex processing. This is consistent with the approaches presented by Pasha et al. (2021), which emphasize the feasibility of using waste from animal and plant sources for biofuel production. The authors note that the use of calcium catalysts enables a high degree of triglyceride conversion, consistent with the 85–95% biodiesel yield reported in the work.

Studies by Pinheiro et al. (2021) show that the physicochemical properties of waste-based biodiesel are close to those of traditional diesel, allowing its use without engine modification. The results obtained in this work confirm these conclusions, in particular regarding the reduction of carbon monoxide and sulfur compound emissions. Subhash et al. (2022) also indicate that optimizing the molar ratio of alcohol to triglycerides is a key factor in increasing the process efficiency, which is fully consistent with the results presented.

Analysis of alternative technologies shows that anaerobic digestion is one of the most environmentally effective methods for the disposal of fatty waste. In particular, the studies of Suzihaque et al. (2023) demonstrate the possibility of integrating biogas technologies into the overall waste processing system, which allows the energy efficiency of production to be increased. The biogas yields obtained in the work (up to 600 m³/t) are consistent with the literature and confirm the feasibility of this approach in food industry enterprises.

At the same time, as Tucki et al. (2020) argue, current trends in biowaste processing aim not only to produce energy products but also bioactive substances of high added value. In the context of fish processing waste, this may include the extraction of omega-3 fatty acids, phospholipids, and protein hydrolysates, which expands the range of possible uses.

A comparison of Ukrainian and international experience reveals significant differences in technological development. As evidenced by the research of Vlasenko et al. (2026), biorefinery concepts are being actively implemented across the European Union and Asia, enabling utilization rates of over 90%. At the same time, in Ukraine, the processing level remains 20–30%, indicating the need to introduce innovative technologies and modernize production.

It should be noted that the results regarding reductions in biochemical oxygen demand and fat content after processing are consistent with the ecological studies by Park et al. (2001), which emphasize the importance of integrated approaches to waste disposal to reduce anthropogenic loads. The reduction of pollution levels by more than 20 times confirms the effectiveness of the proposed technological solutions. However, it is necessary to consider the limitations posed by high humidity and the variability in fatty waste composition. As Androshchuk & Holembovska (2025) point out, preliminary preparation of raw materials is a critically important stage that affects the stability of the process and the quality of the final product. In this regard, a promising direction is the development of combined technologies that combine mechanical, chemical, and biotechnological processing methods. Thus, the study's results confirm that the most effective approach is the integrated processing of fatty waste, combining trancesterification, bioconversion, and the isolation of bioactive components. This aligns with current trends in bioeconomy development and supports the transition to sustainable production systems. Further research should focus on optimizing technological parameters, reducing energy consumption, and expanding the range of processed products.

Further research should focus on the development and justification of energy-efficient integrated technologies for processing fat-containing waste, accounting for their physicochemical heterogeneity. Special attention should be paid to the development of combined processes using rationalization of technological processes (vibromechanical mixing, cavitation, and ultrasonic treatment), which increase lipid extraction efficiency and reduce energy consumption.

A promising direction is the improvement of two-stage technologies for the conversion of raw materials with high free fatty acid content, particularly by optimizing the conditions of acid esterification and subsequent transesterification. It is also important to study the kinetics of the processes and develop mathematical models that predict biodiesel yield as a function of raw material parameters and processing conditions.

Special attention should be paid to the development of biotechnological processing methods, in particular the use of enzymatic catalysts for the selective synthesis of high-value-added products (ω-3 concentrates, functional ingredients). In parallel, it is necessary to explore the possibilities of integrated use of by-products (glycerol, protein residues) in biotechnological and energy processes.

It is also relevant to conduct systematic life cycle studies (LCA) to assess the environmental and economic efficiency of various technological solutions in Ukrainian conditions. This will allow us to substantiate the feasibility of implementing circular recycling models and adapt best European practices to domestic conditions.

## Conclusion

The analysis of scientific and practical approaches to processing fat-containing waste from the fish processing industry enables us to formulate general conclusions. Fat-containing waste is a valuable secondary resource with high energy and biochemical potential; provided that the raw material is properly prepared, the extraction yield of target products reaches 95%. At the same time, the increased humidity and instability of such waste require effective methods of dehydration and stabilization. It has been established that the most effective are combined technological schemes for waste processing that combine chemical and physical-mechanical methods. It has been proven that one of the promising methods for processing fish waste is the production of diesel biofuel, with a yield of 95%.

The use of ultrasound, cavitation, and vibromechanical treatment increases fat extraction and reduces process time. Biotechnological methods are promising for preserving biologically active components but require further optimization. It was determined that biotechnological methods are promising for preserving biologically active components, and the main parameters (temperature, molar ratio of reagents, catalyst concentration, humidity, and acid number of raw materials) significantly affect the processing efficiency.

The assessment of environmental efficiency confirmed that processing fatty waste results in a significant reduction in environmental impact, particularly a 80% reduction in greenhouse gas emissions and a reduction in the volume of organic waste. The most environmentally appropriate are integrated technologies that provide comprehensive utilization of raw materials and the production of renewable energy.

Summarizing the results, it can be stated that fatty waste from the fish processing industry is a strategic resource for the development of bioenergy and food technologies, and the effective use of these technologies is an important direction for increasing resource conservation and environmental safety.

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## References

Androshchuk, O., & Holembovska, N. (2025). Analysis of the current state of the Ukrainian fish market. Human and Nation's Health, 21–36.

Archana, K., Visckram, A. S., Senthil Kumar, P., Manikandan, S., Saravanan, A., & Natrayan, L. (2024). A review on recent technological breakthroughs in anaerobic digestion of organic biowaste for biogas generation: Challenges towards sustainable development goals. Fuel, 358, 130298.

Bal-Prylypko, L., Danylenko, S., Mykhailova, O., Nedorizanyuk, L., Bovkun, A., Slobodyanyuk, N., Omelian, A., & Ivaniuta, A. (2024). Influence of starter cultures on microbiological and physical-chemical parameters of dry-cured products. Potravinarstvo Slovak Journal of Food Sciences, 18, 313–330.

Bal-Prylypko, L., Nikolaenko, M., Stepasyuk, L., Cherednichenko, O., & Lialyk, A. (2022). Forecasting the price of pork sales in agricultural enterprises. Agricultural and Resource Economics, 8(4), 170–187.

Bhattacharya, A., Chowdhury, S., Ikbal, A., Murmu, P., & Nath, S. (2022). Fish processing wastes: Environmental impacts and mitigation measures. Indian Journal of Animal Health, 61(2), 67–82.

Cheliadyn, L., Ribun, V., & Cheliadyn, V. (2020). Technological and environmental aspects of improving the biodiesel production from vegetable oils. Ecological Safety and Balanced Use of Resources, 11(2), 83–91.

Chen, B., Zheng, D., Xu, R., Leng, S., Han, L., Zhang, Q., Liu, N., Dai, C., Wu, B., Yu, G., & Cheng, J. (2022). Disposal methods for used passenger car tires: One of the fastest-growing solid wastes in China. Green Energy and Environment, 7(6), 1298–1309.

Dahiya, A. (2020). Cutting-edge biofuel conversion technologies to integrate into petroleum-based infrastructure and integrated biorefineries. In: Dahiya, A. (Ed.). Bioenergy. Biomass to biofuels and waste to energy. Second edition. Academic Press. Pp. 649–670.

Desai, A., Brennan, M., Gangan, S., & Brennan, C. (2021). Utilization of fish waste as a value-added ingredient: Sources and bioactive properties of fish protein hydrolysate. In: Galanakis, C. M. (Ed.). Sustainable fish production and processing. Academic Press. Pp. 203–225.

Eldiehy, K. S., Daimary, N., Borah, D., Sarmah, D., Bora, U., Mandal, M., & Deka, D. (2022). Towards biodiesel sustainability: Sweet potato leaf waste as a green, heterogeneous catalyst for biodiesel production from microalgal oil and waste cooking oil. Industrial Crops and Products, 187, 115467.

Elvines, D. M., MacLeod, C. K., Ross, D. J., Hopkins, G. A., & White, C. A. (2024). Fate and effects of fish farm organic waste in marine systems: Advances in understanding using biochemical approaches with implications for environmental management. Reviews in Aquaculture, 16(1), 66–85.

Giosuè, A., Calabrese, I., Lupoli, R., Riccardi, G., Vaccaro, O., & Vitale, M. (2022). Relations between the consumption of fatty or lean fish and risk of cardiovascular disease and all-cause mortality: A systematic review and meta-analysis. Advances in Nutrition, 13(5), 1554–1565.

Heidari, M. G., & Rezaei, M. (2022). Extracted pepsin from trout waste and an ultrasound-promoted method for green recovery of fish collagen. Sustainable Chemistry and Pharmacy, 30, 100854.

Holembovska, N., Slobodianiuk, N., & Israelian, V. (2021). Improvement of technology of fish semi-finished products with addition of non-conventional raw materials. Animal Science and Food Technology, 12(2), 14–23.

Jaiswal, K. K., Dutta, S., Banerjee, I., Jaiswal, K. S., Renuka, N., Ratha, S. K., & Jaiswal, A. K. (2024). Valorization of fish processing industry waste for biodiesel production: Opportunities, challenges, and technological perspectives. Renewable Energy, 220, 119601.

Kovalenko, B., Kovalenko, V., Sharylo, D., Polishchuk, N., Korzh, O., & Kirakosian, A. (2021). Growth and survival of clarias catfish (*Clarias gariepinus* B., 1822) at different stages of cultivation with the addition of "Chiktonik" to the fodder. Animal Science and Food Technology, 12(4), 26–37.

Liu, Z., Luo, Y., Ren, J., Yang, L., Li, J., Wei, Z., He, Y., Wang, J., Li, R., He, L., Mu, X., Huang, Y., Song, H., Hu, X., & Peng, X. (2021). Association between fish oil supplementation and cancer risk according to fatty fish consumption: A large prospective population-based cohort study using UK Biobank. International Journal of Cancer, 150(4), 562–571.

Loan, T. T., Trang, D. T. Q., Huy, P. Q., Ninh, P. X., & Van Thuoc, D. (2022). A fermentation process for the production of poly (3-hydroxybutyrate) using waste cooking oil or waste fish oil as an inexpensive carbon substrate. Biotechnology Reports, 33, e00700.

Mamat, M. N. I. B., Abdul Rahman, H., Mohd Razali, N. S., Syed Hussain, S. S., Kasim, K. F., & Sofian-Seng, N.-S. (2025). A review on fish oil extraction from fish by-product as sustainable practices and resource utilization in the fish processing industry. Sains Malaysiana, 54(1), 3627–3636.

Monika, Banga, S., & Pathak, V. V. (2023). Biodiesel production from waste cooking oil: A comprehensive review on the application of heterogeneous catalysts. Energy Nexus, 10, 100209.

Mushtruk, M., Mushtruk, N., Slobodyanyuk, N., Vasyliv, V., & Zheplinska, M. (2024). Enhanced energy independence: Converting animal fat into biodiesel. International Journal of Environmental Studies, 81(1), 134–144.

Mushtruk, N. (2025). Comparative analysis of pectin-containing paste properties using artificial intelligence. Human and Nation's Health, 3(3), 63–79.

Mushtruk, M. M., Chuiuk, R. V., Mushtruk, N. M., Vasyliv, V. P., Slobodyanyuk, N. M., Rudyk, Y. M., & Gruntovskyi, M. S. (2025). Raw material base for the production of food and pharmacological glycerin. Regulatory Mechanisms in Biosystems, 16(2), e25057.

Osman, A. I., Nasr, M., Farghali, M., Rashwan, A. K., Abdelkader, A., Al-Muhtaseb, A. H., Ihara, I., & Rooney, D. W. (2024). Optimizing biodiesel production from waste with computational chemistry, machine learning and policy insights: A review. Environmental Chemistry Letters, 22(3), 1005–1071.

Park, E., Enander, R., Barnett, S. M., & Lee, C. (2001). Pollution prevention and biochemical oxygen demand reduction in a squid processing facility. Journal of Cleaner Production, 9(4), 341–349.

Pasha, M. K., Dai, L., Liu, D., Guo, M., & Du, W. (2021). An overview of process design, simulation, and sustainability evaluation of biodiesel production. Biotechnology for Biofuels, 14, 129.

Pinheiro, C. T., Quina, M. J., & Gando-Ferreira, L. M. (2021). Management of waste lubricant oil in Europe: A circular economy approach. Critical Reviews in Environmental Science and Technology, 51(18), 2015–2050.

Pleissner, D., Schönfelder, S., Händel, N., Dalichow, J., Ettinger, J., Kvangarsnes, K., & Cropotova, J. (2023). Heterotrophic growth of *Galdieria sulphuraria* on residues from aquaculture and fish processing industries. Bioresource Technology, 384, 129281.

Rajabimashhadi, Z., Gallo, N., Salvatore, L., & Lionetto, F. (2023). Collagen derived from the fish industry: progress and challenges. Polymers, 15(3), 544.

Rana, S., Singh, A., Surasani, V. K. R., Kapoor, S., Desai, A., & Kumar, S. (2023). Fish processing waste: A novel source of non-conventional functional proteins. International Journal of Food Science and Technology, 58(5), 2637–2644.

Rathod, N. B., Nirmal, N. P., Pagarkar, A., Özogul, F., & Rocha, J. M. (2022). Antimicrobial impacts of microbial metabolites on the preservation of fish and fishery products: A review with current knowledge. Microorganisms, 10(4), 773.

Reza, M. S., Azad, A. K., Abu Bakar, M. S., Karim, M. R., Sharifpur, M., & Taweekun, J. (2022). Evaluation of thermochemical characteristics and pyrolysis of fish processing waste for renewable energy feedstock. Sustainability, 14(3), 1203.

Rigueto, C. V. T., de Oliveira, R., Gomes, K. S., Alessandretti, I., Nazari, M. T., Rosseto, M., & Dettmer, A. (2023). From waste to value-added products: A review of opportunities for fish waste valorization. Environmental Quality Management, 33(1), 203–221.

Santos, H. O., May, T. L., & Bueno, A. A. (2023). Eating more sardines instead of fish oil supplementation: Beyond omega-3 polyunsaturated fatty acids, a matrix of nutrients with cardiovascular benefits. Frontiers in Nutrition, 10, 1107475.

Shanina, O., Minchenko, S., Gavrysh, T., Sukhenko, Y., Sukhenko, V., Vasyliv, V., Miedviedieva, N., Mushtruk, M., Stechyshyn, M., & Rozbytska, T. (2020). Substantiation of basic stages of gluten-free steamed bread production and its influence on quality of finished product. Potravinarstvo Slovak Journal of Food Sciences, 14, 189–201.

Sher, F., Smječanin, N., Hrnjić, H., Karadža, A., Omanović, R., Šehović, E., & Sulejmanović, J. (2024). Emerging technologies for biogas production: A critical review on recent progress, challenges and future perspectives. Process Safety and Environmental Protection, 188, 834–859.

Smaisim, G. F., Prabu, N. M., & Abed, A. M. (2022). Synthesis of biodiesel from fish processing waste by nano magnetic catalyst and its thermodynamic analysis. Case Studies in Thermal Engineering, 35, 102115.

Statkevych, O. I., Kolomiiets, Y. V., Holembovska, N. V., Israelian, V. M., Babych, O. A., Slobodyanyuk, N. M., Babytskiy, A. I., & Statkevych, A. O. (2024). Effects of nutrient medium on various-age larvae of *Hermetia illucens* (Diptera, Stratiomyidae). Regulatory Mechanisms in Biosystems, 15(4), 907–911.

Subhash, G. V., Rajvanshi, M., Kumar, G. R. K., Sagaram, U. S., Prasad, V., Govindachary, S., & Dasgupta, S. (2022). Challenges in microalgal biofuel production: A perspective on techno-economic feasibility under biorefinery stratagem. Bioresource Technology, 343, 126155.

Suzihaque, M. U. H., Syazwina, N., Alwi, H., Ibrahim, U. K., Abdullah, S., & Haron, N. (2023). A sustainability study of the processing of kitchen waste as a potential source of biofuel: Biodiesel production from waste cooking oil (WCO). Materials Today: Proceedings, 63, S484-S489.

Tucki, K., Orynycz, O., Wasiak, A., Świć, A., Mruk, R., & Botwińska, K. (2020). Estimation of carbon dioxide emissions from a diesel engine powered by lignocellulose-derived fuel for better management of fuel production. Energies, 13(3), 561.

Vlasenko, M., Holembovska, N., Bal, I., Kononenko, R., & Lebskyi, S. (2026). State and prospects of fisheries in the world and in Ukraine. Human and Nation's Health, 4(1), 110–123.

Yang, H., Wang, H., Huang, M., Cao, G., Tao, F., Shen, Q., Zhou, G., & Yang, H. (2022). Repurposing fish waste into gelatin as a potential alternative for mammalian sources: A review. Comprehensive Reviews in Food Science and Food Safety, 21(2), 942–963.

Yari, N., Mostafaei, M., Naderloo, L., & Safieddin Ardebili, S. M. (2019). Energy indicators for microwave-assisted biodiesel production from waste fish oil. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44, 2208–2219.