Sains Malaysiana 54(1)(2025): 165-174
http://doi.org/10.17576/jsm-2025-5401-13

A Review on Fish Oil Extraction from Fish by-Product as Sustainable Practices and Resource Utilization in the Fish Processing Industry

(Tinjauan Mengenai Pengekstrakan Minyak Ikan daripada Produk Sampingan Ikan sebagai Amalan Mampan dan Penggunaan Sumber dalam Industri Pemprosesan Ikan)

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Received: 12 August 2024/Accepted: 2 September 2024

ABSTRACT

The fish processing industry generates significant by-products, such as viscera, skin, bones, and heads, which are valuable for producing food, medicinal products, energy, and industrial feedstock. Fish oil, rich in omega-3 polyunsaturated fatty acids like eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), is widely used in nutritional supplements and other applications. Among these by-products, fish viscera contain the highest concentration of oil, making them an ideal target for extraction due to their cost-effectiveness and environmental benefits. Extracting oil from fish by-product helps reduce environmental pollution and promotes sustainable practices by fully utilizing fish resources. This holistic approach contributes to waste reduction and resource efficiency in the fish processing industry. By incorporating sustainable principles into extraction processes - such as using environmentally friendly solvents, implementing efficient solvent recovery systems, and ensuring compliance with environmental regulations - companies can enhance the sustainability of their operations while extracting valuable components. As demand for fish-based food products rises, effective extraction of fish oil and fishmeal from by-products becomes increasingly important. Various extraction methods, including physical, chemical, and biological approaches, are essential for separating solids, oil, and water to recover valuable components like EPA and DHA. Optimizing these processes and combining different methods can achieve high concentrations of polyunsaturated fatty acids (PUFAs) in fish oil, ranging from 65% to 80%. Emphasizing maximum PUFA content highlights the potential to enhance the quality and nutritional value of fish oil extracted from by-products while advancing sustainability in the fish processing industry.

Keywords: Circular economy; extraction; fish by-products; fish oil; viscera

ABSTRAK

Industri pemprosesan ikan menghasilkan banyak hasil sampingan seperti visera, kulit, tulang dan kepala yang bernilai untuk pengeluaran makanan, produk perubatan, tenaga dan bahan mentah industri. Minyak ikan, kaya dengan asid lemak tak tepu omega-3 seperti asid eicosapentaenoic (EPA) dan asid dokosaheksaenoik (DHA) banyak digunakan dalam makanan tambahan nutrisi dan aplikasi lain. Antara hasil sampingan ini, visera ikan mengandungi kepekatan minyak tertinggi, menjadikannya sasaran utama untuk pengekstrakan kerana kos yang berkesan dan manfaat persekitarannya. Pengekstrakan minyak daripada hasil sampingan ikan membantu mengurangkan pencemaran alam sekitar dan mempromosikan amalan mampan dengan memanfaatkan sepenuhnya sumber ikan. Pendekatan holistik ini menyumbang kepada pengurangan sisa dan kecekapan sumber dalam industri pemprosesan ikan. Dengan menggabungkan prinsip mampan dalam proses pengekstrakan seperti menggunakan pelarut mesra alam, melaksanakan sistem pemulihan pelarut yang cekap dan memastikan pematuhan terhadap peraturan alam sekitar, syarikat boleh meningkatkan kemampanan operasi mereka sambil mengekstrak komponen yang bernilai. Apabila permintaan terhadap produk makanan berasaskan ikan meningkat, pengekstrakan minyak ikan dan tepung ikan yang berkesan daripada hasil sampingan menjadi semakin penting. Pelbagai kaedah pengekstrakan, termasuk pendekatan fizikal, kimia dan biologi, adalah penting untuk memisahkan pepejal, minyak dan air bagi memulihkan komponen berharga seperti EPA dan DHA. Mengoptimumkan proses ini dan menggabungkan kaedah yang berbeza boleh mencapai kepekatan tinggi asid lemak tak tepu (PUFA) dalam minyak ikan, antara 65% hingga 80%. Menekankan kandungan PUFA maksimum menunjukkan potensi untuk meningkatkan kualiti dan nilai pemakanan minyak ikan yang diekstrak daripada hasil sampingan sambil memajukan kemampanan dalam industri pemprosesan ikan.

Kata kunci: Ekonomi membulat; minyak ikan; pengekstrakan; produk sampingan ikan; visera

INTRODUCTION

The fish processing industry generates substantial solid and liquid by-products, which differ in composition depending on the species and processing methods. The fat content among fish species varies significantly, ranging from lean to high-fat types, influencing the lipid extraction potential from their by-products. Effective utilization of these by-products is critical to minimizing environmental impact and advancing toward a zero-waste approach (Alfio, Manzo & Micillo 2021; Kratky & Zamazal 2020; Thirukumaran et al. 2022).

Table 1 illustrates the fish oil yield extracted from the by-products of various fish species, highlighting the potential value of these underutilized materials. By employing green approaches and innovative extraction methods, fish by-products can be transformed into high-value products for industries such as pharmaceuticals, nutraceuticals, animal feed, and biofuels (Afreen & Ucak 2020; Mutalipassi et al. 2021; Ozogul et al. 2021, Vázquez et al. 2020a). To optimize lipid extraction, it is essential to consider the specific composition of different fish species and tissues involved, with the goal of producing high-quality fish oil

TABLE 1. Oil yield from different by-products of various fish species using various extraction technique

Fish type	Fish by-products	Extraction technique used	Yield of extracted oil (%)	Reference
Nile tilapia	Viscera	Physical extraction	48%	Mota et al. (2019)
Tilapia	Viscera	Wet rendering	21.6%	Purnamayati et al. (2023)
Common carp (*Cyprinus carpio* L.)	Viscera	Physical (boiling) chemical (acid fermentation)	57.14% 35.71%	Salih, Najim & Al-Noor (2021)
Red tilapia (*Oreochromis* sp.)	Viscera	Direct heating, direct heating with freezing, ultrasound assisted solvent extraction	92%, 61%, 55%	Arias et al. (2022)
Bighead Carp (*Hypophthalmichthys nobilis*)	Scales	Ultrasonic assisted extraction	46.67 %	Tu et al. (2015)
Common carp (*Cyprinus carpio* L.)	Viscera	Infrared-assisted oil extraction	23.73%	Al-Hilphy et al. (2020)
Common carp (*Cyprinus carpio* L.)	Viscera	Ohmic heating	26.66%	Al-Hilphy et al. (2022)
Yellowfin tuna (*Thunnus albacares*)	Head	Ultra-high-pressure pre-treatment + enzymatic hydrolysis	67%	Zhang et al. (2021)
Indian Mackerel (*Restrelliger kanagurta*)	Skin, viscera, heads	Soxhlet extraction	53.2 %	Sahena et al. (2010)
Aji-aji fish (*Seriola nigrofasciata*)	Mix waste	Soxhlet extraction	18.3 %	Rishitha et al. (2020)
Salmon by-products	Gut, head, frame	Enzymatic extraction	80.01 % (gut), 59.92 % (head), 78.58 % (frame)	Carvalho et al. (2019)

rich in essential fatty acids like eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Al-Hilphy et al. 2022; Arias et al. 2022; Purnamayati et al. 2023; Rishitha et al. 2020; Salih, Najim & Al-Noor 2021). Fish oil serves as a primary source of long-chain polyunsaturated fatty acids (PUFAs) for human consumption, playing a vital role in promoting general health and well-being (Zubairi et al. 2021). However, as estimated by the Marine Ingredients Organization, approximately 75% of the annual global production of fish oil is still directed toward aquaculture feed formulation (Saleh, Wassef & Abdel-Mohsen 2022).

Fish by-products, including tails, frame bones, heads, viscera, fins, skin, and scales, are valuable resources that, if not utilized properly, can pose environmental burdens. Adopting green approaches is essential to address waste issues in the fish industry. By commercializing low-value fractions and producing high-value products for pharmaceuticals and nutraceuticals, the industry can move towards zero waste (Wan-Mohtar et al. 2023). The use of fish by-products can be tailored to meet macronutrient needs, with fat separation for PUFA-oil supplements or conversion into biofuels and fertilizers, while protein-rich fractions are used in animal feed production (Pinela et al. 2022; Vázquez et al. 2020b).

FISH OIL EXTRACTION PROCESS

Fish oil extraction methods involve physical, chemical, and biological processes, each offering unique advantages and challenges. Physical methods, such as rendering, include homogenizing, heating, pressing, and filtering to extract oil from various fish by-products (Dave et al. 2024; Pudtikajorn & Benjakul 2020; Purnamayati et al. 2023). Chemical extraction methods often employ organic solvents, but these approaches raise concerns regarding toxicity and the potential loss of functional properties (Alfio, Manzo & Micillo 2021; Marsol-Vall et al. 2022). In contrast, biological methods, such as enzymatic hydrolysis, are increasingly favored for their lower environmental impact, making them greener and safer alternatives to traditional solvent extraction (Aitta et al. 2022; Marsol-Vall et al. 2022).

PHYSICAL METHOD FOR FISH OIL EXTRACTION

The physical extraction of fish oil, commonly known as rendering, is primarily aimed at obtaining oil rather than fishmeal. This method involves heating visceral organs with warm water, followed by separating solid residues from the liquor. Rendering can be done either wet or dry (Dave et al. 2024; Djamaludin et al. 2023; Pudtikajorn & Benjakul 2020; Purnamayati et al. 2023; Suseno et al. 2021). The purification of the resulting liquid, which contains water, oil, and dry materials, is typically achieved through separation based on specific gravities. Mechanical pressing and centrifugation may be used to extract additional oil from the residues. Mechanical pressing and centrifugation can be employed to extract additional oil from the remaining residues. However, the oil obtained through rendering still requires several refining steps, including degumming, deacidification, bleaching, and deodorization, to ensure it meets quality standards (Marsol-Vall et al. 2022).

Research has indicated that wet rendering, particularly when applied to tuna (*Thunnus albacares*) heads, yields higher oil extraction percentages compared to methods like acid silage and solvent extraction (Nazir, Diana & Sayuti 2017). The method has been preferred due to its high PUFA content of up to 44% in the extracted oil. This method is often preferred due to the high polyunsaturated fatty acid (PUFA) content, reaching up to 44% in the extracted oil. Additional studies on tuna heads and various fish species have further demonstrated the effectiveness of wet rendering in producing fish oil rich in PUFA. For example, Pudtikajorn and Benjakul (2020) reported that oil extracted from skipjack tuna (ST) eyeballs using the wet rendering method at 121 °C resulted in all oil samples having a high PUFA content (40.46-41.00%).

The wet rendering method for fish oil extraction is effective in yielding a relatively high quantity of oil but faces challenges in terms of oil quality due to the high peroxide value caused by oxidation during the heat treatment process (Djamaludin et al. 2023). The denaturation of proteins and the release of free radicals due to pre-cooking can hinder oil release and increase oxidation rates. The resulting high peroxide value can negatively impact the quality of fish oil extracted using the wet rendering technique (Jamshidi et al. 2020). This issue is particularly critical for oils rich in omega-3 PUFAs, as their multiple double bonds make them highly susceptible to oxidation, leading to the formation of lipid oxidation products that cause off-flavours and diminish the oil's value.

To address these challenges, researchers are exploring methods to improve the oxidation stability of PUFA-enriched oils. By optimizing processing conditions and incorporating antioxidants, the fish processing industry can enhance the quality and shelf life of fish oil products, aligning with the growing demand for high-quality, health-conscious food options (Arab-Tehrany et al. 2012).

CHEMICAL METHODS FOR FISH OIL EXTRACTION

Chemical methods for fish oil extraction involve the use of various solvents and innovative techniques that can impact both efficiency and sustainability (Alfio, Manzo & Micillo 2021; Marsol-Vall et al. 2022). The choice of solvents is crucial, as it affects the environmental footprint of the process. By selecting environmentally friendly solvents with lower toxicity and reduced persistence, the industry can mitigate negative environmental effects. Additionally, recycling and reusing solvents not only minimize waste and reduce environmental impact but also offer cost savings and enhance sustainability. Efficient solvent recovery systems are crucial in decreasing the consumption of virgin solvents. Proper disposal of waste solvents and strict adherence to environmental regulations are essential to maintaining sustainability in fish oil extraction (Caruso et al. 2020; Marsol-Vall et al. 2022; Mgbechidinma et al. 2023; Wang et al. 2021).

The solvent extraction of fish oil typically employs organic solvents such as hexane, benzene, cyclohexane, acetone, and chloroform to dissolve lipids (Mokhtar et al. 2021). Hexane is particularly popular for large-scale extraction due to its effectiveness; however, its environmental impact necessitates careful management (Iberahim & Tan 2020). Solvent selection depends on solubility, recovery ease, economic viability, toxicity, availability, and reusability. Solvent selection criteria include solubility, ease of recovery, economic viability, toxicity, availability, and reusability. Effective solvents must disrupt lipid interactions within tissue matrices, a process that can be enhanced by adjusting pH or ionic strength. Enzyme deactivation is sometimes required to improve lipid extraction efficiency. Despite its efficacy, traditional solvent extraction presents challenges, such as the generation of substantial waste solvents, high recycling costs, safety concerns, and potential product contamination (Alfio, Manzo & Micillo 2021; Marsol-Vall et al. 2022).

One advanced variation of solvent extraction is Accelerated Solvent Extraction (ASE), an automated method that uses low-boiling solvents under high pressure to enhance extraction efficiency and reduce waste. ASE eliminates manual sample preparation, accelerates the process, and improves reproducibility, though further research is needed for large-scale applications (Chen et al. 2020; Wang et al. 2021). Another method, acid-alkali-aided extraction, employs acids or alkalis to dissolve proteins and isolate fish oils. While effective, this method risks extracting non-lipid compounds, complicating fatty acid profiling. Careful process control is necessary to minimize chemical degradation (Hossain 2022; Sivaranjani et al. 2024).

Recent advancements in chemical extraction methods have focused on improving sustainability, including the use of Supercritical Fluid Extraction (SCFE) and the integration of physical pre-treatments such as microwave or ultrasound techniques. Microwave-Assisted Extraction (MAE) leverages microwave energy to heat solvents, enhancing lipid yields and reproducibility while reducing solvent use and energy consumption. MAE offers faster extraction rates and operates at lower temperatures, thus minimizing environmental impact compared to traditional methods. Innovations such as microwave-assisted Soxhlet extraction further reduce extraction time and energy consumption, contributing to sustainability (Keskin Çavdar et al. 2023; Pinela et al. 2022).

Ultrasound-Assisted Extraction (UAE) relies on the cavitation effect of ultrasonic waves, which facilitates extraction and mass transport by disrupting cell walls (Mokhtar et al. 2024). However, UAE has yet to be applied on an industrial scale for fish oil extraction (Hashim et al. 2022; Keskin Çavdar et al. 2023; Putri et al. 2023). Supercritical Fluid Extraction (SCFE), which uses supercritical CO_2 as an environmentally friendly solvent (Isa, Sofian-Seng & Wan Mustapha 2021), extracts fish oils with minimal toxic residue. SCFE is particularly suitable for thermally sensitive products, offering rapid extraction and high purity. It is effective across various fish by-products, although it may be less efficient in extracting heavy metals (Franklin et al. 2020; Jamalluddin et al. 2022; Melgosa, Sanz & Beltrán 2021). Membrane-coupled SC-CO_2 extraction combines membrane technology with SC-CO_2 to separate triglycerides, enhancing product purity while reducing energy requirements for CO_2 recycling (Chozhavendhan et al. 2020). This technique is valuable for producing high-quality fish oils for various industries, supporting both sustainability and product quality.

To further enhance sustainability in chemical extraction, the fish oil industry can focus on adopting green solvents by prioritizing low-toxicity, biodegradable options to minimize environmental impact. Implementing efficient solvent recovery and recycling systems can significantly reduce waste and resource consumption. Innovations like MAE and ASE also help lower energy use, thereby reducing the overall carbon footprint. Proper waste management, including responsible disposal and compliance with environmental regulations, ensures sustainable operations. Additionally, a new class of non-conventional solvents known as natural deep eutectic solvents (NADES) has emerged. These solvents, often derived from choline chloride (ChCl), carboxylic acids, and other hydrogen-bond donors like urea, citric acid, succinic acid, and glycerol, share similar properties with ionic liquids but are less expensive to produce, less toxic, and frequently biodegradable (Chemat et al. 2017). By adopting these strategies, the fish oil industry can advance sustainable practices, balancing efficiency with environmental responsibility.

BIOLOGICAL METHODS FOR FISH OIL EXTRACTION

The extraction of fish oil using biological methods, such as enzymatic hydrolysis and fermentation, presents promising approaches that align well with sustainability goals. These methods leverage natural processes to efficiently extract valuable lipids while minimizing environmental impact. Enzymatic hydrolysis utilizes protease enzymes to extract fish oil by breaking down proteins into fatty acids or triglycerides. This process results in the formation of distinct layers: oil, emulsion, protein substrate, and sludge. Although enzymatic hydrolysis is a greener alternative to chemical methods, it can result in oil-lipid emulsions with high lipid content but reduced oil quality. The efficiency of enzymatic hydrolysis can be enhanced by using external enzymes and optimizing conditions such as pH and enzyme activity. Enzymes sourced from animals, plants, or microbes, like the Alcalase enzyme from *Bacillus subtilis* (Garofalo et al. 2023) or *Bacillus licheniformis* (Araujo et al. 2021), have demonstrated improved lipid recovery.

Table 2 shows enzymatic hydrolysis extraction of oil from different fish by-products samples from several prior research. For instance, studies by Liu et al. (2021) successfully recovered up to 26% of lipids through enzymatic extraction from by-products of farmed Atlantic salmon, including heads, frames, and viscera. Despite these benefits, challenges remain, such as the cost of enzymes, extended reaction times, and the formation of oil-water emulsions. Research by Liu and Dave (2022) addresses the issue of enzyme reuse and cost by developing a method to immobilize Alcalase, allowing it to be reused for at least three batches without significant decreases in oil yield, demonstrating its potential for effective and consecutive oil extraction from salmon by-products. Another circular economy approach generation of using the fish viscera in order to extract the proteolytic enzyme has been reported by Borges et al. (2023), as a sustainable approach to obtain enzymes. Proper storage conditions and monitoring are essential to maintain the quality of the extracted oil. Enzymatic treatment is a promising

TABLE 2. Enzymatic hydrolysis extraction of oil from different fish by-products samples

Fish-by products	Enzyme	Fish oil yield (%)	Reference
Farmed Atlantic salmon - heads, frames and viscera	Alcalase, Flavourzyme and SEBPro	26	Liu et al. (2021)
Baltic herring (*Clupea harengus* membras) - heads, fins, tails and viscera	Alcalase, Neutrase and Protamex	48-65	Aitta et al. (2021)
Yellowfin tuna (*Thunnus albacares*) heads	Ultra-high pressure with trypsin, bromelain, or papain	17 - 68	Zhang et al. (2021)
Yellowfin tuna (*Thunnus albacares*) viscera	Alcalase	15- 81.4	Garofalo et al. (2023)
Atlantic mackerel processing residues without viscera	Alcalase	13.55	Bashiri et al. (2024)
Southern eagle ray (*Myliobatis goodei*) liver	Immobilized biocatalyst (Alcalase 2.4 L and Purazyme AS 60 L)	84-87	Morales et al. (2024)
Atlantic salmon (*Salmo salar*) by-products	Immobilized Alcalase on chitosan-coated magnetic nanoparticles	20.55	Liu & Dave (2022)
Medium-sized fsh heads (like salmon), skins, viscera, mangled muscles of fish, small fshes, as well as mollusks such as squid and mussels	Alcalase 2.4 L, Flavourzyme 1000 L, Neutrase 0.8 L, Pancreatic Trypsin 6.0 S and Protamex	55-75	Araujo et al. (2021)
Fish waste from marine mackerel (*Scomberomorus sinensis*), freshwater Crucian carp (*Carassius auratus*)	Alcalase	24-66.7	Mgbechidinma et al. (2023)

valorization method for the simultaneous extraction of oil, protein hydrolysates, and bioactive compounds from fish and fish by-products, provided these challenges are addressed (Araujo et al. 2020).

Post-fermentation refining processes, such as degumming, deacidification, decolorization, and deodorization, are necessary to ensure fish oil quality and prevent rancidity. Conversely, certain lactic acid bacteria (LAB) produce natural antioxidants that help prevent the oxidation of fatty acids. The addition of natural external antioxidants can also provide oxidation protection while offering health-promoting properties (Hrebień-Filisińska 2021). Additionally, fermentation improves the digestibility of proteins compared to those found in acid silage (Marsol-Vall et al. 2022).

Despite these challenges, fermentation offers significant advantages, including enhanced stability of fish oil and the production of high-quality silage for animal feed. The process is energy-efficient and preserves the nutritional value of fish oil, with lower investment and running cost, making it an economically viable and environmentally friendly method for fish oil production (Özyurt et al. 2019). Additionally, the process can be fine-tuned by terminating autolysis at a specific time to optimize outcomes (Sajib et al. 2022) (Table 3).

TABLE 3. Extraction of oil from different fish by-products via fermentation

Fish by-producrs	Fermentation parameters	Fish oil yield (%)	References
Herring (*Clupea harengus*) filleting co-products - mix of heads, frames, tails, skins, guts, and other intestinal organs	Ensilaged with formic acid up to 2 days	9.7	Sajib et al. (2022)
Saithe (*Pollachius virens*) viscera	Ensilaged with formic acid up to 3 days	16.5	Meidell et al. (2023)
Klunzinger's ponyfish ,Gibel carp	Silage inoculated with lactic acid bacteria cultures (*Lb. plantarum*, *Pd. acidilactici*, *Ent. gallinarum*, *Lb. brevis* and *Streptococcus* spp)	70 – 87.4	Özyurt et al. (2019)
Spotted sorubim (*Pseudoplatystoma corruscans*) and pacu (*Piaractus mesopotamicus*) fish viscera	Biological silages with *Lactobacillus rhamnosus*, *Bifidobacterium longum*, *Lactobacillus sakei*, *Lactobacillus brevis*, *Pediococcus acidilactici*, *Leuconostoc lactis*, *Lactobacillus casei*	Up to 55.9 unsaturated fatty acids	Bezerra & Fonseca (2023)
Rainbow trout viscera	Ensilaged with formic acid, lactic acid and propionic acid up to 30 days with *Lactobacillus plantarum*	19 – 28.5	Raeesi, Shabanpour & Pourashouri (2021)
Common carp viscera	Acid fermentation with acetic and citric acid	35.7	Salih, Najim & Al-Noor (2021)
Plaice (*Pleuronectes platessa*), sole (*Solea solea*), and flounder (*Platichthys flesus*), whiting (*Merlangius merlangus*)	Ensilaged with formic acid for 3 months	26-28.7 PUFA 16.4-19.2 EPA + DHA	van't Land, Vanderperren & Raes (2017)

CONCLUSION

Extracting fish oil from by-products offers a cost-effective and sustainable approach to obtaining valuable lipids. Unlike plant-based oil extraction, the process for fish oil is more complex due to the muscle-based lipid samples involved. The yield and purity of fish oil are significantly influenced by the chosen extraction method, making it crucial to select the most appropriate technique. The development of green technologies for producing oils rich in n-3 PUFAs from aquatic sources is an expanding area of research. While much of the focus has been on green strategies for extracting crude oil from raw materials, there has been less emphasis on refining these oils. Therefore, increased efforts should be directed toward recovering and valorizing these fractions.

Currently, a significant portion of fish oil is refined from crude oils produced as by-products of fish meal production. However, by optimizing enzymatic hydrolysis and fermentation processes, the fish processing industry can achieve high-quality fish oil production. These methods not only improve oil yield but also reduce environmental impact, thereby enhancing resource efficiency and contributing to a more sustainable industry.

ACKNOWLEDGEMENTS

We acknowledged the financial support from Universiti Kebangsaan Malaysia with the Research Grant of University (GUP-2018-1111). The highest appreciation is also extended to the laboratory officer at the Pilot Plant Laboratory and Innovative Centre for Confectionery Technology (MANIS), Science and Technology Faculty, Universiti Kebangsaan Malaysia, for the facilities provided to conduct the analysis of the study.

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