

Circular Economy Applications: The Sustainable Utilisation of Fish By-Products for Seafood Production and Its Impact on Human Health

Ioannis Fotodimas, Kosmas L. Vidalis, Panagiotis Logothetis, Grigorios Kanlis

Department of Fisheries and Aquaculture, School of Agricultural Sciences, University of Patras, Messolonghi, Greece
Email: fotodimasjohn@gmail.com, up1119778@upatras.gr

How to cite this paper: Fotodimas, I., Vidalis, K.L., Logothetis, P. and Kanlis, G. (2025) Circular Economy Applications: The Sustainable Utilisation of Fish By-Products for Seafood Production and Its Impact on Human Health. *Advances in Bioscience and Biotechnology*, 16, 305-331.

<https://doi.org/10.4236/abb.2025.168020>

Received: July 30, 2025

Accepted: August 18, 2025

Published: August 21, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Seafood is an important part of a balanced diet, and the demand for fishery and aquaculture products has increased significantly in recent years, leading to considerable development in aquaculture and fish processing generates large quantities of by-products such as heads, skin, viscera, and bones, which account for around 60% of the total biomass. Despite their high protein value, a large proportion of these waste are disposed of into the environment, leading to eutrophication and degradation of aquatic ecosystems. This threatens marine biodiversity and the sustainability of the fishing and aquaculture industry. Enzymatic hydrolysis (EH) has established itself as an efficient and environmentally friendly method for valorising these by-products. This process produces fish protein hydrolysates (FPH), which are rich in bioactive peptides (BAPs) and free amino acids and have antioxidant, antimicrobial and immune-boosting properties. FPH are used in aquaculture fish feed, functional foods, and pharmaceutical products. Their inclusion in the feed of farmed fish improves growth and health while reducing dependence on fishmeal, the availability of which is decreasing due to declining fish stocks. In addition, fish fed with FPH-enriched feed provide compounds that are beneficial to human health. Regular consumption of such fish may contribute, as observed in in vitro studies, to the prevention and treatment of chronic diseases such as high blood pressure, diabetes, and cancer, while improving digestive and immune function as observed in laboratory studies. This review highlights the sustainable and environmentally friendly use of EH to extract bioactive compounds from fish by-products. It analyzes pre-treatment methods and the applications

of the resulting FPH as an alternative to fishmeal, with the aim of increasing aquaculture productivity and promoting human health.

Keywords

Fish By-Product, FPH, Enzymatic Hydrolysis, Fish Feed, Human Health Effects, Sustainable Aquaculture, Circular Economy

1. Introduction

Seafood consumption is an essential part of a balanced diet, as it contributes significantly to maintaining human health. Consumers are showing an increasing interest in products with high nutritional value, with a focus on both fishery and aquaculture products. In recent years, the aquaculture sector has become increasingly oriented towards the principles of the circular economy, promoting sustainable development through the valorisation of fish waste with the aim of reducing environmental impact and developing new, innovative products. The rapid growth of the fishing industry, combined with the aquaculture sector, produces 140 M t of fishery products, of which approximately 110 M t are intended for human consumption [1]. According to the FAO in 2018, aquaculture is one of the fastest growing sectors of food production worldwide and meets the protein needs of the world's population [2]. During fish processing, about 60% of the biomass is by-product, usually consisting of skin, heads, offal and bones, while the remaining 40% of the edible biomass is destined for human consumption [3]. The remaining 40% primarily consists of fillets intended for direct human consumption [4]. The continuous disposal of fish waste into the environment increases the concentration of organic and inorganic nutrients in marine ecosystems, leading to eutrophication and a deterioration in water quality [5] [6]. The decomposition of fish waste reduces the oxygen content on the seabed, which has a negative impact on marine ecosystems and their biodiversity. The environmental problems resulting from the disposal of such waste threaten the sustainability of fisheries and aquaculture and jeopardise the development and stability of the sector [5] [6]. Fish proteins contain specific sequences of BAPs that offer significant health benefits for humans. The muscle tissue of fish accounts for 15% - 25% of the total protein, which is categorised into three main types: myofibrillar proteins 50% - 60%, sarcoplasmic proteins about 30% and stromal proteins 10% - 20%. Due to the high content of muscle tissue, fish by-products is a valuable source of proteins that can be effectively utilised in various industrial applications [7] [8]. Utilisation of fish by-products biomass is achieved through enzymatic protein hydrolysis, resulting in rich sources of FPH [9]. EH is one of the most widely used methods for protein production, with applications in various areas of the food and pharmaceutical industries [10]. It is a simple and environmentally friendly method of processing fish by-products that enables the release of bioavailable peptides that improve

physiological functions when consumed. Through the action of proteases, peptide bonds are broken and peptides and other bioactive compounds are released. Hydrolysed proteins derived from fish by-products are widely used in health, pharmaceuticals and functional foods, offering increased nutritional value and significant bioactive properties [11]-[13]. Fishmeal and fish oil are essential components of aquaculture feeds as they contain high concentrations of proteins and other nutrients necessary for fish growth and survival. However, the decline in fish stocks has significantly limited the supply of fishmeal and fish oil, so that production costs have increased and alternative protein sources such as FPH need to be found [14]. Partial and/or complete replacement of fishmeal can potentially be achieved by recovered FPH produced by EH of by-products from the fishing industry. Their high bioavailability combined with their rich composition of free amino acids and BAPs contributes significantly to improving the growth, health and immune response of farmed fish. In addition, the addition of FPH to fish feed reduces dependence on expensive fishmeal and offers a sustainable and cost-effective alternative [15]. Farmed fish enriched with recovered FPH not only benefit in terms of their own growth and health, but can also contribute significantly to improving human health through their consumption. In particular, FPH have strong bioactive properties, such as antioxidant and antimicrobial activity, the ability to regulate blood pressure and blood sugar levels, the strengthening of the immune system and anti-cancer effects. In addition, they support good digestive function and improve nutrient absorption. Due to these properties, FPH are widely used as both functional foods and aquaculture products that have the potential to prevent and/or treat chronic diseases [16]-[18]. This review focuses on the method of EH to utilise by-products from various commercially important fish species, the pre-treatment techniques of by-products prior to hydrolysis and the potential use of recovered FPH as a partial and/or complete alternative to fishmeal in the diet of captive farmed fish. At the same time, the positive effects of the addition of FPH on fish health and growth will be investigated. Finally, the bioactive properties of FPH and their contribution to the prevention and/or treatment of chronic diseases in humans through diet will be reviewed.

2. Methodology

The data used in the present study were selected on the basis of specific scientific criteria, focusing on the method of EH of fish by-products and retaining common scientific characteristics. A total of 110 scientific articles were screened, of which 100 met the predefined criteria and were included in the analysis. However, 6 articles were excluded because they combined EH with other processing technologies that were outside the scope of this study. Articles were found in the Elsevier, Springer, Google Scholar and Scopus databases using a combination of keywords: Fish by-products, fish protein hydrolysates, enzymatic hydrolysis, fish feed, human health effects, sustainable aquaculture, circular economy. The studies included in this review cover the period from 1995 to 2025, providing a broad

timeframe that reflects the evolutionary course of scientific research in this field. The selection of this period allows an in-depth evaluation of the EH method with different proteolytic enzymes and contributes to a better understanding of the developments, innovations and trends that have characterised the fish processing industry.

3. Valorisation of Fishery and Aquaculture Waste through Advanced Extraction Techniques: Focus on Bioactive Protein Recovery

Various processing methods have been used for the valorisation of fishery and aquaculture by-product and the recovery of bioactive compounds, such as EH, chemical hydrolysis, thermal processing, ultrasound-assisted extraction and extraction with supercritical carbon dioxide. The choice of method and the type of by-product used have a significant impact on the type and quality of the bioactive compounds obtained. According to the study by Liaset *et al.*, 2000, EH is applied to fish by-products such as headless frames from species such as Atlantic salmon *Salmo salar* L., and Atlantic cod *Gadus morhua* L. The fish by-product biomass is shredded and heated to 90°C to inactivate the endogenous enzymes. It is then mixed with water and homogenised, with the pH and temperature adjusted under controlled conditions depending on the type of proteolytic enzyme used. Commonly used proteolytic enzymes include Alcalase, Pepsin and Neutrase. The duration of hydrolysis is up to 120 min in the first step and up to 720 min in the second step. Hydrolysis is terminated by inactivating the enzyme at ≥90°C for a few min. The hydrolysate is then separated into supernatant and sediment by centrifugation. The product obtained contained up to 67.6% FPH. According to the study by Pontoh, 2019, various fish by-products such as heads, guts and belly flaps collected from the northern part of Lake Tondano in North Sulawesi are thermally processed. The biomass is cut into 1 cm² thick pieces and boiled in water twice the volume of the sample. Thermal processing takes 60 min at 100°C. After thermal processing, the hot mixture is transferred to a bottle with a long, narrow neck and left undisturbed to achieve natural phase separation. The oily fraction that accumulates at the top is collected with a syphon and transferred to centrifuge tubes where it is centrifuged for 15 min. The product obtained contained of fish oil. According to the study by Wai *et al.*, 2020, chemical hydrolysis is applied to a variety of fish by-products collected by the local producer Keropok Lekor Ghani Black in the Kuantan region. The biomass is washed with distilled water, dried at 180°C for 30 min and ground into powder form. Demineralisation is carried out by immersing the biomass in an aqueous hydrochloric acid (HCl) solution at concentrations of 0.2 M to 1.0 M for 30 - 150 min at room temperature with constant stirring at 150 rpm. The ratio of solid to liquid is kept at 1:10. After demineralisation, the biomass is rinsed with distilled water and dried at 60°C for 5 h. Deproteinisation is then carried out by adding the dried biomass to a 1.0 mol/L sodium hydroxide solution. The temperature is maintained at 60°C and stirring is contin-

ued for 30 to 150 min. The process is completed by repeated washing with distilled water until the sample reaches a neutral pH 7.0. The product obtained contained a variety of antioxidant compounds. In the study by, Melgosa *et al.*, 2020 an extraction technique using supercritical carbon dioxide in combination with subcritical water extraction is applied for the valorisation of *sardines Sardina pilchardus* from a cannery. The biomass was first subjected to supercritical CO₂ extraction at 250 bar and 40°C, which yielded an extract with a high content of polyunsaturated omega-3 fatty acids (PUFAs) of 17.2% by weight. The defatted fraction was then subjected to subcritical water treatment at different temperatures (90°C, 140°C, 190°C and 250°C) and the product obtained showed an increased protein content with strong antioxidant activity. According to the study by Chongkhong, 2023, ultrasound-assisted extraction was applied to by-products such as the skin of the purple spotted bigeye obtained from the Pae Khai-Lium minced fish production plant of Pacific Fish Processing Co., Ltd. in Songkhla, Thailand. The biomass was cut into approximately 0.5 cm² pieces, washed, drained and then dried at 80°C until the moisture content was reduced to 8%. It was then subjected to ultrasound-assisted extraction, first with ethanol and then with hexane, under controlled conditions: Temperature 30°C, ultrasonic frequency 37 kHz and extraction time 60 min. The product obtained contained lipids with a recovery rate of up to 91.3%. In conclusion, the above-mentioned processing methods for the valorisation of fishery and aquaculture by-product contribute to the recovery of bioactive compounds such as lipids, fish oil, omega-3 polyunsaturated fatty acids PUFAs, FPH and proteins in general, as well as antioxidant compounds. The EH method is considered environmentally friendly because, unlike chemical hydrolysis and ultrasound-assisted extraction, which rely on such solvents, it does not require organic solvents. In addition, it does not require expensive and/or energy-intensive equipment, as is the case with thermal processes, supercritical CO₂ extraction or its combination with subcritical water and ultrasound-assisted extraction with organic solvents. Therefore, EH is an effective method for recovering high-quality hydrolysed proteins from fish by-product, as the recovered proteins retain their bioactive properties, such as their antioxidant activity. Potentially, these bioactive compounds can be utilised in various industrial applications, contributing to the circular economy and sustainability of companies [19]-[23].

3.1. Preparation of Fish By-Product Samples

The fish species used in the EH experiments are listed in **Table 1**, while the different sample preparation processes are described in **Figure 1**. According to the data from this literature review, fish is either used whole as raw material or after some processing in which used directly or further processed the inedible portions, referred to as by-products or fish waste.

The raw fish material is generally referred to as fish meat, muscle meat internal organs and frames [24]-[27], more specifically backbone, bones, carcass, fins, flesh, head, frame, tail, skin, guts, viscera, trimmings, liver, roe and gills. The countries

of origin of the fish biomass are spread all over the world and include the following countries: Algeria, Brazil, Canada, China, India, Indonesia, Iran, Lithuania, Malaysia, South Korea, Spain and Vietnam. The biomass comes from local fish landing centre, fish processing plants, fishing activities, limited liability companies, and local markets. Fish from fisheries is immediately frozen on board at a temperature of no more than -20°C [25] [28]-[30]. Similarly, farmed fish from aquaculture are collected and stored in plastic bags, plastic containers while being covered with ice in polystyrene boxes [26] [28] [31]. Both fish from fisheries and aquaculture are transported to the laboratory after first being packed in sterile flasks under controlled conditions to avoid contamination and then stored in freezers at -20°C to -80°C until further use [18] [26]-[28] [32]. Prior to the application of EH, the fish by-products and/or waste are used directly or further processed. During processing, the biomass is cleaned with cold water, deionised water or chlorinated water (2 g/l) to remove unwanted substances such as blood, mucus and other impurities [27] [33] [34]. The biomass is subjected to thermal treatment or boiling at 85°C - 100°C for 20 - 30 min to inactivate the endogenous enzymes [29] [32] [35]. The by-products are then ground, homogenised and dried in a hot air oven at 180°C for one h to remove moisture [36]. To remove the oils from the fish biomass, centrifugation is carried out at 6000 - 10,000 \times g for 15 - 30 min at 4°C - 10°C [27] [35] [37]. The above processes are carried out individually or in combination to ensure proper preparation of the samples for the EH process in appropriately prepared biomass from fish by-products to recover specific bioactive substances.

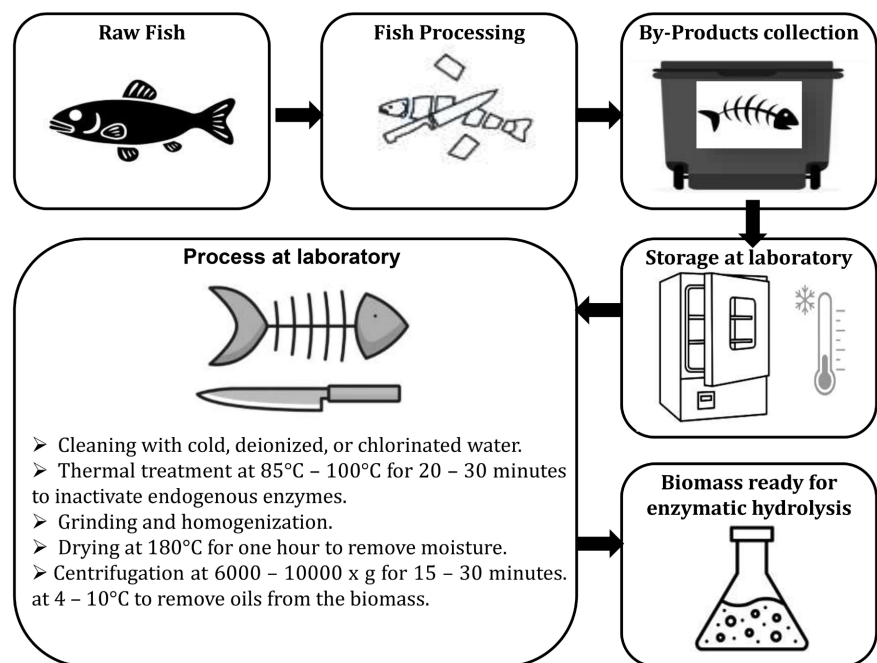


Figure 1. Management and processing of raw fish by-products before performing enzymatic hydrolysis.

Table 1. Description of the conditions of enzymatic hydrolysis of fish by-products.

Scientific Names of Species	A: Country B: Company	Fish biomass	General Description of by-product and Preparation before Hydrolysis	References
<i>Catla catla</i>	A: India B: Not specified	Visceral	Collection of raw material was transported to the laboratory under cold conditions. Thermal inactivation of enzymes was carried out at 85 °C for 20 min to inactivate the endogenous stomach enzymes. Centrifuged at 10 °C for 20 min at 6000 g to separate the oil from the solid material, and Storage at –80 °C until use.	[35]
<i>Pangasius sp.</i>	A: Indonesia B: Fish market	Fish waste	Collection of raw material was transported to the laboratory and stored until further use.	[60]
<i>Thunnus thynnus</i>	A: South Korea B: “Dongwon Fisheries Co”.	Backbone	Collection of raw material was transported to the laboratory and Storage at –80 °C until use.	[38]
<i>Sardina pilchardus</i>	A: Algeria B: “Dellys fishery”.	Fish waste	Collection of raw material was transported in sterile flasks under aseptic conditions at 4 °C. Thermal inactivation of enzymes was carried out at 100 °C for 30 min to inactivate the endogenous stomach enzymes, and the material was stored at 20 °C until use.	[32]
<i>Catla catla</i>	A: India B: Local Market	Visceral	The collection of raw material was transported to the laboratory in sterile pouches, under chilled conditions, and stored until further use.	[39]
<i>Thunnus albacares</i>	A: Iran B: “Darya-Khorak Co”.	Viscera	Fish were caught during the winter season and immediately frozen on board at –20 °C. They were delivered to the processing plant under frozen conditions at –20 °C. The by-products were removed using an electric saw, minced twice using an electric mixer, packaged in plastic containers, and stored at –20 °C until further use.	[28]
<i>Thunnus albacares</i>	A: India B: Local fish landing centre	Skin, Gills, Viscera, Fins, Head	The fish were collected and transported to the laboratory, where they were minced using an electric grinder. Thermal inactivation of endogenous enzymes was performed by cooking at 100 °C for 30 min.	[29]
<i>Sardinella sp.</i>	A: Not specified B: Not specified	Heads, Viscera, Bones, and Tails	Collection of mixed raw by-products was homogenised using a blender with deionised water and stored at 20 °C until further use.	[34]
<i>Labeo rohita</i>	A: India B: Not specified	Viscera	Collection of raw material under cold conditions was transported to the laboratory. They were washed with cold water to remove the blood, slime, and any other potentially adhered impurities and stored at –18 °C ± 2 °C until further use.	[33]
Decapterus <i>Macrosoma</i>	A: Malaysia B: “Maperow sdn. Bhd”	Bones, Tails	The collection of raw material was washed and stored at –80 °C until further use.	[18]
<i>Acipenser sinensis</i>	A: China B: Aquatic Products Science and Technology Industry Co., Ltd.	Viscera	The fish were collected and transported to the laboratory, where they were cleaned, and the viscera were removed and stored frozen at –20 °C, until further use.	[30]

Continued

<i>Rachycentron canadum</i>	A: Brazil B: "Aqualider Maricultura Ltda"	Fish meat	The fish were collected in ice-filled containers and transported to the Laboratory, where they were washed with chlorinated water (2 g/l). The fish were beheaded and eviscerated to remove the skin and spines, the meat was stored in plastic containers, and kept frozen at $-18^{\circ}\text{C} \pm 2^{\circ}\text{C}$ until further use. Before the use, the waste was then centrifuged at 8667 x g for 30 min in order to reduce the lipid content	[27]
<i>Gadus morhua</i>	A: Lithuania B: "Espersen A/S"	Cod frames	The fish were filleted and transported in a frozen state, then stored at -40°C until further use.	[40]
<i>Pangasius hypophthalmus</i>	A: Vietnam B: "Nam Viet Corporation"	Head, Viscera, Trimmings, Frames, Skin, Liver, Roes	The collection of raw material was packaged in polyethylene bags and covered with ice in Styrofoam boxes, then transported to the laboratory. It was then ground, mixed, weighed in 100 g portions, packaged in polyethylene bags, and stored at -18°C until use.	[31]
<i>Mallotus villosus</i>	A: Canada B: Not specified	-	The fish were collected and transported to the Laboratory	[41]
<i>Oreochromis niloticus</i>	A: Brazil B: Local market	Bones, Carcass, Fins	The collection of raw material was separated from the carcass, ground, homogenised , and dried in a convection oven at 180°C for one hour to remove the moisture, and then stored at -80°C until further use.	[36]
<i>Oreochromis niloticus</i>	A: Brazil B: "Noronha Pescados Ltd".	Viscera, Carcass	The collection of raw material was homogenised in distilled water 4°C , the mixture was centrifuged at $10,000 \times \text{g}$ for 15 min at 4°C , and the supernatant was frozen at -20°C for future use.	[37]
<i>Scomber scombrus</i>	A: Canada B: "Clearwater" and "Sea Crest Fisheries"	Flesh, Head, Frames, Fin, Tail, Skin, Guts	The fish were collected in sealed plastic bags and transported to the laboratory, and stored in a freezer at -20°C until further use.	[26]
<i>Lepturacanthus savala</i>	A: India B: Local market	Internal organs	The fish were beheaded, and the internal organs were removed, homogenised , and stored at -20°C until further use.	[25]
<i>Squalus canicula</i>	A: Spain B: Local market	Muscle flesh	The raw material was thawed, the muscle flesh was removed, ground, and stored in sealed plastic bags at -20°C until further use.	[42]

3.2. Preparation of Fish By-Product Samples

The articles on EH were categorised and analysed according to key parameters, including the type of fish waste or by-products used, the type of proteolytic enzymes used, and the pH, temperature and incubation time of the hydrolysis process. In addition, temperature and duration required for enzyme inactivation and the types of extracts obtained were also taken into account. The specific conditions for the EH of fish waste and/or by-products are listed in **Table 2**. The process of EH is outlined in **Figure 2**, which provides an overview of the process.

Table 2. Description of the conditions of enzymatic hydrolysis of fish by-products.

Fish Biomass	Proteolytic Enzymes	Incubation (pH)	Incubation Temperature	Incubation Time	Enzyme Inhibition Temp./Time	Recovered Extracts	References
Frames without heads	Neutrase	Single pH 6.3 - 6.5	Single temp. 47°C - 50°C	Different periods 1 min, 15 min, 30 min, 45 min, 60 min, 90 min, 120 min	90°C for 10 min	Protein	[19]
	Alcalase	7.3 - 7.6	56°C - 60°C				
	Pepsin	2.4 - 2.8	36°C - 38°C				
	Kojizyme	5.5 - 5.9	46°C - 55°C				
Heads							
Skins, Viscera, Mangled muscles	Alcalase	Single pH 8.0	Single temp. 50°C	Single time 180 min	Not specified	FPH, Collagen, Fish oil	[54]
Low-valued fish (by-catch)	Papain	Single pH 5.0	Single temp. 40°C	Different periods: 5 h, 10 h, 15 h	Not specified	Protein	[61]
Fish Soluble Concentrate	Flavourzyme	Single pH 5.9 - 6.0	-	Single time 1 - 6 h	85°C for 15 min	Protein	[62]
Viscera, Backbone, Spine	Flavourzyme	Single pH 5.0 - 7.0	Single temp. 50°C	Single time 60 min	90°C for 5 min	FPH, Fish oil	[53]
	Neutrase	5.5 - 7.5	45°C - 55°C	60 min			
nonspecified	Alcalase	Single pH 8.5	Single temp. 60°C	Single time 180 min	90°C for 10 min	FPH	[59]
	Protana	5.5	55°C	180 min			
Minced	Papain	Single pH 7.0	Different temp. 40°C, 60°C, 80°C	Different periods: 5 h, 10 h, 15 h	90°C for 15 min	FPH	[49]
	Alcalase	7.0					
Visceral	Protease P “Amano” 6		Single temp. 40°C,	Single time: 2 h	85°C for 20 min	Lipids, FPH, Collagen	[44]
	Alcalase	Not specified	40°C	2 h			
	Protex 7L		40°C	2 h			
	Neutrase		40°C	2 h			
Heads, Frames, Viscera	Alcalase	Single pH 8.0	Single temp. 55°C	Single time 2 - 4 h	90°C for 10 min	Fish oil, FPH	[48]
	Flavourzyme	6.5	50°C	2 - 4 h			
	SEBPro	4.5	50°C	2 - 4 h			
Heads	Papain	Single pH 6.0 - 7.0	Single temp. 55°C	Single time 120 min	Not specified	Fish oil, DHA EPA	[56]
	Bromelain	6.0 - 8.0	50°C	120 min			
	Trypsin	7.5 - 8.0	45°C	120 min			
Viscera	Alcalase	Single pH 8.5	Single temp. 55°C	Different periods: 30 min, 75 min, 120 min	90°C for 10 min	Fish oil, Omega-3	[55]
Head, Tail, Fins	Alcalase	Single pH 8.0	Single temp. 55°C ± 1°C	-	95°C for 10 min	Protein	[58]
Frames,	Protamex	Not specified	Single temp. 55°C	Single time 60 min	95°C for 10 min	FPH, Insoluble fraction	[24]

Continued

Backbone	Flavourzyme	Single pH 7.0	Single temp. 50 °C	Different periods: 0,5 h, 1 h, 2 h, 3 h	95 °C for 15 min	Protein	[45]
Discards	Alcalase	Single pH 8.65	Single temp. 60 °C	Single time 4 h	90 °C for 15 min	FPH	[46]
Fillets	Papain Bromelain	Not specified	Single temp. 40 °C ± 1 °C 40 °C ± 1 °C	Different periods: 20 min, 60 min, 120 min	Addition of hydrogen peroxide	FPH	[50]
By-products	Alcalase Trypsin	Single pH 8.5	Single temp. 55 °C	Single time 2 - 4 h	95 °C/20min	-	[43]
		7.0	37 °C	2 - 4 h			
Scales	Alcalase	Single pH 8.0	Single temp. 55 °C	Single time 2 - 4 h	100 °C/10min	FPH, Gelatin	[52]
Fish powder	Protease	Single pH 6.0	Single temp. 60 °C	Single time 15 h	95 °C for 20 min	FPH	[51]

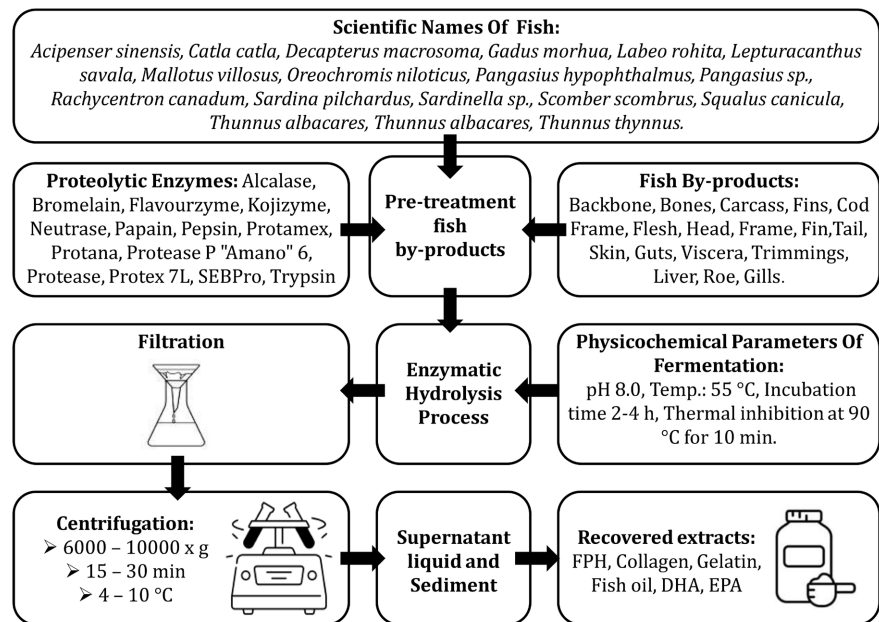


Figure 2. Description of the enzymatic hydrolysis process with the use of proteolytic enzymes for the recovery of bioactive components from raw fish by-products.

According to the data from this literature review, the biomass used to conduct fish EH experiments is mainly derived from processing waste and/or fish by-products [43] [44]. When conducting EH experiments, the corresponding processed fish biomass is placed in a vessel with water at a ratio of 1:2 or 1:3 (w/v) [45] [46]. EH is achieved by using endogenous enzymes that contribute to the degradation of the substrate [47]. The following proteolytic enzymes: alcalase, flavourzyme, papain, neutrase and trypsin [43] [44] [48] [49] seem to be used more frequently than the following: Protamex, Kojizyme and bromelain [19] [24] [50]. As shown in **Table 2**, EH is successfully accomplished primarily by selecting the appropriate

proteolytic enzyme in combination with the type of by-product. Secondly, the enzymes are influenced by certain physico-chemical fermentation parameters such as pH, temperature, incubation time and the method of enzyme inhibition [47]. Certain enzymes require the dissolution of the substrate in an acidic or alkaline environment in order to be activated. Pepsin, for example, functions in an acidic pH environment, typically at a pH of 2.4 - 2.8 [19], while alcalase is used in an alkaline environment with a pH of 7.3 - 8.65 [19] [46]. The minimum incubation temperature for trypsin is 37°C [43], while the maximum incubation temperature for papain and alcalase can reach up to 80°C [49]. The incubation time for neutrase, alcalase, pepsin and kojizyme ranges from 1 min [19] to 15 h in general for various proteases [51]. The EH process is completed by enzyme inhibition, which is achieved by thermal inactivation at temperatures between 85°C and 100°C for 5 to 20 min and/or by the use of additives such as hydrogen peroxide. The temperature of the hydrolysate is gradually brought to ambient temperature [43] [44] [52] [53]. The hydrolysate produced is then centrifuged to separate the hydrolysate into a supernatant liquid and a sediment. The supernatant liquid contains the proteins often referred to as FPH [49] [51]. In summary, after the EH process, the supernatant liquid and sediment are the resulting products. Further processing of these recovered products leads to the recovery of bioactive compounds, which are not the focus of this review but are nevertheless worth mentioning. These include bioactive components such as collagen, gelatin [44] [52] [54] oils and lipids, fish oil, DHA, EPA [44] [48] [53]-[56], which are summarised in **Table 2** and **Figure 2**. To summarise, based on the collected articles in this review, the typical process for the EH of fish by-products to obtain FPH is as follows: First, the pre-processed fish by-product biomass is mixed in a vessel with water at a ratio of 1:1 (w/v) [11] [57]. The EH of the fish biomass is usually achieved by the proteolytic action of the enzyme alcalase [43] [46] [48] [52] [55], whereby the fermentation conditions are set as follows: pH 8 [48] [52] [58] and a temperature of 55°C [24] [43] [52]. The fermentation process takes 2 - 4 h and enzyme inhibition is usually achieved by heating at 90°C for 10 min [48] [55] [59]. The quantification of FPH is usually carried out by chemical analyses that determine the protein content of the hydrolysate. One of the most common methods is the Kjeldahl method, which calculates the nitrogen content of the sample and then estimates the percentage of protein content on a dry weight basis [60].

4. The Use of FPH as an Alternative Protein Source Compared to Fish Meal

A significant proportion of global production of fishmeal and fish oil is used to provide protein for the production of fish feed to support the intensive farming of carnivorous fish in aquaculture [63]. According to Sales, 2003 [64], the protein requirement in the diet ranges from about 30% for the breeding of omnivorous goldfish *Carassius auratus* to 50% for carnivorous discus fish *Symphysodon aequifasciata*. Around 5 kilograms of wild fish are needed to produce 1 kilogram of car-

nivorous farmed fish [63]. To reduce this dependency, the scientific community is focusing on the development of alternative protein sources such as FPH, which are obtained by EH processes from waste or by-products of fisheries and aquaculture. The articles included in this literature review **Table 3** and **Figure 3** show that the addition of FPH to the feed of farmed fish is used at almost all stages of their life cycle.

Table 3. The impact of protein hydrolysate inclusion in diets on farmed fish species and its associated benefits.

Farmed Fish: A: Common name B: Scientific name	Inclusion percentage of protein hydrolysate in diets	Feeding trial at Initial Weight (g)	Feeding Duration	Benefits	References
A: Atlantic salmon B: <i>Salmo salar</i>	FPH: 5%, 10%, 15% of total dietary	Average Initial weight: 163 g	68 days	Improved growth, Higher protein, and digestibility compared to fish meal	[66]
A: Atlantic salmon B: <i>Salmo salar</i>	Squid Protein Hydrolysate: 3% of total dietary	Average Initial weight: 327 - 642 g	85 days	Improved growth, Higher protein and lipid digestibility compared to fish meal	[65]
A: Japanese flounder B: <i>Paralichthys olivaceus</i>	FPH: 37 g/kg or 3.7% of total dietary	-	60 days	Improved growth, Protein digestibility,	[69]
A: Pabda catfish B: <i>Ompok pabda</i>	FPH: 0.5%, 1%, 2% of total dietary	Average Initial weight: 2.00 ± 0.09 g	90 days	Improved growth, Survival and disease, Resistance to <i>Aeromonas hydrophila</i>	[15]
A: Atlantic salmon B: <i>Salmo salar</i>	FPH: 10% of total dietary	-	12 weeks	Improved growth, Enhanced amino acid levels,	[79]
A: Juvenile Turbot B: <i>Scophthalmus maximus</i>	FPH: 5%, 10%, 20% of total dietary	Average Initial weight: 4.16 ± 0.01 g	12 weeks	Improved growth, Decrease in triacylglycerol and cholesterol levels in the blood	[72]
A: Nile tilapia B: <i>Oreochromis niloticus</i>	FPH: 2%, 4%, 6%, 8% of total dietary	-	-	Improved growth, Protein digestibility	[70]
A: Barramundi B: <i>Lates calcarifer</i>	(FPH)	Average Initial weight: 6.18 ± 0.08 g	60 days	Improved growth, Increase in white blood cells and Protein levels in blood, Reduction in mortality from <i>Vibrio harvei</i> .	[73]
A: Juvenile African catfish B: <i>Clarias gariepinus</i>	FPH: 5%, 10%, 15%, 20% of total dietary	-	10 weeks	Increased growth, increased immunoglobulin levels in the blood, improvement in body composition regarding moisture and lipids.	[71]
A: Yellow croaker B: <i>Pseudosciaena crocea</i> R.	FPH: 5%, 10%, 15% of total dietary	Average Initial weight: 162.75 ± 23.85 g	8 weeks	Enhanced immune response.	[80]
A: Olive flounder B: <i>Paralichthys olivaceus</i>	Krill hydrolysate protein and FPH 2% of total dietary	Average Initial weight: 24.5 ± 0.3 g	9 weeks	Improved growth, Protein digestibility, Enhanced immune response, and Increased resistance to <i>Edwardsiella tarda</i>	[68]

Continued

A: Juvenile Turbot B: <i>Scophthalmus maximus</i> L.	FPH: 1.2%, 3.7% of total dietary	Average Initial weight: 27.87 ± 0.04 g	8 weeks	Improved of growth, and antioxidant capacity	[77]
A: Largemouth Bass B: <i>Micropterus salmoides</i>	FPH: 10%, 30%, 50% of total dietary	Average Initial weight: 9.51 ± 0.0 g	56 days	Improvement of Growth, Intestinal Health, and Enhancement of Immune Response	[67]
A: Juvenile Turbot B: <i>Scophthalmus maximus</i> L.	FPH: 5%, 10%, 15%, 20%	Average Initial weight: 16.05 ± 0.03	68 days	Improved of Growth	[81]
A: Japanese flounder B: <i>Paralichthys olivaceus</i>	FPH: 6%, 11%, 16%, 21%, 26% of total dietary	Average Initial weight: 38.80 ± 1.11 g	-	Improved growth, Antioxidant capacity, and free radical combat.	[78]
A: Atlantic salmon B: <i>Salmo salar</i>	FPH: 10% of total dietary	Average Initial weight: 4.3 g	5 weeks	Improved growth, Enhanced immunity, and Better infection resistance Improved growth, Immune response with enhanced leukocyte and erythrocyte counts	[74]
A: Nile Tilapia B: <i>Oreochromis niloticus</i>	FPH: 0.5%, 1%, 2% of total dietary	-	90 days	Better gut and liver health, Increased resistance to <i>Streptococcus</i>	[75]
A: Blue Whiting B: <i>Micromesistius poutassou</i>	FPH: 1.4 g and 2.8 g/kg or 0.14% and 0.28% of total dietary	-	45 and 90 days	-	[82]

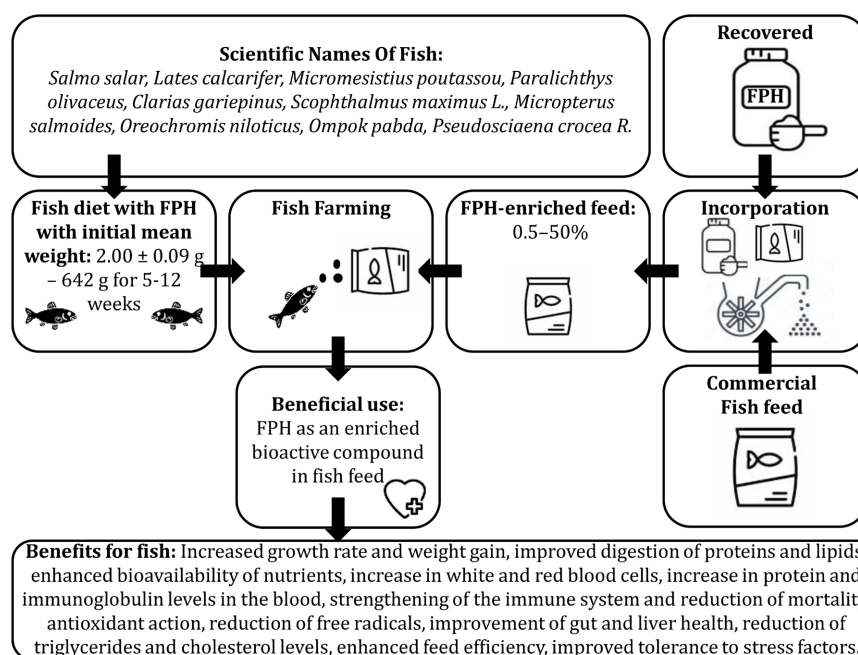


Figure 3. Description of the production of fish feeds with FPH and its benefit to farmed fish.

Experimental feeding trials start with a minimum average weight of about 2.00

± 0.09 g [15], for farmed fish of the species *Ompok pabda*, while, in the case of the farmed fish species *Salmo salar*, the experimental feeding trials start with a maximum average weight of 642 g [65]. Experimental feeding trials with smaller farmed fish of the species *Salmo salar* appear to end with an average final weight of between 323 and 377 g [65]. In contrast, feeding trials with larger farmed fish of the same species appear to reach a maximum individual weight of 642 g [65] [66]. A proportion of 3% - 50% hydrolyzed proteins from fish waste, by-products and other related sources, such as squid, can effectively support rapid fish growth, comparable to a diet based solely on fishmeal [65]-[67]. In addition, small amounts of hydrolyzed proteins can improve the digestibility of proteins and lipids compared to fishmeal [65] [66]. The following farmed fish species *Clarias gariepinus*, *Lates calcarifer*, *Micromesistius poutassou*, *Ompok pabda*, *Oreochromis niloticus*, *Paralichthys olivaceus*, *Pseudosciaena crocea*, *Salmo salar* and *Scophthalmus maximus* have been used in various studies to evaluate the effects and efficiency of FPH, squid protein hydrolysates and krill hydrolysate protein [65] [66] [68]. Most experimental feeding trials with FPH-enriched diets and other compatible hydrolyzed seafood proteins focus primarily on the partial replacement of fishmeal and the bioavailability of these specific bioactive compounds in the fish body. The expected results mainly concern fish growth parameters compared to control diets (containing only fishmeal) and diets containing certain percentages 0.5% - 50% of hydrolyzed proteins from fish and other protein-rich marine organisms [65]-[68]. The duration of the experimental feeding trials varies depending on the research question of the study. In the short term, the bioavailability of the hydrolyzed proteins in the fish body is investigated, while in the long term the overall growth of the farmed fish is evaluated. In general, the experiments are carried out over a period of 5 - 12 weeks. Farmed fish of the species *Salmo salar* and *Paralichthys olivaceus* reared with certain concentrations of FPH show positive results in terms of growth compared to conventional feeds consisting only of fishmeal [65] [66] [69]. Similar positive results were also observed with regard to the bioavailability of proteins and lipids [65] [66] [68]-[71]. When analyzing the hematological parameters of farmed fish of the species *Scophthalmus maximus*, *Lates calcarifer* and *Clarias gariepinus* fed with diets containing FPH in an amount of 5% - 20% of the total diet, significant improvements in hematological parameters were observed [71]-[73]. The results of the tests showed a decrease in triacylglycerol and cholesterol levels in the blood as well as an increase in white blood cells, protein levels and immunoglobulins in the blood. These results indicate an improved metabolism and an enhanced immune response in the farmed fish [71]-[73]. From an immune response perspective, it appears that FPH improve gut and liver health in farmed fish such as *Lates calcarifer*, *Ompok pabda*, *Oreochromis niloticus*, *Paralichthys olivaceus* and *Salmo salar* in a positive way, particularly by increasing white and red blood cell counts. Consequently, these bioactive compounds reduce mortality by boosting immunity against pathogenic microorganisms such as *Streptococcus*, *Edwardsiella tarda* and *Aeromonas hydrophila*, making the fish

more resistant to infections and diseases under culture conditions [15] [68] [73]-[75]. Fish farming can induce stress due to various factors, e.g. environmental factors that lead to an increase in free radicals and oxidative damage, which weakens the immune system of fish. Feed rich in hydrolyzed proteins can act as antioxidants, neutralise free radicals and strengthen the immune defense of fish [76]-[78].

5. Fish Protein Hydrolysate and Their Impact on Human Health

The continuous growth of aquaculture is directly related to the increase in the efficiency of fish feed. Consequently, this development must be fully in line with the principles of the circular economy to ensure the sustainable growth of aquaculture. The management and utilization of fish by-products through biotechnological applications, such as EH with appropriate proteolytic enzymes, contribute to the production of usable bioactive compounds, such as hydrolyzed fish proteins FPH. If these hydrolyzed proteins partially or completely replace fishmeal in fish feed production, there are two major benefits: Firstly, the circular economy is strengthened, and secondly, fish feed with new biological properties is created. The rich BAPs and amino acids produced by EH become more digestible and absorbable by farmed fish, which brings corresponding benefits to the human body through nutrition [17] [18]. It is possible that the consumption of fish containing assimilable FPH is not limited to its high nutritional value, but may also provide significant health benefits for humans. As **Figure 4** shows, hydrolyzed fish proteins support the smooth functioning of gene regulation by promoting the production of antioxidant enzymes such as glutathione and catalase.

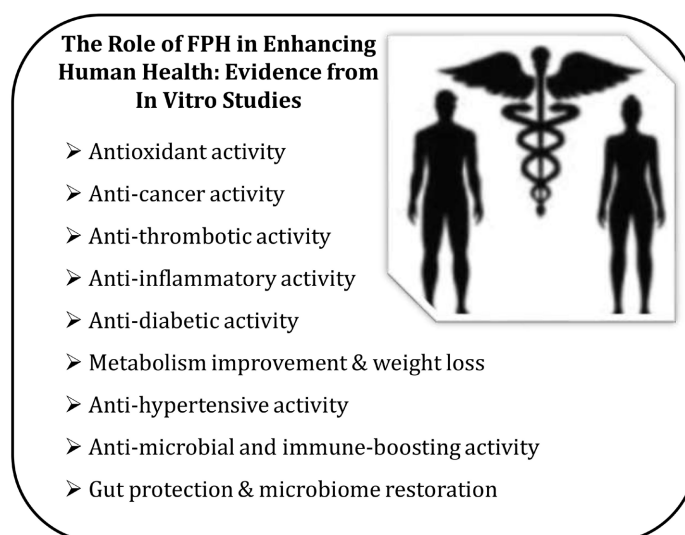


Figure 4. FPH and their impact on human health.

These enzymes help neutralize free radicals due to their strong antioxidant effect. Free radicals, in turn, cause cell damage that exacerbates conditions such as

aging, inflammation and other diseases [83]-[88]. Compared to other foods, hydrolyzed fish proteins contain lower amounts of arsenic and cadmium, indicating lower toxicity. Toxicity is generally associated with serious diseases such as cancer and kidney dysfunction [89]. The bioactive compounds mentioned above appear to influence the development of human cancer cell lines *in vitro*, which may be associated with mechanisms related to carcinogenesis inhibition. However, it is important to emphasize that the available data are primarily based on laboratory studies, and there is currently insufficient evidence to support their effectiveness in human clinical trials. Therefore, although the consumption of FPH could represent a subject of future research, additional scientific data particularly at the clinical level are required before substantiated and reliable claims can be made regarding the prevention or treatment of cancers such as colorectal, breast, and liver cancer [18] [84] [86] [87] [89]-[92]. In addition, the bioactive compounds mentioned above have an anticoagulant effect and contain peptides and amino acids of high nutritional value, which contribute to lowering triglycerides and blood cholesterol [88] [93]. Consequently, the consumption of hydrolyzed proteins has a positive effect on the prevention of cardiovascular diseases and arterial damage such as atherosclerosis [18] [88]. They also have an antioxidant effect due to their composition, which contains branched-chain amino acids such as leucine, isoleucine and valine. These amino acids contribute to the reduction of inflammatory reactions and give the proteins strong anti-inflammatory properties. As a result, these peptides and amino acids can help prevent and treat inflammatory bowel disease, reduce damage to the intestinal mucosa, restore intestinal function and treat colitis [91] [94] [95]. Due to their high nutritional value, hydrolyzed fish proteins help in the treatment of metabolic and digestive disorders as well as food allergies. At the same time, they help to regulate the metabolism in a desirable way [4] [17] [84] [88]. As dietary supplements, they help to reduce obesity, support weight loss, maintain muscle mass and burn fat. At the same time, they promote general health and well-being [17] [85] [95]. Hydrolyzed fish proteins also have a blood pressure-lowering effect [18] [84] [88] and contribute to lowering blood pressure [88] [93]. They have strong antibacterial and antimicrobial properties [18] [84] [87], strengthen the immune system [4] and increase resistance to infections and diseases. They also help to regulate blood sugar levels and thus support the treatment of diabetes. Their antidiabetic effect is also associated with the regulation of platelet aggregation and thus promotes general health [85] [93]. The partial and/or total replacement of fishmeal in fish feed contributes to the development of new innovative feeds that exert bioactive effects on farmed fish in different ways and offer them numerous benefits during their captive rearing. In addition, the presence of these bioactive compounds can provide equally significant benefits to the human body through the diet. Although hydrolyzed proteins have been shown to have beneficial effects on farmed fish, certain scientific questions regarding the extent to which these bioactive compounds are absorbed by the human body remain unanswered. It is important to determine the optimal concen-

tration of hydrolyzed proteins required to achieve positive effects on human health without causing problems in fish production. In addition, it is necessary to identify the age groups that can benefit from the intake of these proteins, as well as those that may need to be excluded. The study of the appropriate administration period is also crucial to ensure the maximisation of their beneficial effects on the human organism. Therefore, further scientific research is essential to answer the above questions and to clarify the role of these bioactive compounds in human health. It can be confidently argued that farmed fish enriched with hydrolyzed fish proteins can help combat malnutrition while supporting the circular economy and promoting the sustainable development of aquaculture. Regular consumption of such foods could serve as a natural dietary supplement thanks to their high antioxidant activity and contribute to improving human health and well-being [88].

6. Trends and Future Challenges of Fish By-Product Utilization

In recent years, there has been an increasing trend in the management and utilization of fish by-products aimed at obtaining bioactive compounds of high economic interest. To achieve this goal, proteolytic enzymes for protein hydrolysis have been used in several studies. The biotechnological method of EH is directly linked to the circular economy as it is user-friendly and environmentally friendly. However, the cost of proteolytic enzymes is still high. A key challenge for future research is to optimise the reuse of proteolytic enzymes and to maintain or improve their activity across successive hydrolysis cycles. One strategy to address these challenges is the immobilisation and/or entrapment of enzymes in a two-phase system, where one phase contains only the enzyme and the other only the product. Immobilization or containment of enzymes offers a cost-effective solution that increases productivity during the hydrolysis process, as it facilitates the separation of the enzyme from the product, reduces potential contamination risks of the product, and allows the reuse of enzymes. However, the reuse of enzymes in the context of fish by-product processing is still under development, and further research is required to optimise its application and confirm its viability at an industrial scale [96] [97]. Addressing the above issues coupled with improving the uptake of hydrolyzed proteins by farmed fish and transferring these benefits to the human body through the diet is expected to increase the demand for FPH from various fishery and aquaculture by-products due to the reduction of the environmental footprint. This will have a positive impact on human health. Another challenge for the future is the competition between partial or complete replacement of fishmeal with hydrolyzed proteins, assuming that certain concentrations of FPH provide significant benefits to farmed fish. In this case, dependence on fishmeal will decrease, leading to a shift in fishmeal production trends, which will cause significant change in the global fish feed market [65] [66]. The raw material for fishmeal production comes from certain marine organisms such as anchovies

and sardines, which are caught using specific methods. These organisms have a low commercial value and are therefore not intended for human consumption [98]. Similarly, the raw material for the production of hydrolyzed proteins consists of various fishery and aquaculture by-products such as skins, skeletal remains (frame, backbone, spine, tails, fins, scales and fillet remains (Table 2). The predominant processing method for the production of fishmeal is thermal drying using hot air and/or vacuum conditions to remove moisture [99]. In contrast, the production of hydrolyzed proteins is based on EH, which is carried out by fermentation with proteolytic enzymes. Depending on the type of enzyme, different bioactive compounds are produced that have a high added value, in contrast to fishmeal production, which is limited to fishmeal and fish oil [98] [99]. The increasing emphasis on the circular economy and environmental protection is expected to have a significant impact on the management and use of raw materials. The use of by-products from fisheries and aquaculture is expected to be strengthened, as the abundance of these materials represents a more sustainable and environmentally friendly alternative to anchovy and sardine fishing [98]. A possible future challenge will be the replacement of fishmeal by FPH, which will contribute to the circular economy. Many recent studies, such as the research by Bhati and Hayes, 2025 [100], highlight that Fish Protein Hydrolysates FPH represent a promising solution to reduce the use of fishmeal in aquafeeds, offering improved growth and survival, as well as enhanced immune response in fish. However, future challenges that need to be addressed include ensuring the consistent production of high-quality FPH at economically viable levels, adapting hydrolysis technologies to efficient and low-cost raw materials, in order to achieve results comparable to those based on high levels of fishmeal. At the same time, the management and utilisation of industrial by-products from the fishing and aquaculture industries will lead to a reduction in environmental degradation, enhancing sustainable development.

7. Discussion

The rapid growth of fisheries and aquaculture is making a significant contribution to tackling the global malnutrition crisis. However, the lack of application of circular economy principles leads to uncontrolled pollution from by-products, which harms marine biodiversity and jeopardises the sustainability of ecosystems. The valorisation of by-products through EH into FPH offers a sustainable alternative protein source that reduces the environmental footprint and improves global food security. The production of FPH is mainly based on proteolytic enzymes (e.g. alcalase) under controlled conditions (pH 8, 55°C, 2 - 4 h). However, the high cost of the enzymes is still a major limitation. Research into recovery and reuse methods, such as the immobilisation of enzymes, aims to improve the economic efficiency of the process. The addition of FPH to the feed of farmed fish promotes growth, immune response and resistance to pathogens, while the consumption of enriched fish is associated with human health benefits due to BAPs

that show antioxidant, anti-inflammatory and other beneficial effects. However, further clinical studies are needed to confirm their safety and efficacy. The transition to a circular economy through the valorisation of fishery and aquaculture by-products is key to the development of high value-added farmed fish. This transition requires the optimisation of processes, the reduction of enzyme costs and the introduction of strict regulations to ensure quality and safety.

8. Conclusions

- Proteolytic enzymes such as alcalase are used for the production of FPH from various fish by-products. The enzyme alcalase is more commonly used under certain fermentation conditions, specifically at pH 8, temperature of 55°C and incubation time of 2 - 4 h, while inhibition of the enzyme is achieved by thermal inhibition at 90°C for 10 min.
- Fish feed containing small amounts of FPH, used for farmed fish with an initial weight of 2.00 ± 0.09 g up to 642 g over a period of no more than 5 - 12 weeks, showed positive effects on the growth and health of the fish. Partial replacement of fishmeal with hydrolyzed proteins could be of greater benefit to farmed fish.
- Preliminary evidence suggests that consumption of fish enriched with hydrolyzed proteins may offer health benefits, potentially contributing to the prevention and management of certain diseases. However, further clinical studies are required to confirm these effects.
- Unlike conventional fishmeal, which is made from caught fish not intended for human consumption, this process uses discarded fish biomass as a raw material. By recycling these by-products, the ecological footprint can be reduced and the efficiency of production processes in the fish industry can be improved.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Halim, N.R.A., Yusof, H.M. and Sarbon, N.M. (2016) Functional and Bioactive Properties of Fish Protein Hydrolysates and Peptides: A Comprehensive Review. *Trends in Food Science & Technology*, **51**, 24-33. <https://doi.org/10.1016/j.tifs.2016.02.007>
- [2] Siddik, M.A.B., Howieson, J., Fotedar, R. and Partridge, G.J. (2020) Enzymatic Fish Protein Hydrolysates in Finfish Aquaculture: A Review. *Reviews in Aquaculture*, **13**, 406-430. <https://doi.org/10.1111/raq.12481>
- [3] Chalamaiyah, M., Dinesh kumar, B., Hemalatha, R. and Jyothirmayi, T. (2012) Fish Protein Hydrolysates: Proximate Composition, Amino Acid Composition, Antioxidant Activities and Applications: A Review. *Food Chemistry*, **135**, 3020-3038. <https://doi.org/10.1016/j.foodchem.2012.06.100>
- [4] Kristinsson, H.G. and Rasco, B.A. (2000) Fish Protein Hydrolysates: Production, Biochemical, and Functional Properties. *Critical Reviews in Food Science and Nutri-*

- tion, **40**, 43-81. <https://doi.org/10.1080/10408690091189266>
- [5] Zamora-Sillero, J., Gharsallaoui, A. and Prentice, C. (2018) Peptides from Fish By-Product Protein Hydrolysates and Its Functional Properties: An Overview. *Marine Biotechnology*, **20**, 118-130. <https://doi.org/10.1007/s10126-018-9799-3>
- [6] Arvanitoyannis, I.S. and Kassaveti, A. (2008) Fish Industry Waste: Treatments, Environmental Impacts, Current and Potential Uses. *International Journal of Food Science & Technology*, **43**, 726-745. <https://doi.org/10.1111/j.1365-2621.2006.01513.x>
- [7] Strasburg, G.M. and Xiong, Y.L. (2017) Physiology and Chemistry of Edible Muscle Tissues. In: Damodaran, S. and Parkin, K.L., Eds., *Fennema's Food Chemistry*, CRC Press, 955-1015.
- [8] Abdullah, F.I., Hamid, N.H., Abd Karim, M.M., Ismail, M.F., Sin, N.L.W.W. and Kamaruddin, M.S. (2024) Fish Protein Hydrolysate for Fish Health. *Biocatalysis and Agricultural Biotechnology*, **60**, Article 103292. <https://doi.org/10.1016/j.bcab.2024.103292>
- [9] Ishak, N.H. and Sarbon, N.M. (2017) Optimization of the Enzymatic Hydrolysis Conditions of Waste from Shortfin Scad (*Decapterus macrosoma*) for the Production of Angiotensin I-Converting Enzyme (ACE) Inhibitory Peptide Using Response Surface Methodology. *International Food Research Journal*, **24**, 1735-1743.
- [10] Wangkheirakpam, M.R., Mahanand, S.S., Majumdar, R.K., Sharma, S., Hidangmayum, D.D. and Netam, S. (2019) Fish Waste Utilization with Reference to Fish Protein Hydrolysate—A Review. *Fishery Technology*, **56**, 169-178.
- [11] Fotodimas, I., Ioannou, Z. and Kanlis, G. (2024) A Review of the Benefits of the Sustainable Utilization of Shrimp Waste to Produce Novel Foods and the Impact on Human Health. *Sustainability*, **16**, Article 6909. <https://doi.org/10.3390/su16166909>
- [12] Sharkey, S.J., Harnedy-Rothwell, P.A., Allsopp, P.J., Hollywood, L.E., FitzGerald, R.J. and O'Harte, F.P.M. (2020) A Narrative Review of the Anti-Hyperglycemic and Satiating Effects of Fish Protein Hydrolysates and Their Bioactive Peptides. *Molecular Nutrition & Food Research*, **64**, Article ID: 2000403. <https://doi.org/10.1002/mnfr.202000403>
- [13] Idowu, A.T., Igiehon, O.O., Idowu, S., Olatunde, O.O. and Benjakul, S. (2021) Bioactivity Potentials and General Applications of Fish Protein Hydrolysates. *International Journal of Peptide Research and Therapeutics*, **27**, 109-118. <https://doi.org/10.1007/s10989-020-10071-1>
- [14] Hodar, A.R., Vasava, R.J., Mahayadiya, D.R. and Joshi, N.H. (2020) Fish Meal and Fish Oil Replacement for Aqua Feed Formulation by Using Alternative Sources: A Review. *Journal of Experimental Zoology-India*, **23**, 13-21.
- [15] Suma, A.Y., Nandi, S.K., Abdul Kari, Z., Goh, K.W., Wei, L.S., Tahiluddin, A.B., et al. (2023) Beneficial Effects of Graded Levels of Fish Protein Hydrolysate (FPH) on the Growth Performance, Blood Biochemistry, Liver and Intestinal Health, Economics Efficiency, and Disease Resistance to *Aeromonas Hydrophila* of Pabda (*Ompok pabda*) Fingerling. *Fishes*, **8**, Article 147. <https://doi.org/10.3390/fishes8030147>
- [16] Nirmal, N.P., Santivarangkna, C., Rajput, M.S., Benjakul, S. and Maqsood, S. (2022) Valorization of Fish Byproducts: Sources to End-Product Applications of Bioactive Protein Hydrolysate. *Comprehensive Reviews in Food Science and Food Safety*, **21**, 1803-1842. <https://doi.org/10.1111/1541-4337.12917>
- [17] Ryu, B., Shin, K. and Kim, S. (2021) Muscle Protein Hydrolysates and Amino Acid Composition in Fish. *Marine Drugs*, **19**, Article 377. <https://doi.org/10.3390/md19070377>

- [18] Ishak, N.H. and Sarbon, N.M. (2018) A Review of Protein Hydrolysates and Bioactive Peptides Deriving from Wastes Generated by Fish Processing. *Food and Bioprocess Technology*, **11**, 2-16. <https://doi.org/10.1007/s11947-017-1940-1>
- [19] Liaset, B., Lied, E. and Espe, M. (2000) Enzymatic Hydrolysis of By-Products from the Fish-Filleting Industry; Chemical Characterisation and Nutritional Evaluation. *Journal of the Science of Food and Agriculture*, **80**, 581-589. [https://doi.org/10.1002/\(sici\)1097-0010\(200004\)80:5<581::aid-jsfa578>3.0.co;2-i](https://doi.org/10.1002/(sici)1097-0010(200004)80:5<581::aid-jsfa578>3.0.co;2-i)
- [20] Pontoh, J. (2019) Extraction and Characterization of Fish Oil from Various Parts of Snakehead Fish (*Chana striata*). *International Journal of ChemTech Research*, **12**, 323-328. <https://doi.org/10.20902/ijctr.2019.120139>
- [21] Wai, A.L.S., Man, R.C., Mudalip, S.K.A., Sulaiman, S.Z., Arshad, Z.I.M. and Shaarani, S.M. (2020) Effects of Chemical Hydrolysis Operating Parameters on the Production of Antioxidant from Fish Waste. *IOP Conference Series: Materials Science and Engineering*, **991**, Article 012062. <https://doi.org/10.1088/1757-899x/991/1/012062>
- [22] Melgosa, R., Trigueros, E., Sanz, M.T., Carneira, M., Rodrigues, L., Fernández, N., *et al.* (2020) Supercritical CO₂ and Subcritical Water Technologies for the Production of Bioactive Extracts from Sardine (*Sardina pilchardus*) Waste. *The Journal of Supercritical Fluids*, **164**, Article 104943. <https://doi.org/10.1016/j.supflu.2020.104943>
- [23] Chongkhong, S. (2023) Optimisation of Ultrasound-Assisted Lipid Extraction in the Pretreatment of Purple-Spotted Bigeye Fish Skin. *International Food Research Journal*, **30**, 668-682. <https://doi.org/10.47836/ifrj.30.3.11>
- [24] Liaset, B. and Espe, M. (2008) Nutritional Composition of Soluble and Insoluble Fractions Obtained by Enzymatic Hydrolysis of Fish-Raw Materials. *Process Biochemistry*, **43**, 42-48. <https://doi.org/10.1016/j.procbio.2007.10.007>
- [25] Yathisha, U.G., Vaidya, S. and Sheshappa, M.B. (2022) Functional Properties of Protein Hydrolyzate from Ribbon Fish (*Lepturacanthus savala*) as Prepared by Enzymatic Hydrolysis. *International Journal of Food Properties*, **25**, 187-203. <https://doi.org/10.1080/10942912.2022.2027964>
- [26] VV, R. (2013) Extraction of Proteins from Mackerel Fish Processing Waste Using Alcalase Enzyme. *Journal of Bioprocessing & Biotechniques*, **3**, Article 1000130. <https://doi.org/10.4172/2155-9821.1000130>
- [27] Fonseca, R.A.S., Silva, C.B.M., Fernandes, G. and Prentice, C. (2016) Enzymatic Hydrolysis of Cobia (*Rachycentron canadum*) Meat and Wastes Using Different Microbial Enzymes. *International Food Research Journal*, **23**, 152-160.
- [28] Ovissipour, M., Abedian Kenari, A., Motamedzadegan, A. and Nazari, R.M. (2012) Optimization of Enzymatic Hydrolysis of Visceral Waste Proteins of Yellowfin Tuna (*Thunnus albacares*). *Food and Bioprocess Technology*, **5**, 696-705. <https://doi.org/10.1007/s11947-010-0357-x>
- [29] Parvathy, U., Zynudheen, A.A., Panda, S.K., Jeyakumari, A. and Anandan, R. (2016) Extraction of Protein from Yellowfin Tuna (*Thunnus albacares*) Waste by Enzymatic Hydrolysis and its Characterization. *Fishery Technology*, **53**, 115-124.
- [30] Noman, A., Xu, Y., AL-Bukhaiti, W.Q., Abed, S.M., Ali, A.H., Ramadhan, A.H., *et al.* (2018) Influence of Enzymatic Hydrolysis Conditions on the Degree of Hydrolysis and Functional Properties of Protein Hydrolysate Obtained from Chinese Sturgeon (*Acipenser sinensis*) by Using Papain Enzyme. *Process Biochemistry*, **67**, 19-28. <https://doi.org/10.1016/j.procbio.2018.01.009>
- [31] Nam, P.V., Van Hoa, N., Anh, T.T.L. and Trung, T.S. (2020) Towards Zero-Waste Recovery of Bioactive Compounds from Catfish (*Pangasius hypophthalmus*) By-Products Using an Enzymatic Method. *Waste and Biomass Valorization*, **11**, 4195-

4206. <https://doi.org/10.1007/s12649-019-00758-y>
- [32] Benhabiles, M.S., Abdi, N., Drouiche, N., Lounici, H., Pauss, A., Goosen, M.F.A., *et al.* (2012) Fish Protein Hydrolysate Production from Sardine Solid Waste by Crude Pepsin Enzymatic Hydrolysis in a Bioreactor Coupled to an Ultrafiltration Unit. *Materials Science and Engineering: C*, **32**, 922-928. <https://doi.org/10.1016/j.msec.2012.02.013>
- [33] Mohanty, U., Majumdar, R.K., Mohanty, B., Mehta, N.K. and Parhi, J. (2021) Influence of the Extent of Enzymatic Hydrolysis on the Functional Properties of Protein Hydrolysates from Visceral Waste of Labeo Rohita. *Journal of Food Science and Technology*, **58**, 4349-4358. <https://doi.org/10.1007/s13197-020-04915-3>
- [34] Duarte, J.G., Silva, L.L.S., Freire, D.M.G., Cammarota, M.C. and Gutarra, M.L.E. (2015) Enzymatic Hydrolysis and Anaerobic Biological Treatment of Fish Industry Effluent: Evaluation of the Mesophilic and Thermophilic Conditions. *Renewable Energy*, **83**, 455-462. <https://doi.org/10.1016/j.renene.2015.04.056>
- [35] Bhaskar, N., Benila, T., Radha, C. and Lalitha, R.G. (2008) Optimization of Enzymatic Hydrolysis of Visceral Waste Proteins of Catla (*Catla catla*) for Preparing Protein Hydrolysate Using a Commercial Protease. *Bioresource Technology*, **99**, 335-343. <https://doi.org/10.1016/j.biortech.2006.12.015>
- [36] Moreira, T.F.M., Pessoa, L.G.A., Seixas, F.A.V., Ineu, R.P., Gonçalves, O.H., Leimann, F.V., *et al.* (2022) Chemometric Evaluation of Enzymatic Hydrolysis in the Production of Fish Protein Hydrolysates with Acetylcholinesterase Inhibitory Activity. *Food Chemistry*, **367**, Article 130728. <https://doi.org/10.1016/j.foodchem.2021.130728>
- [37] Silva, J.F.X., Ribeiro, K., Silva, J.F., Cahú, T.B. and Bezerra, R.S. (2014) Utilization of Tilapia Processing Waste for the Production of Fish Protein Hydrolysate. *Animal Feed Science and Technology*, **196**, 96-106. <https://doi.org/10.1016/j.anifeedsci.2014.06.010>
- [38] Je, J., Qian, Z., Byun, H. and Kim, S. (2007) Purification and Characterization of an Antioxidant Peptide Obtained from Tuna Backbone Protein by Enzymatic Hydrolysis. *Process Biochemistry*, **42**, 840-846. <https://doi.org/10.1016/j.procbio.2007.02.006>
- [39] Rai, A.K., Bhaskar, N. and Baskaran, V. (2014) Effect of Feeding Lipids Recovered from Fish Processing Waste by Lactic Acid Fermentation and Enzymatic Hydrolysis on Antioxidant and Membrane Bound Enzymes in Rats. *Journal of Food Science and Technology*, **52**, 3701-3710. <https://doi.org/10.1007/s13197-014-1442-3>
- [40] Jafarpour, A., Gomes, R.M., Gregersen, S., Sloth, J.J., Jacobsen, C. and Moltke Sørensen, A. (2020) Characterization of Cod (*Gadus morhua*) Frame Composition and Its Valorization by Enzymatic Hydrolysis. *Journal of Food Composition and Analysis*, **89**, Article 103469. <https://doi.org/10.1016/j.jfca.2020.103469>
- [41] Martin, A.M. and Porter, D. (1995) Studies on the Hydrolysis of Fish Protein by Enzymatic Treatment. In: *Developments in Food Science*, Elsevier, 1395-1404. [https://doi.org/10.1016/s0167-4501\(06\)80241-4](https://doi.org/10.1016/s0167-4501(06)80241-4)
- [42] Vázquez, J., Blanco, M., Massa, A., Amado, I. and Pérez-Martín, R. (2017) Production of Fish Protein Hydrolysates from *Scyliorhinus canicula* Discards with Antihypertensive and Antioxidant Activities by Enzymatic Hydrolysis and Mathematical Optimization Using Response Surface Methodology. *Marine Drugs*, **15**, Article 306. <https://doi.org/10.3390/md15100306>
- [43] Fallah, M., Bahram, S. and Javadian, S.R. (2015) Fish Peptone Development Using Enzymatic Hydrolysis of Silver Carp By-Products as a Nitrogen Source in *Staphylococcus aureus* Media. *Food Science & Nutrition*, **3**, 153-157.

- <https://doi.org/10.1002/fsn3.198>
- [44] Hathwar, S.C., Bijinu, B., Rai, A.K. and Narayan, B. (2011) Simultaneous Recovery of Lipids and Proteins by Enzymatic Hydrolysis of Fish Industry Waste Using Different Commercial Proteases. *Applied Biochemistry and Biotechnology*, **164**, 115-124. <https://doi.org/10.1007/s12010-010-9119-5>
- [45] Dong, Y., Yan, W., Zhang, X., Dai, Z. and Zhang, Y. (2021) Steam Explosion-Assisted Extraction of Protein from Fish Backbones and Effect of Enzymatic Hydrolysis on the Extracts. *Foods*, **10**, Article 1942. <https://doi.org/10.3390/foods10081942>
- [46] Vázquez, J.A., Fraguas, J., Mirón, J., Valcárcel, J., Pérez-Martín, R.I. and Antelo, L.T. (2020) Valorisation of Fish Discards Assisted by Enzymatic Hydrolysis and Microbial Bioconversion: Lab and Pilot Plant Studies and Preliminary Sustainability Evaluation. *Journal of Cleaner Production*, **246**, Article 119027. <https://doi.org/10.1016/j.jclepro.2019.119027>
- [47] Motta, J.F.G., de Freitas, B.C.B., de Almeida, A.F., de Souza Martins, G.A. and Borges, S.V. (2023) Use of Enzymes in the Food Industry: A Review. *Food Science and Technology*, **43**, e106222. <https://doi.org/10.1590/fst.106222>
- [48] Liu, Y., Ramakrishnan, V.V. and Dave, D. (2021) Enzymatic Hydrolysis of Farmed Atlantic Salmon By-Products: Investigation of Operational Parameters on Extracted Oil Yield and Quality. *Process Biochemistry*, **100**, 10-19. <https://doi.org/10.1016/j.procbio.2020.09.019>
- [49] Wisuthiphaet, N., Klinchan, S. and Kongruang, S. (2016) Fish Protein Hydrolysate Production by Acid and Enzymatic Hydrolysis. *King Mongkut's University of Technology North Bangkok International Journal of Applied Science and Technology*, **9**, 261-27. <https://doi.org/10.14416/j.ijast.2016.11.004>
- [50] Himonides, A.T., Taylor, A.K.D. and Morris, A.J. (2011) A Study of the Enzymatic Hydrolysis of Fish Frames Using Model Systems. *Food and Nutrition Sciences*, **02**, 575-585. <https://doi.org/10.4236/fns.2011.26081>
- [51] Peinado, I., Koutsidis, G. and Ames, J. (2016) Production of Seafood Flavour Formulations from Enzymatic Hydrolysates of Fish By-Products. *LWT-Food Science and Technology*, **66**, 444-452. <https://doi.org/10.1016/j.lwt.2015.09.025>
- [52] Zhang, Y., Tu, D., Shen, Q. and Dai, Z. (2019) Fish Scale Valorization by Hydrothermal Pretreatment Followed by Enzymatic Hydrolysis for Gelatin Hydrolysate Production. *Molecules*, **24**, Article 2998. <https://doi.org/10.3390/molecules24162998>
- [53] Šližyte, R., Daukšas, E., Falch, E., Storrø, I. and Rustad, T. (2005) Yield and Composition of Different Fractions Obtained after Enzymatic Hydrolysis of Cod (*Gadus morhua*) By-Products. *Process Biochemistry*, **40**, 1415-1424. <https://doi.org/10.1016/j.procbio.2004.06.033>
- [54] Araujo, J., Sica, P., Costa, C. and Márquez, M.C. (2021) Enzymatic Hydrolysis of Fish Waste as an Alternative to Produce High Value-Added Products. *Waste and Biomass Valorization*, **12**, 847-855. <https://doi.org/10.1007/s12649-020-01029-x>
- [55] Fraterrigo Garofalo, S., Cavallini, N., Demichelis, F., Savorani, F., Mancini, G., Fino, D., *et al.* (2023) From Tuna Viscera to Added-Value Products: A Circular Approach for Fish-Waste Recovery by Green Enzymatic Hydrolysis. *Food and Bioprocess Processing*, **137**, 155-167. <https://doi.org/10.1016/j.fbp.2022.11.006>
- [56] Zhang, Y., Sun, Q., Liu, S., Wei, S., Xia, Q., Ji, H., *et al.* (2021) Extraction of Fish Oil from Fish Heads Using Ultra-High Pressure Pre-Treatment Prior to Enzymatic Hydrolysis. *Innovative Food Science & Emerging Technologies*, **70**, Article 102670. <https://doi.org/10.1016/j.ifset.2021.102670>

- [57] Gildberg, A. and Stenberg, E. (2001) A New Process for Advanced Utilisation of Shrimp Waste. *Process Biochemistry*, **36**, 809-812. [https://doi.org/10.1016/s0032-9592\(00\)00278-8](https://doi.org/10.1016/s0032-9592(00)00278-8)
- [58] Hemker, A.K., Nguyen, L.T., Karwe, M. and Salvi, D. (2020) Effects of Pressure-Assisted Enzymatic Hydrolysis on Functional and Bioactive Properties of Tilapia (*Oreochromis niloticus*) By-Product Protein Hydrolysates. *LWT*, **122**, Article 109003. <https://doi.org/10.1016/j.lwt.2019.109003>
- [59] Sapatinha, M., Camacho, C., Pais-Costa, A.J., Fernando, A.L., Marques, A. and Pires, C. (2024) Enzymatic Hydrolysis Systems Enhance the Efficiency and Biological Properties of Hydrolysates from Frozen Fish Processing Co-products. *Marine Drugs*, **23**, Article 14. <https://doi.org/10.3390/md23010014>
- [60] Utomo, B.S.B., Suryanigrum, T.D. and Harianto, H.R. (2014) Optimization of Enzymatic Hydrolysis of Fish Protein Hydrolysate (FPH) Processing from Waste of Catfish Fillet Production. *Squalen Bulletin of Marine and Fisheries Postharvest and Biotechnology*, **9**, Article 115. <https://doi.org/10.15578/squalen.v9i3.79>
- [61] Wisuthiphaet, N., Kongruang, S. and Chamcheun, C. (2015) Production of Fish Protein Hydrolysates by Acid and Enzymatic Hydrolysis. *Journal of Medical and Bioengineering*, **4**, 466-470. <https://doi.org/10.12720/jomb.4.6.466-470>
- [62] Nilsang, S., Lertsiri, S., Suphantharika, M. and Assavanig, A. (2005) Optimization of Enzymatic Hydrolysis of Fish Soluble Concentrate by Commercial Proteases. *Journal of Food Engineering*, **70**, 571-578. <https://doi.org/10.1016/j.jfoodeng.2004.10.011>
- [63] Majluf, P., Matthews, K., Pauly, D., Skerritt, D.J. and Palomares, M.L.D. (2024) A Review of the Global Use of Fishmeal and Fish Oil and the Fish In:fish Out Metric. *Science Advances*, **10**, eadn5650. <https://doi.org/10.1126/sciadv.adn5650>
- [64] Sales, J. (2003) Nutrient Requirements of Ornamental Fish. *Aquatic Living Resources*, **16**, 533-540. <https://doi.org/10.1016/j.aquiliv.2003.06.001>
- [65] Espe, M., Lemme, A., Petri, A. and El-Mowafi, A. (2007) Assessment of Lysine Requirement for Maximal Protein Accretion in Atlantic Salmon Using Plant Protein Diets. *Aquaculture*, **263**, 168-178. <https://doi.org/10.1016/j.aquaculture.2006.10.018>
- [66] Refstie, S., Olli, J.J. and Standal, H. (2004) Feed Intake, Growth, and Protein Utilisation by Post-Smolt Atlantic Salmon (*Salmo salar*) in Response to Graded Levels of Fish Protein Hydrolysate in the Diet. *Aquaculture*, **239**, 331-349. <https://doi.org/10.1016/j.aquaculture.2004.06.015>
- [67] Fan, Z., Wu, D., Li, J., Zhang, Y., Cui, Z., Li, T., *et al.* (2022) Assessment of Fish Protein Hydrolysates in Juvenile Largemouth Bass (*Micropterus salmoides*) Diets: Effect on Growth, Intestinal Antioxidant Status, Immunity, and Microflora. *Frontiers in Nutrition*, **9**, Article ID: 816341. <https://doi.org/10.3389/fnut.2022.816341>
- [68] Khosravi, S., Bui, H.T.D., Rahimnejad, S., Herault, M., Fournier, V., Kim, S., *et al.* (2015) Dietary Supplementation of Marine Protein Hydrolysates in Fish-Meal Based Diets for Red Sea Bream (*Pagrus major*) and Olive Flounder (*Paralichthys olivaceus*). *Aquaculture*, **435**, 371-376. <https://doi.org/10.1016/j.aquaculture.2014.10.019>
- [69] Zheng, K., Liang, M., Yao, H., Wang, J. and Chang, Q. (2011) Effect of Dietary Fish Protein Hydrolysate on Growth, Feed Utilization and IGF-I Levels of Japanese Flounder (*Paralichthys olivaceus*). *Aquaculture Nutrition*, **18**, 297-303. <https://doi.org/10.1111/j.1365-2095.2011.00896.x>
- [70] Da Silva, T.C., Rocha, J.D.M., Moreira, P., Signor, A. and Boscolo, W.R. (2017) Fish Protein Hydrolysate in Diets for Nile Tilapia Post-Larvae. *Pesquisa Agropecuária Brasileira*, **52**, 485-492. <https://doi.org/10.1590/s0100-204x2017000700002>

- [71] Swanepoel, J.C. and Goosen, N.J. (2018) Evaluation of Fish Protein Hydrolysates in Juvenile African Catfish (*Clarias gariepinus*) Diets. *Aquaculture*, **496**, 262-269. <https://doi.org/10.1016/j.aquaculture.2018.06.084>
- [72] Xu, H., Mu, Y., Zhang, Y., Li, J., Liang, M., Zheng, K., *et al.* (2016) Graded Levels of Fish Protein Hydrolysate in High Plant Diets for Turbot (*Scophthalmus maximus*): Effects on Growth Performance and Lipid Accumulation. *Aquaculture*, **454**, 140-147. <https://doi.org/10.1016/j.aquaculture.2015.12.006>
- [73] Siddik, M.A.B., Pham, H.D., Francis, D.S., Vo, B.V. and Shahjahan, M. (2021) Dietary Supplementation of Fish Protein Hydrolysate in High Plant Protein Diets Modulates Growth, Liver and Kidney Health, and Immunity of Barramundi (*Lates calcarifer*). *Aquaculture Nutrition*, **27**, 86-98. <https://doi.org/10.1111/anu.13404>
- [74] Gildberg, A., Johansen, A. and Bøgwald, J. (1995) Growth and Survival of Atlantic Salmon (*Salmo salar*) Fry Given Diets Supplemented with Fish Protein Hydrolysate and Lactic Acid Bacteria during a Challenge Trial with *Aeromonas Salmonicida*. *Aquaculture*, **138**, 23-34. [https://doi.org/10.1016/0044-8486\(95\)01144-7](https://doi.org/10.1016/0044-8486(95)01144-7)
- [75] Kabir, M.A., Nandi, S.K., Suma, A.Y., Abdul Kari, Z., Mohamad Sukri, S.A., Wei, L.S., *et al.* (2024) The Potential of Fish Protein Hydrolysate Supplementation in Nile Tilapia Diets: Effects on Growth and Health Performance, Disease Resistance, and Farm Economic Analysis. *Applied Biochemistry and Biotechnology*, **196**, 7145-7167. <https://doi.org/10.1007/s12010-024-04913-7>
- [76] Sánchez-Velázquez, J., Peña-Herrejón, G.A. and Aguirre-Becerra, H. (2024) Fish Responses to Alternative Feeding Ingredients under Abiotic Chronic Stress. *Animals*, **14**, Article 765. <https://doi.org/10.3390/ani14050765>
- [77] Zheng, K., Liang, M., Yao, H., Wang, J. and Chang, Q. (2012) Effect of Size-Fractionated Fish Protein Hydrolysate on Growth and Feed Utilization of Turbot (*Scophthalmus maximus*). *Aquaculture Research*, **44**, 895-902. <https://doi.org/10.1111/j.1365-2109.2012.03094.x>
- [78] Zheng, K., Xu, T., Qian, C., Liang, M. and Wang, X. (2013) Effect of Low Molecular Weight Fish Protein Hydrolysate on Growth Performance and IGF-I Expression in Japanese Flounder (*Paralichthys olivaceus*) Fed High Plant Protein Diets. *Aquaculture Nutrition*, **20**, 372-380. <https://doi.org/10.1111/anu.12090>
- [79] Egerton, S., Wan, A., Murphy, K., Collins, F., Ahern, G., Sugrue, I., *et al.* (2020) Replacing Fishmeal with Plant Protein in Atlantic Salmon (*Salmo salar*) Diets by Supplementation with Fish Protein Hydrolysate. *Scientific Reports*, **10**, Article No. 4194. <https://doi.org/10.1038/s41598-020-60325-7>
- [80] Tang, H., Wu, T., Zhao, Z. and Pan, X. (2008) Effects of Fish Protein Hydrolysate on Growth Performance and Humoral Immune Response in Large Yellow Croaker (*Pseudosciaena crocea* R.). *Journal of Zhejiang University SCIENCE B*, **9**, 684-690. <https://doi.org/10.1631/jzus.b0820088>
- [81] Wei, Y., Liang, M., Mu, Y., Zheng, K. and Xu, H. (2015) The Effect of Ultrafiltered Fish Protein Hydrolysate Level on Growth Performance, Protein Digestibility and Mrna Expression of Pept1 in Juvenile Turbot (*Scophthalmus maximus*). *Aquaculture Nutrition*, **22**, 1006-1017. <https://doi.org/10.1111/anu.12319>
- [82] Nobile, V., Duclos, E., Michelotti, A., Bizzaro, G., Negro, M. and Soisson, F. (2016) Supplementation with a Fish Protein Hydrolysate (*Micromesistius poutassou*): Effects on Body Weight, Body Composition, and CCK/GLP-1 Secretion. *Food & Nutrition Research*, **60**, Article 29857. <https://doi.org/10.3402/fnr.v60.29857>
- [83] De Oliveira, G.V., Volino-Souza, M., Cordeiro, E.M., Conte-Junior, C.A. and Alvares, T.S. (2019) Effects of Fish Protein Hydrolysate Ingestion on Endothelial Function

- Compared to Whey Protein Hydrolysate in Humans. *International Journal of Food Sciences and Nutrition*, **71**, 242-248. <https://doi.org/10.1080/09637486.2019.1635090>
- [84] Baco, N., Oslan, S.N.H., Shapawi, R., Mohhtar, R.A.M., Noordin, W.N.M. and Huda, N. (2022) Antibacterial Activity of Functional Bioactive Peptides Derived from Fish Protein Hydrolysate. *IOP Conference Series: Earth and Environmental Science*, **967**, Article 012019. <https://doi.org/10.1088/1755-1315/967/1/012019>
- [85] Chalamaiah, M., Keskin Ulug, S., Hong, H. and Wu, J. (2019) Regulatory Requirements of Bioactive Peptides (*Protein hydrolysates*) from Food Proteins. *Journal of Functional Foods*, **58**, 123-129. <https://doi.org/10.1016/j.jff.2019.04.050>
- [86] Ng, W., Wong, F., Abd Manan, F., Chow, Y., Ooi, A., Ong, M., et al. (2024) Antioxidant Peptides and Protein Hydrolysates from Tilapia: Cellular and in Vivo Evidences for Human Health Benefits. *Foods*, **13**, Article 2945. <https://doi.org/10.3390/foods13182945>
- [87] Moya Moreira, T.F., Gonçalves, O.H., Leimann, F.V. and Ribeiro, R.P. (2023) Fish Protein Hydrolysates: Bioactive Properties, Encapsulation and New Technologies for Enhancing Peptides Bioavailability. *Current Pharmaceutical Design*, **29**, 824-836. <https://doi.org/10.2174/1381612829666230110141811>
- [88] Alvares, T.S., Conte-Junior, C.A., Pierucci, A.P., de Oliveira, G.V. and Cordeiro, E.M. (2018) Acute Effect of Fish Protein Hydrolysate Supplementation on Vascular Function in Healthy Individuals. *Journal of Functional Foods*, **46**, 250-255. <https://doi.org/10.1016/j.jff.2018.04.066>
- [89] He, S., Franco, C. and Zhang, W. (2015) Fish Protein Hydrolysates: Application in Deep-Fried Food and Food Safety Analysis. *Journal of Food Science*, **80**, E108-E115. <https://doi.org/10.1111/1750-3841.12684>
- [90] Herpandi, N.H., Rosma, A. and Wan Nadiah, W.A. (2011) The Tuna Fishing Industry: A New Outlook on Fish Protein Hydrolysates. *Comprehensive Reviews in Food Science and Food Safety*, **10**, 195-207. <https://doi.org/10.1111/j.1541-4337.2011.00155.x>
- [91] Ahn, C., Je, J. and Cho, Y. (2012) Antioxidant and Anti-Inflammatory Peptide Fraction from Salmon Byproduct Protein Hydrolysates by Peptic Hydrolysis. *Food Research International*, **49**, 92-98. <https://doi.org/10.1016/j.foodres.2012.08.002>
- [92] Kandyliari, A., Golla, J.P., Chen, Y., Papandroulakis, N., Kapsokefalou, M. and Vasilio, V. (2020) Antiproliferative Activity of Protein Hydrolysates Derived from Fish By-Products on Human Colon and Breast Cancer Cells. *Proceedings of the Nutrition Society*, **79**, E282. <https://doi.org/10.1017/s002966512000230x>
- [93] Honrado, A., Miguel, M., Ardila, P., Beltrán, J.A. and Calanche, J.B. (2024) From Waste to Value: Fish Protein Hydrolysates as a Technological and Functional Ingredient in Human Nutrition. *Foods*, **13**, Article 3120. <https://doi.org/10.3390/foods13193120>
- [94] Da Silva, M.S., Bigo, C., Barbier, O. and Rudkowska, I. (2017) Whey Protein Hydrolysate and Branched-Chain Amino Acids Downregulate Inflammation-Related Genes in Vascular Endothelial Cells. *Nutrition Research*, **38**, 43-51. <https://doi.org/10.1016/j.nutres.2017.01.005>
- [95] Dai, W., Zhan, X., Peng, W., Liu, X., Peng, W., Mei, Q., et al. (2021) *Ficus pandurata* Hance Inhibits Ulcerative Colitis and Colitis-associated Secondary Liver Damage of Mice by Enhancing Antioxidation Activity. *Oxidative Medicine and Cellular Longevity*, **2021**, Article ID: 2617881. <https://doi.org/10.1155/2021/2617881>
- [96] Rizzello, C.G., Tagliazucchi, D., Babini, E., Sefora Rutella, G., Taneyo Saa, D.L. and Gianotti, A. (2016) Bioactive Peptides from Vegetable Food Matrices: Research Trends

-
- and Novel Biotechnologies for Synthesis and Recovery. *Journal of Functional Foods*, **27**, 549-569. <https://doi.org/10.1016/j.jff.2016.09.023>
- [97] Cruz-Casas, D.E., Aguilar, C.N., Ascacio-Valdés, J.A., Rodríguez-Herrera, R., Chávez-González, M.L. and Flores-Gallegos, A.C. (2021) Enzymatic Hydrolysis and Microbial Fermentation: The Most Favorable Biotechnological Methods for the Release of Bioactive Peptides. *Food Chemistry: Molecular Sciences*, **3**, Article 100047. <https://doi.org/10.1016/j.fochms.2021.100047>
- [98] Oceana (2021) Fishmeal. Oceana USA. <https://usa.oceana.org/fishmeal/>
- [99] Caruso, G., Floris, R., Serangeli, C. and Di Paola, L. (2020) Fishery Wastes as a Yet Undiscovered Treasure from the Sea: Biomolecules Sources, Extraction Methods and Valorization. *Marine Drugs*, **18**, Article 622. <https://doi.org/10.3390/md18120622>
- [100] Bhati, D. and Hayes, M. (2025) From Ocean to Market: Technical Applications of Fish Protein Hydrolysates in Human Functional Food, Pet Wellness, Aquaculture and Agricultural Bio-Stimulant Product Sectors. *Applied Sciences*, **15**, Article 5769. <https://doi.org/10.3390/app15105769>