

Advancements in fermentation of fish by-products: A systematic review of omega-3 lipid extraction for sustainable aquaculture

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Abstract. Aquaculture is one of the fastest-growing food production sectors and a vital contributor to global nutrition security. A major challenge to its sustainability lies in the provision of long-chain omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), essential for fish growth, health, and reproduction. Conventional sources such as fishmeal and fish oil derived from wild fisheries are increasingly constrained by overfishing and environmental pressures, while fish processing generates 50–70% by-products rich in proteins, lipids, and bioactive compounds that remain underutilized. This systematic review synthesizes recent advancements in fermenting fish by-products for omega-3 lipid recovery and sustainable aquaculture applications. Following PRISMA guidelines, a comprehensive Scopus search (January 2015–July 2025) identified 90 records, of which seven empirical studies met the inclusion criteria. The included studies examined fermentation approaches, including lactic acid bacteria (LAB)-based silage, multi-microbial solid-state fermentation, submerged fermentation, and yeast–bacteria co-fermentation. The available evidence suggests that LAB fermentation consistently stabilized oils and preserved EPA/DHA, while multi-microbial systems enriched protein content and fatty acid profiles. In several cases, fermentation produced oils with high oxidative stability and increased omega-3 concentrations. Feeding trials demonstrated improvements in digestibility, antioxidant status, and fish health, though excessive inclusion impaired growth. Overall, fermentation emerges as a promising, eco-friendly, and economically viable strategy to valorize fish by-products, contributing to circular economy principles and sustainable resource use. Remaining challenges include optimizing process parameters, ensuring microbial safety, and validating large-scale applications. Future research should prioritize protocol standardization, techno-economic and life-cycle assessments, and integration of fermentation into biorefinery models to maximize recovery of high-value omega-3 lipids.

Keywords: eicosapentaenoic acid, docosahexaenoic acid, lactic acid bacteria, microbial silage.

Introduction. Aquaculture has rapidly expanded over the past decades and currently represents one of the fastest-growing sectors of global food production (Nie 2023). As the global population continues to grow, aquaculture is expected to play a crucial role in meeting the rising global demand for protein-rich foods, especially seafood (Pratama et al 2022). Central to the development and sustainability of aquaculture is the provision of high-quality nutrients, particularly omega-3 polyunsaturated fatty acids (PUFAs), which include eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Omega-3 fatty acids are essential for the optimal growth, reproduction, and overall health of farmed aquatic organisms due to their critical roles in cell membrane integrity, immune function, and stress response regulation (Varga et al 2020). Moreover, omega-3-rich fish products significantly contribute to human nutrition, promoting cardiovascular health, reducing inflammation, and supporting cognitive function (Ibrahim et al 2022).

Currently, global demand for omega-3 continues to rise significantly, driven by increased public awareness of their health benefits and a rapidly expanding aquaculture

industry (Glencross et al 2025). Nevertheless, traditional sources such as marine fish oils and fishmeal derived from wild-captured fisheries are becoming increasingly limited due to overfishing, climate change, and ecosystem degradation (Mulyasari et al 2020). Consequently, there is an urgent need to identify and develop alternative, sustainable sources of omega-3 fatty acids to support the continued expansion and environmental sustainability of aquaculture systems.

Fish processing generates substantial quantities of by-products, including heads, skins, viscera, bones, and scales, which often remain underutilized or discarded as waste (Muzaifa et al 2012). These by-products constitute approximately 50-70% of the initial fish biomass, representing significant loss of valuable nutrients and posing environmental challenges associated with waste disposal (Zhang et al 2023). However, fish by-products contain high levels of bioactive compounds, including omega-3 fatty acids, proteins, minerals, and antioxidants, making them an excellent potential resource for value-added product development (Ozogul et al 2021). More broadly, recent Indonesian natural-product research also supports the value of locally available biological resources as experimentally validated materials, reinforcing the importance of systematic valorization of underutilized bioresources (Sholih et al 2025).

Harnessing fish by-products as an alternative source of omega-3 lipids is aligned with principles of circular economy and sustainability. Through effective recycling and valorization strategies, these by-products can not only reduce waste and environmental pollution but also enhance resource efficiency and economic profitability in the seafood industry (Rashid et al 2018). Recent research suggests that employing biotechnological approaches, such as fermentation, could significantly increase the recovery and availability of omega-3 lipids from fish by-products (Siddiqui et al 2025). Fermentation has emerged as a promising biotechnological method for the extraction and enrichment of omega-3 fatty acids from fish by-products. The fermentation process utilizes microbial enzymes and metabolic pathways to break down complex biological matrices, improving the bioavailability and yield of omega-3 fatty acids (Xia et al 2020). Compared to conventional chemical extraction methods, fermentation is considered more environmentally friendly, energy-efficient, and economically feasible, making it a viable and sustainable alternative (Agrawal et al 2023). Different fermentation methods, such as solid-state fermentation (SSF) and submerged fermentation (SmF), have been explored for their effectiveness in extracting omega-3 lipids (Asadi et al 2015). SSF, involving microorganisms grown on a solid substrate without free-flowing water, is advantageous due to its lower water usage, reduced wastewater generation, and high yield of bioactive compounds (Verduzco-Oliva & Gutierrez-Urbe 2020). Conversely, SmF utilizes liquid media, offering more controlled conditions for microbial growth and enzyme production, although it may entail higher operational costs and complexity in downstream processing (Hindra et al 2021). Each fermentation approach presents unique advantages and challenges regarding omega-3 lipid extraction efficiency, process scalability, and environmental impact.

Despite the evident potential of fermentation technologies, a comprehensive review specifically addressing advancements in fermentation processes for omega-3 extraction from fish by-products remains limited. Existing studies often focus narrowly on individual fermentation techniques or specific fish species, with less attention devoted to systematically comparing different fermentation methods and assessing their sustainability in aquaculture contexts (Siddik et al 2018a). Therefore, there is a clear need for a systematic review that synthesizes recent advancements, compares the effectiveness of various fermentation technologies, and evaluates their practical applications in sustainable aquaculture systems.

This systematic literature review aims to bridge these research gaps by identifying, analyzing, and critically evaluating recent advancements in the fermentation of fish by-products specifically for omega-3 lipid extraction. The primary objective of this review is to provide comprehensive insights into the efficiency, sustainability, and potential economic and environmental benefits of fermentative approaches. Additionally, this review addresses the challenges and limitations associated with current fermentation technologies, aiming to identify opportunities for improving process efficiency and supporting the transition towards more sustainable aquaculture practices.

Material and Method. Systematic literature reviews (SLR) aim to answer a set of research questions that help identify current gaps, contrast hypotheses, or expand the scope of knowledge in a specific area (van Dinter et al 2021). By providing a comprehensive synthesis of existing evidence, systematic reviews enable stakeholders, practitioners, and researchers to make informed decisions and guide future studies to address identified gaps (Johnson et al 2022).

This review was conducted to evaluate advancements in the fermentation of fish by-products for omega-3 lipid extraction in the context of sustainable aquaculture. The review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which provide a structured, evidence-based framework to ensure transparency, accuracy, and scientific rigor throughout the process (Page et al 2021a; Page et al 2021b). For the study, we proposed the research questions (RQs) indicated in Table 1 with their description. Figure 1 depicts the PRISMA flow diagram.

Table 1

RQs for the SLR with their description

<i>RQs</i>	<i>Description</i>
What are the recent advancements in fermentation technologies used for fish by-products, specifically in the context of omega-3 lipid extraction?	This question aims to identify the latest developments in fermentation techniques applied to fish by-products for extracting omega-3 lipids. The focus is on technologies that improve sustainability in aquaculture.
How do different fermentation methods (e.g., solid-state fermentation, liquid fermentation) compare in terms of efficiency and effectiveness in extracting omega-3 lipids from fish by-products?	This question seeks to compare and evaluate the performance of various fermentation methods, with an emphasis on how they affect omega-3 lipid extraction from fish by-products.
What are the environmental and economic benefits of using fermented fish by-products as a source of omega-3 in sustainable aquaculture?	This question investigates the environmental and economic impacts of using fermented fish by-products, particularly in terms of omega-3 production, to support sustainable practices in aquaculture.
What are the potential challenges and limitations in the current applications of fermentation for omega-3 extraction in aquaculture?	This question identifies and explores the challenges and limitations that hinder the widespread application of fermentation technologies for omega-3 extraction in aquaculture.
How can fermentation of fish by-products contribute to improving the efficiency and sustainability of omega-3 production in aquaculture?	This question examines the role of fermentation in enhancing the efficiency and sustainability of omega-3 production, focusing on its application to fish by-products in aquaculture systems.

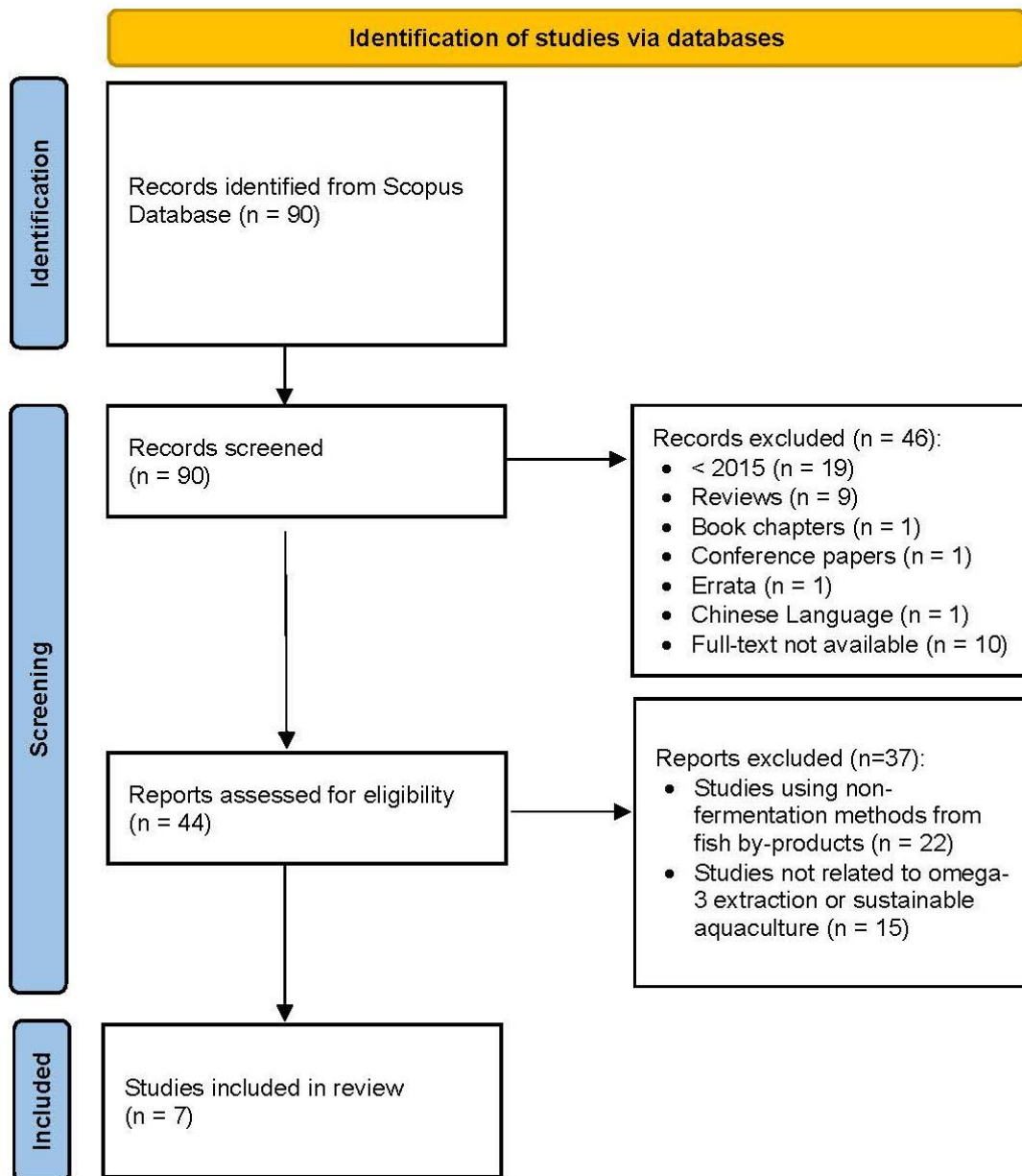


Figure 1. PRISMA flow diagram.

The systematic review process comprised three main phases: identification, screening, and inclusion. The literature search covered studies published from January 2015 to July 2025. This ten-year timeframe was selected to capture recent developments in fermentation-based valorization of fish by-products, particularly in relation to omega-3 lipid recovery, lipid stabilization, and sustainable aquaculture applications. During the identification phase, keywords were refined and expanded by identifying relevant synonyms. A comprehensive search string was developed focusing on fermentation, fish by-products, omega-3 fatty acids, and aquaculture-related sustainability terms. The search was performed using the Scopus database accessed via Universitas Padjadjaran. Scopus was selected due to the fact that it provides broad multidisciplinary coverage of peer-reviewed literature relevant to aquaculture, food science, biotechnology, waste valorization, and sustainability research. The search was applied to the Title-Abstract-Keywords field using the following search concept: "fermentation" AND "fish by-products" OR "fish waste" OR "fish processing waste" AND "omega-3" OR "EPA" OR "DHA" OR "polyunsaturated fatty acids" AND "aquaculture" OR "aquafeed" OR "sustainable aquaculture". The initial search yielded 90 records.

During screening, duplicate records, reviews, book chapters, conference papers, errata, non-English publications, and studies published outside the predefined timeframe were excluded. The remaining articles were assessed for eligibility based on title, abstract, and full-text relevance. Studies were included if they met the following criteria: they investigated fish by-products or fish processing residues as substrates; they applied a fermentation-based process, including lactic acid fermentation, silage fermentation, solid-state fermentation, submerged fermentation, or microbial co-fermentation; and they reported outcomes related to omega-3 fatty acids, lipid recovery, lipid stability, fatty acid composition, nutritional quality, or aquaculture feed application. Studies were excluded if they focused exclusively on non-fermentation extraction methods, non-fish substrates, unrelated fermented foods, or applications outside the scope of aquaculture and omega-3 valorization. Ultimately, seven empirical studies met the inclusion criteria and were analyzed in detail. Although this number is limited for a ten-year search period, it reflects the narrow and highly specific eligibility criteria applied in this review. Many retrieved studies addressed fish by-product utilization, fermentation, or omega-3-related outcomes separately, but only a small subset simultaneously investigated fermentation-based processing of fish by-products with outcomes relevant to omega-3 lipid recovery, fatty acid composition, lipid stability, or aquaculture application.

Results and Discussion

Overview of studies included. This systematic literature review included a total of 7 peer-reviewed articles meeting the defined inclusion criteria, published between the years 2015 and 2025. The studies represented a global scope with research conducted primarily in Europe (Italy), South America (Brazil), Asia (Turkey, Indonesia, and Bangladesh), and Australia. Such broad geographical distribution underscores international interest in optimizing fermentation techniques to valorize fish by-products for sustainable aquaculture. All 7 studies employed experimental research designs, focusing on evaluating various fermentation approaches, characterizing the biochemical composition of fermented fish waste, and assessing the nutritional value or practical applications of the extracted omega-3-rich products.

As summarized in Table 2, the reviewed studies investigated a wide range of substrates, including striped catfish (*Pangasianodon hypophthalmus*) processing residues, European seabass (*Dicentrarchus labrax*) trimmings, tuna processing by-products; species not specified in the original study, tambaqui (*Colossoma macropomum*) viscera, and discard fish species such as ponyfish (*Equulites* sp.) and Prussian carp (*Carassius gibelio*). All employed experimental research designs, ranging from controlled laboratory-scale trials to pilot-scale fermentations. The primary objectives across studies were to assess the feasibility of fermentation techniques, characterize changes in biochemical composition, particularly the stability and recovery of omega-3 fatty acids, and evaluate the nutritional or functional value of the resulting products for aquaculture applications. The limited number of eligible studies should be interpreted as an important feature of the evidence base rather than merely a numerical weakness. Although research on fish by-product valorization and fermented fish silage is relatively broad, studies that directly link fermentation-based processing with omega-3 retention, lipid recovery, fatty acid stability, and aquaculture application remain scarce. This restricted evidence base indicates that fermentation-assisted omega-3 valorization from fish by-products is still an emerging research area. Consequently, the findings of this review should be interpreted cautiously and used primarily to identify methodological trends, knowledge gaps, and priorities for future validation rather than to support broad generalization across all fish by-products, microbial systems, or aquaculture species.

Table 2

Overview of study characteristics and fermentation methods

Country	Fish by-product substrate	Microbial agent(s)	Fermentation method	Duration	Main objective	Reference
Italy	European Seabass processing residues (heads, viscera, bones, skin) + lemon peel	<i>Saccharomyces cerevisiae</i> (yeast); <i>Lactobacillus reuteri</i> (LAB)	Submerged batch fermentation (SmF-like, co-culture (yeast + LAB in solid substrate))	5 days (120 h)	Develop a protein-rich, probiotic aquafeed supplement from fish waste	Tropea et al 2021
Indonesia	Striped catfish processing residues (head, viscera, fins, bones)	Consortium: <i>Pseudomonas aeruginosa</i> ; <i>Rhizopus microsporus</i> ; <i>Yarrowia lipolytica</i>	Solid-State Fermentation (SSF) (Multi-microbial fermentation)	2, 4, 8 days (optimal 4 days)	Convert fish waste into a high-value feed supplement (improved protein & fatty acids)	Abun et al 2025
Brazil	Tambaqui viscera (liver, gut, stomach, kidney)	Lactic acid bacteria (e.g., <i>Lactobacillus</i> spp., plus 0.25% sorbic acid)	Fermentation-based silage (LAB ensiling with added carbohydrate) vs acid silage	7–10 days (initial ensiling; then stored)	Produce both acid and fermented fish viscera silage and evaluate nutrient content and energy digestibility in fish feed (tambaqui)	Santana et al 2023
Australia / Bangladesh / Indonesia	Tuna processing discards, fish hydrolysate	Not specified; likely LAB and/or yeast for fermentation of hydrolysate	Submerged fermentation (SmF)	4 days fermentation; 56-day feeding trial	Replacing fishmeal with fermented tuna by-product hydrolysate on growth, feed utilization, and health (aquafeed application)	Siddik et al 2018a
Turkey	Whole discard fish (Ponyfish and Prussian carp)	Lactic acid bacteria (strain not specified, natural LAB fermentation)	Fermentation-based silage (LAB-induced) vs acid-preserved	14 days (ensiling period, monitored)	Investigate silage preparation from low-value discard fish and evaluate the yield and quality of oils extracted for	Özyurt et al 2019

Country	Fish by-product substrate	Microbial agent(s)	Fermentation method	Duration	Main objective	Reference
					human use (omega-3 source)	
Turkey	Discard fish (ponyfish)	<i>Lactobacillus plantarum</i> ; <i>Streptococcus thermophilus</i> (LAB starters)	Fermentation-based silage vs. chemical acidification (formic/sulfuric acids)	60 days (ambient storage with periodic sampling)	Compare nutritional quality (fatty acid retention) and safety (biogenic amine formation, microbial counts) between acidified and fermented fish silage	Özyurt et al 2015
Turkey	European Sea bass processing waste	<i>Lactobacillus plantarum</i> ; <i>Pediococcus acidilactici</i> ; <i>Enterococcus gallinarum</i> ; <i>Lactobacillus brevis</i> ; <i>Streptococcus</i> spp. (multiple LAB strains)	Parallel silage: formic acid silage vs. fermentations with different LAB cultures	7 days (fermentation), then oil extracted and analyzed	Evaluate the fatty acid profile and oxidative stability of oils from fish waste silage, comparing organic acid treatment to various LAB fermentation starters for suitability in food/feed applications	Özyurt et al 2018

Fermentation approaches and microbial agents. Three main fermentation strategies were applied across the seven included studies: solid-state fermentation (SSF), submerged fermentation (SmF), and fermentation-based silage. SSF, such as the striped catfish waste fermentation using a bacterial–fungal–yeast consortium (*Pseudomonas aeruginosa*, *Rhizopus microsporus*, *Yarrowia lipolytica*) (Abun et al 2025), effectively enriched omega-3 fatty acids and improved the nutritional profile of by-products, though process optimization and microbial control remain critical challenges. Fermented seabass by-products with *Saccharomyces cerevisiae* and *Lactobacillus reuteri* in a submerged batch system (SmF-like) (Tropea et al 2021) produces a probiotic-rich, protein-enhanced feed ingredient, though with some reduction in PUFA levels. LAB-based silages consistently showed superior lipid stability, effective protein hydrolysis, and better preservation of EPA and DHA compared to chemical acidification, confirming their suitability for both aquafeed and oil recovery (Santana et al 2023; Özyurt et al 2019; Özyurt et al 2015; Özyurt et al 2018; Siddik et al 2018a). The choice of microbial agents strongly influenced fermentation outcomes (Li et al 2024). LAB, particularly *Lactobacillus plantarum*, *Pediococcus acidilactici*, and *Streptococcus* spp., were most frequently used, consistently lowering pH, improving protein hydrolysis, and preserving omega-3 fatty acids by reducing lipid oxidation compared with acid silage (Kim et al 2021). Beyond silage, more advanced methods included multi-microbial solid-state fermentation and co-fermentation. Yeast–bacteria consortia, such as *S. cerevisiae* with *L. reuteri* (Tropea et al 2021) or *S. cerevisiae* with *L. casei* (Siddik et al 2018a), provided additional probiotic benefits, generating feed ingredients with both nutritional and functional properties. More complex consortia, such as those involving bacteria, fungi, and yeast (Abun et al 2025), further boosted enzymatic hydrolysis, improved protein content, enriched essential fatty acid profiles, and reduced anti-nutritional factors, thereby producing functional feed supplements. These findings suggest that careful optimization of fermentation strategies and microbial combinations is critical to maximize nutrient recovery, stabilize omega-3 fatty acids, and generate value-added products for aquaculture and food systems. Table 3 provides a comparative summary of the fermentation methods and outcomes across the studies.

Nutritional outcomes and omega-3 valorization. The nutritional outcomes of fermented fish by-products varied depending on the substrate and fermentation method. In terms of fatty acid composition, the long-chain omega-3s - docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) - were consistently retained or enriched in fermented products (Freije 2017). DHA was more abundant than EPA, aligning with its natural predominance in marine-derived tissues (Rincón-Cervera et al 2020). LAB silage preserved stable levels of EPA and DHA, while multi-microbial SSF substantially increased DHA concentrations compared with controls (Abun et al 2025). Oils derived from fermented silage also showed higher oxidative stability, meeting quality standards for edible or feed applications (Özyurt et al 2018; Özyurt et al 2015; Özyurt et al 2019). Substrate composition strongly influenced yields. Fermentation of oily by-products achieved lipid recoveries exceeding 60% of dry matter, with substantial DHA and EPA concentrations (Santana et al 2023). Fermentations of leaner fish wastes enhanced protein content, with omega-3 levels ranging from 0.5% to 2% of dry matter (Abun et al 2025). These variations underscore the role of raw material selection, microbial activity, and process optimization in determining omega-3 recovery. Feeding trials further highlighted the nutritional value of fermented products. Juvenile tambaqui fed diets containing fermented viscera silage exhibited high protein and lipid digestibility (>90%) (Santana et al 2023). In juvenile barramundi (*Lates calcarifer*), inclusion of fermented tuna hydrolysates affected growth performance and liver health, indicating that optimal inclusion levels are necessary to balance benefits and potential risks (Siddik et al 2018a). Collectively, these findings demonstrate that fermentation not only preserves key fatty acids but also generates functional ingredients capable of improving digestibility, antioxidant status, and overall fish health. Although some fermentations altered the overall fatty acid profile, occasionally reducing polyunsaturated fatty acids (PUFAs), the consistent presence of DHA and EPA across studies highlights the nutritional value of fermented fish by-products as potential aquafeed ingredients. Table 4 provides a comparative summary of omega-3 yields and fatty acid profiles.

Table 3

Summary of fermentation methods and outcomes

Method	Substrate	Microorganisms	Duration	Temperature	Omega-3 results and method advantages/Limitations	Reference
Submerged fermentation (SmF-like, batch)	European seabass residues + lemon peel	<i>S. cerevisiae</i> , <i>L. reuteri</i>	5d	35°C	Preserved omega-3; increased protein, microbial safety; moderate omega-3 reduction	Tropea et al 2021
Solid-State Fermentation (SSF)	Striped catfish processing residues	<i>P. aeruginosa</i> , <i>R. microsporus</i> , <i>Y. lipolytica</i>	4 d	30°C	Increased omega-3 & protein content; antioxidant properties; complex microbial control required	Abun et al 2025
Fermented silage (LAB + carbohydrate support)	Tambaqui viscera	LAB (unspecified yogurt culture)	7–10 d	Ambient	High omega-3 preservation, excellent digestibility; no growth trial	Santana et al 2023
Submerged fermentation (SmF)	Tuna processing discards	LAB (<i>S. cerevisiae</i> , <i>L. casei</i>) and unspecified yeast strains	4 d	Ambient	Moderate omega-3 preservation; antioxidant benefits; growth issues at high inclusion	Siddik et al 2018a
LAB fermented silage	Discard species (Ponyfish and Prussian carp)	LAB (<i>L. plantarum</i> , <i>P. acidilactici</i> , etc.)	21 d	27-28°C	Excellent oxidative stability, preserved omega-3; minor increase in biogenic amines	Özyurt et al 2019
LAB fermented silage	Ponyfish	<i>L. plantarum</i> , <i>S. thermophilus</i>	60 d	Ambient	High omega-3, low oxidation; increased biogenic amines during extended storage	Özyurt et al 2015
LAB fermented silage	European Sea bass by-products	<i>L. plantarum</i> , <i>P. acidilactici</i> , <i>E. gallinarum</i> , etc.	21 d	Ambient	Better omega-3 retention, superior oxidative stability compared to acid silage	Özyurt et al 2018

Table 4

Comparative omega-3 and lipid-related outcomes across included studies

<i>Study context</i>	<i>Reported lipid or omega-3-related outcome</i>	<i>EPA outcome</i>	<i>DHA outcome</i>	<i>Interpretive note</i>	<i>Reference</i>
European seabass processing residues with lemon peel; Italy	No dedicated oil extraction was performed. The fermented product retained a lipid fraction of approximately 15%, although the PUFA fraction decreased during fermentation	EPA was reported at a very low level and decreased after fermentation (approximately 0.16 to 0.03% of total fatty acids)	DHA remained detectable and relatively better retained than EPA (approximately 2.4% of total fatty acids after fermentation)	Supports the value of co-fermentation for feed ingredient development, but the study should not be interpreted as direct omega-3 oil extraction	Tropea et al 2021
Striped catfish processing residues; Indonesia	Solid-state fermentation increased total fatty acids and reported omega-3 fractions compared with the non-fermented control	EPA increased under the optimized fermentation condition, with the study reporting an increase of approximately 114%.	DHA increased under the optimized fermentation condition, with the study reporting an increase of approximately 129%	Promising for nutrient enrichment, but the application was positioned mainly as a feed-supplement study; aquaculture-specific feeding validation remains needed	Abun et al 2025
Tambaqui viscera silage; Brazil	The silage had a high lipid fraction, with lipid content reported at approximately 62.9% of dry matter in the silage product.	EPA was reported in the range of approximately 5.4-17.8 mg g ⁻¹ lipid, varying by silage type and processing condition	DHA was reported in the range of approximately 1.7-8.9 mg/g lipid, varying by silage type and processing condition.	Indicates strong potential for lipid-rich by-product valorization and digestible aquafeed ingredients, although growth performance was not fully validated.	Santana et al 2023
Tuna hydrolysate from tuna-processing by-products; Australia	Specific omega-3 yield or lipid recovery was not quantified. The study focused on fermented and non-fermented tuna hydrolysate as a fishmeal replacement ingredient	NR. EPA was not explicitly quantified as an omega-3 recovery outcome	NR. DHA was not explicitly quantified as an omega-3 recovery outcome	Relevant for aquaculture application in juvenile barramundi (<i>Lates calcarifer</i>), but it should not be used as direct evidence for EPA/DHA extraction efficiency	Siddik et al 2018a
Discard fish species, including	Silage processing enabled recovery of oils from low-value discard fish, with oil	EPA was retained in recovered oils, although values	DHA was retained as a nutritionally relevant PUFA fraction, with	Useful for demonstrating valorization of discard fish oils, but cross-study	Özyurt et al 2019

<i>Study context</i>	<i>Reported lipid or omega-3-related outcome</i>	<i>EPA outcome</i>	<i>DHA outcome</i>	<i>Interpretive note</i>	<i>Reference</i>
ponyfish and Prussian carp; Turkey	quality and fatty acid composition assessed for potential use.	varied with species and preservation condition	values varying by substrate and silage condition	comparison is limited by differences in substrate and reporting units	
Ponyfish/discard fish silage; Turkey	Fermented silage retained a nutritionally relevant PUFA fraction, with total PUFA values close to those of the raw material	EPA remained relatively stable in fermented silage (approximately 0.7-0.8% of total fatty acids)	DHA remained the dominant PUFA (approximately 8-9% of total fatty acids), with only limited reduction compared with raw fish	Supports the role of LAB fermentation in fatty acid preservation, but prolonged storage may increase biogenic amine concerns	Özyurt et al 2015
European seabass by-products; Turkey	Oil recovered from LAB-fermented silage showed improved oxidative stability compared with acid silage and retained nutritionally relevant PUFAs	EPA was largely maintained in recovered silage oil (approximately 2.5% of total fatty acids)	DHA was slightly lower than in raw material but remained present at approximately 3.6-4.3% of total fatty acids	Provides strong evidence for lipid stabilization through LAB fermentation, although feeding validation was not performed	Özyurt et al 2018

NR, not reported. Values are reported as stated in the original studies and are not directly comparable because outcomes were expressed using different units, including percentage of total fatty acids, mg/g lipid, percentage of dry matter, and oil recovery.

Aquaculture applications of omega-3 extracted from fish by-products. Fermented fish by-products not only serve as sources of protein and omega-3 fatty acids but also act as functional feed ingredients (Marti-Quijal et al 2020). The presence of lactic acid bacteria, yeasts, and their metabolites introduces probiotic and immunostimulatory compounds (e.g., β -glucans, mannan-oligosaccharides) that can enhance gut health, improve antioxidant status, and strengthen disease resistance (Filidou et al 2024). Feeding trials have shown that moderate dietary inclusion of fermented fish hydrolysates can support fish growth while providing health benefits (Siddik et al 2018b). For instance, juvenile barramundi fed fermented tuna hydrolysate demonstrated improved antioxidant enzyme activity and reduced liver stress compared to fish fed unfermented hydrolysates, even though excessive replacement of fishmeal ($\geq 50\%$) reduced growth performance (Siddik et al 2018a). Similarly, studies on viscera silage reported high nutrient digestibility ($>90\%$ protein), indicating that fermented products are efficiently utilized in fish diets (Santana et al 2023). These findings suggest that fermentation mitigates some limitations of raw fish waste, such as oxidative instability and anti-nutritional factors, thereby improving feed safety and functionality. However, optimal inclusion levels must be carefully determined, as very high replacement of fishmeal can impair growth and metabolic health. Overall, omega-3-rich fermented products show strong potential to improve aquafeed quality by combining nutritional and functional benefits. Valorizing fish by-products through fermentation contributes to circular economy practices by reducing waste streams and generating value-added products (Zhao et al 2022). Redirecting fish waste into omega-3-rich feeds alleviates pressure on wild fisheries, lowers disposal costs, and minimizes environmental impacts such as eutrophication (Alfio et al 2021). Economically, converting by-products into feed supplements transforms waste management from a cost burden into a revenue stream, while also reducing reliance on expensive fishmeal and fish oil (Sampathkumar et al 2023). This dual benefit enhances both ecological sustainability and farm profitability.

Comparison of studies and key trends. Across the literature, fermentation reliably preserved EPA and DHA while improving oil stability compared with chemical acidification. Variability in results largely stemmed from differences in substrates, microbial strains, and fermentation conditions. LAB-based fermentations consistently preserved PUFA stability, whereas mixed-culture fermentations sometimes shifted fatty acid profiles. Feeding trials consistently indicated health and digestibility benefits but highlighted inclusion thresholds beyond which performance declined (van Nerom et al 2024). Key factors shaping omega-3 yield and quality include fermentation duration, temperature, pH, substrate composition, and microbial selection (Xie et al 2017). Optimal conditions - typically mesophilic temperatures, rapid acidification by LAB, and medium inoculum levels - maximize lipid recovery while limiting oxidation (Wei et al 2024). Lipid-rich substrates (e.g., viscera) naturally yield higher omega-3 contents, while lean substrates primarily enhance protein fractions (Huang et al 2024). The choice of microbial strains also plays a crucial role, with LAB providing antioxidant protection and stability, whereas multi-microbial consortia can boost enzymatic breakdown and nutrient release (Khubber et al 2022). Table 5 presents a comparison of studies (key findings and trends).

Table 5

Evidence map of key findings, aquaculture relevance, and limitations across included studies

<i>Fermentation system and substrate</i>	<i>Directly reported omega-3, lipid, or nutritional evidence</i>	<i>Aquaculture or feed relevance</i>	<i>Safety or stability evidence</i>	<i>Key interpretation for this review</i>	<i>Reference</i>
Yeast-LAB co-fermentation of European seabass processing residues with lemon peel; <i>S. cerevisiae</i> and <i>L. reuteri</i>	Produced a fermented ingredient with improved protein-associated value and retained lipid fractions, although PUFA reduction was reported; omega-3 extraction was not the central endpoint	Proposed as a protein-rich aquafeed supplement; no fish feeding trial was conducted	Laboratory-scale fermentation and microbial quality were assessed, but long-term storage and in vivo safety validation were limited	Supports waste-to-feed valorization, but provides indirect rather than definitive evidence for omega-3-rich aquafeed application	Tropea et al 2021
Solid-state fermentation of striped catfish processing residues using <i>P. aeruginosa</i> , <i>R. microsporus</i> , and <i>Y. lipolytica</i>	Reported increased protein content and improved fatty acid profile, including increases in EPA, DHA, and total omega-3-related fractions under optimized fermentation conditions	Developed as a feed supplement, but the reported application was not an aquaculture feeding trial; direct aquafeed validation remains absent	Use of <i>P. aeruginosa</i> requires strict microbial safety verification, including confirmation that no viable pathogenic cells remain in the final product	Provides a strong nutrient-enrichment signal, but aquaculture relevance and microbial safety must be validated before feed-scale application	Abun et al 2025
Lactic acid bacteria-based silage of tambaqui viscera, with carbohydrate support and preservative treatment; compared with acid silage	Reported lipid-rich silage, EPA and DHA measurements, and high apparent digestibility of nutrients and energy	Digestibility was evaluated in juvenile tambaqui, providing direct aquaculture-relevant evidence; however, no long-term growth trial was performed	Fermentation supported preservation of viscera and nutrient digestibility, but oxidative stability and safety parameters require broader standardization	Represents one of the strongest aquaculture-relevant studies, but conclusions remain species- and substrate-specific	Santana et al 2023
Fermented and non-fermented tuna hydrolysate derived	Did not quantify omega-3 recovery or EPA/DHA yield; focused on growth, digestibility,	Feeding trial in juvenile barramundi (<i>Lates calcarifer</i>); high fishmeal	High inclusion levels were associated with adverse liver histopathology,	Provides critical evidence that fermented by-products cannot be	Siddik et al 2018a

<i>Fermentation system and substrate</i>	<i>Directly reported omega-3, lipid, or nutritional evidence</i>	<i>Aquaculture or feed relevance</i>	<i>Safety or stability evidence</i>	<i>Key interpretation for this review</i>	<i>Reference</i>
from tuna-processing by-products	biochemical response, antioxidant status, and liver health	replacement levels with tuna hydrolysate reduced growth and feed utilization	indicating the need to optimize inclusion levels and product quality	assumed beneficial at high inclusion levels; dose and physiological tolerance are central	
LAB-based silage of discard fish, including ponyfish and Prussian carp; compared with acid-preserved silage	Recovered oils with favorable fatty acid composition and EPA/DHA retention, indicating potential for lipid valorization from low-value fish biomass	No aquaculture feeding trial was conducted; feed relevance is inferred from oil quality and by-product valorization potential	Oil quality and oxidative stability were evaluated; fermentation-based preservation showed potential for maintaining lipid quality	Strong evidence for oil recovery and quality preservation, but direct aquafeed performance remains untested	Özyurt et al 2019
Acidified and LAB-fermented fish silage from discard fish, with <i>L. plantarum</i> and <i>S. thermophilus</i> as starter cultures	EPA and DHA were largely retained during silage preparation, with DHA remaining a dominant PUFA fraction	No feeding trial was performed; relevance to aquaculture is based on nutritional composition and potential use as a feed ingredient	Biogenic amines and microbial counts were monitored; extended storage may increase amine formation, especially in fermented silage	Useful evidence for fatty acid retention, while also highlighting safety and storage constraints that must be controlled	Özyurt et al 2015
LAB fermentation and acid silage of European seabass by-products using multiple LAB strains, including <i>L. plantarum</i> , <i>P. acidilactici</i> , <i>E. gallinarum</i> , and <i>L. brevis</i>	Recovered silage oils showed EPA/DHA retention and favorable fatty acid profiles relative to raw material and acid-silage comparators	No feeding trial was conducted; relevance is based on oil recovery, fatty acid profile, and potential ingredient application	Oxidative stability of recovered oils was assessed, and outcomes varied with preservation method and microbial starter	Provides direct evidence that LAB-based processing can preserve oil quality, but feed-scale performance and long-term safety require validation	Özyurt et al 2018

Challenges, research gaps, and future perspectives. Despite promising results, the reviewed studies face several methodological and practical constraints. Most experiments were conducted at laboratory or pilot scale, often with single fish species, specific by-products, and short fermentation or feeding durations. For instance, Santana et al (2023) focused only on tambaqui viscera silage and reported digestibility, but did not test growth responses in vivo, while Siddik et al (2018a) applied high inclusion levels (50–75%) of fermented tuna hydrolysate that impaired growth and liver health in juvenile barramundi. Tropea et al (2021) characterized the biochemical properties of seabass by-product fermentation but lacked validation through animal trials. Özyurt et al (2018), Özyurt et al (2015) and Özyurt et al (2019) provided detailed analyses of oil stability and fatty acid preservation, but did not extend findings to feeding trials. Safety concerns were not always resolved, Özyurt et al (2015) reported higher levels of biogenic amines in fermented silages compared to acid-treated controls, highlighting the need for stricter monitoring. Generality and practical applicability also remain limited. Trial durations were relatively short (≤ 56 days) and no study assessed long-term growth efficiency or product quality over a full production cycle (Siddik et al 2018a). The approach used by Haetami et al (2026), which coupled process-controlled SSF, extract characterization, post-pellet application, and fish performance endpoints, provides a useful methodological model for future fish by-product studies. Although some authors, such as Tropea et al (2021), acknowledged the need for cost-benefit and life-cycle analyses, such evaluations have yet to be conducted. Collectively, these limitations mean that while laboratory findings are encouraging, caution is needed when extrapolating results to commercial aquaculture systems.

Future work should focus on refining fermentation methodologies and translating them into scalable and sustainable applications. First, optimization of fermentation parameters, including microbial selection, inoculum density, and fermentation time, is crucial to maximize omega-3 recovery while minimizing undesirable by-products (Sousa et al 2024). Novel microbial consortia, such as those combining bacteria, fungi, and yeasts (Abun et al 2025) show potential to enhance nutrient release and product stability, but require systematic testing. Strain-specific effects observed in silage fermentations suggest opportunities to screen for microbes with superior lipid-preserving or antioxidant capabilities (Özyurt et al 2015; Özyurt et al 2018). Second, scaling up requires pilot or industrial trials combined with economic and environmental assessments (Soffa et al 2024). Life-cycle analyses, energy use, and carbon footprint studies should be prioritized to verify that fermentation-based omega-3 recovery offers genuine sustainability benefits compared with conventional fish oil extraction (Davis et al 2021). Issues of storage stability, refining, and regulatory standards (e.g., thresholds for biogenic amines or microbial contaminants) also need to be addressed to ensure safe large-scale adoption (Paparella et al 2025). Third, moderate dietary inclusion must be tested in aquaculture applications, across diverse species and production stages, focusing not only on growth but also on immune status, gut microbiota, broodstock performance, and fillet quality (Tran et al 2022).

A limitation of the current study lies in the small number of eligible empirical studies identified over the ten-year search period and the reliance on Scopus as the sole bibliographic database. The limited evidence base reflects the strict inclusion criteria and the fragmented nature of the current literature, in which fish silage production, by-product valorization, lipid extraction, and aquafeed application are often investigated as separate topics rather than as integrated fermentation-based omega-3 valorization systems. Although Scopus provides broad multidisciplinary coverage of peer-reviewed literature in aquaculture, food science, biotechnology, and sustainability, relevant studies indexed only in Web of Science, CAB Abstracts, PubMed, ScienceDirect, or regional databases may have been missed. Therefore, the findings are interpreted as a structured synthesis of Scopus-indexed evidence and as an exploratory evidence map rather than an exhaustive assessment of all available literature. Future reviews should adopt multi-database search strategies with backward and forward citation tracking, while future empirical studies should use standardized experimental designs, consistently report EPA and DHA outcomes, include appropriate controls, evaluate oxidative stability and safety parameters, and validate fermented products through aquaculture feeding trials.

Conclusions. Fermenting fishery by-products represents a promising strategy to obtain omega-3-rich ingredients for sustainable aquaculture. Based on the limited number of eligible empirical studies, fermentation appears to be a promising strategy for improving the nutritional value and lipid stability of selected fishery by-products. The available evidence suggests that microbial fermentation, particularly lactic acid bacteria-based silage, can support EPA and DHA retention, improve oxidative stability, and generate value-added ingredients with potential relevance for aquaculture feeds. However, the current evidence remains insufficient for broad generalization because most studies were conducted at laboratory or pilot scale, used different substrates and microbial systems, and rarely included long-term aquaculture feeding validation. Future research should focus on standardizing fermentation parameters, ensuring product safety, and validating nutritional and economic benefits under commercial farming conditions. By advancing these aspects, fermentation of fish by-products can contribute significantly to a circular and resilient aquaculture sector.

Acknowledgements. The authors would like to express their gratitude to Universitas Padjadjaran and Universitas Singaperbangsa Karawang for providing access to research facilities and scientific databases. Special thanks are extended to the colleagues who provided valuable comments that improved the quality of this manuscript.

Authors Contributions. Conceptualization: KH, AY, AA, and MAM; Methodology: KH, AA, FAR, and MAM; Formal analysis: KH, FAR, and MAM; Investigation: KH, AA, FAR, and MAM; Data curation: FAR and MAM; Writing – original draft: KH, AY, AA, FAR, and MAM; Writing – review & editing: KH, AY, AA, FAR, and MAM; Supervision: KH, AY, AA, and MAM.

Conflict of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding. This research was funded by the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia through the Universitas Padjadjaran Research Operational Assistance Program, Fiscal Year 2025, under Contract No. 1597/UN6.3.1/PT.00/2025.

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Received: 30 November 2025. Accepted: 29 May 2026. Published online: 17 June 2026.

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How to cite this article:

Haetami K., Yustiati A., Abun A., Rahmani F. A., Mulki M. A., 2026 Advancements in fermentation of fish by-products: A systematic review of omega-3 lipid extraction for sustainable aquaculture. *AAFL Bioflux* 19(3):1323-1341.