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# Transforming Fish Waste into High-value Resources: A Sustainable Approach to Circular Bioeconomy

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

The growing global population drives urbanization, industrial growth, increased fishing, and aquaculture production. This will lead to significant waste generation, impacting the environment profoundly. Approximately two-thirds of the total fish are discarded as waste, presenting substantial financial and environmental challenges. To safeguard the environment in the long run, we must

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address the unique waste production processes. The recycling and disposal of these wastes have become critical issues. Utilizing underutilized or discarded marine material can be a sustainable approach to achieving a circular bioeconomy, especially as the circular economy gains increasing attention by producing high-value materials. This article explores the management of fish waste and the conversion of proteins released by fish into valuable products. It provides a comprehensive analysis of various high-value substances derived from fish by-products, such as collagen, enzymes, and bioactive peptides, and their potential applications in multiple industries. Fish waste is becoming increasingly popular as a novel raw material for synthesizing biopolymers with substantial economic and environmental benefits, primarily in the food packaging industry. Furthermore, addressing the complex task of increasing agricultural yields involves managing water and artificial fertilizers, assessing land suitability for farming, optimizing production methods, and implementing effective fisheries and aquaculture waste management procedures in response to climate change. Traditional methods are continuously reassessed in the quest for process intensification and sustainable production techniques, due to challenges in recovering intracellular bioactive compounds, selectivity issues, and energy requirements. However, within the framework of "zero waste" and "biorefinery for high-value compounds," these innovative approaches present numerous opportunities for technological advancement. Alongside detailing these efforts, this article highlights the significant untapped potential in this field. This review paper provides an overview of the latest developments in the process of turning fish waste into biopolymers for use in food packaging. The problems with trash from the fishing business, fish bycatch, and the possibility of recycling. The recent developments in the value-adding of fish industry waste for the production of biopolymers for use in food packaging are compiled in this review.

*Keywords: Fish waste; bioactive peptides; industrial growth; high-value compounds; fisheries and aquaculture waste.*

## 1. INTRODUCTION

Fish is consumed by a large population globally, with Japan, Vietnam, Myanmar, and China being the primary consumers. These countries consume more fish than any other nation worldwide, leading to significant fish waste production. There are many methods to manage fish waste, including using it for animal feed, biodiesel/biogas, natural colors, chitosan in food packaging, collagen in cosmetics, enzyme isolation, soil fertilizer, and hydrolysates for moisture retention in food. According to FAO (2020), the global fish production by aquaculture was projected to reach 178.5 million tons in 2018, with a compound annual growth rate of 2-3.5%. Fish is a nutrient-dense food, accounting for over 17% of the global animal protein intake (Obiero et al., 2019). Its content varies based on season, species, age, sex, and health. Fish waste is rich in phosphate, nitrogen, and vitamin C. By reducing the amount of helpful bacteria in the soil, applying fish manure promotes soil health. These beneficial nutrients may be more readily accessed by plants. Due to their simultaneous benefits to the environment and the financial sides of society, food loss and waste have emerged as global challenges.

Despite the sector's increased attention recently, the reasons for the ineffective use of fish processing leftovers in developing countries like India remain unclear (Kruijssen, 2020). This is largely caused by underuse and poor quality, which is brought on by broken force chains, unpleasant running, spastic cold chains, timid temperature monitoring, and other issues. An obstacle stands in the way of any experimenter attempting to comprehend the potential of utilizing these co-streams of fish processing in a developing frugality to optimize consumption, profitable sustainability, minimizing rejects, and fostering circularity (Ritchie, 2018). The authors respond to this need for exploration by demonstrating the legitimacy of this field in the context of both national and global exploration communities through a thorough evaluation that employs content analysis and bibliometric analysis.

Numerous researchers have explored a wealth of literature, uncovering two key trends: (i) an increasing focus on producing bio-methane from hydroxyapatite products, transesterification procedures, biomass, and other raw materials derived from fish processing, and (ii) a declining interest in force chain-related topics, despite their importance (Tayebi-Khorami, 2019). To address this gap, particularly in India, barriers to utilizing by-products have been identified, and recommendations for improvements have been proposed. These findings will lay the groundwork for an indirect, sustainable force chain that repurposes seafood in developing aquaculture. Fully exploiting seafood waste to create bioactive compounds and functional ingredients for use in the food sector is a crucial strategy for sustainable resource management and a primary goal of the circular economy.

## 2. FISH PROCESSING

The technique of processing fish involves many procedures such as intoxication, sorting, decapitation, washing, scraping, skinning, and cutting fish, meat cuts, steaks, and fillets. Depending on the type of fish and degree of processing, these steps produced a significant amount of waste (20–80%) during the day. Hence, a sizable quantity of waste is thrown away annually. An enormous amount of transportable waste is also needed for fish processing, resulting in sewage production.

Most fish waste is disposed off in the ocean, where aerobic bacteria consume the oxygen in the water to break down the organic matter. This process increases the oxygen demand for other aquatic species. High concentrations of phosphorus, nitrogen, and ammonia from fish can cause a pH shift, leading to water turbidity and algae decomposition. Reduced oxygen levels in the water create anaerobic conditions, which significantly contribute to the development of harmful gases like ammonia and hydrogen sulfide, as well as organic acids and greenhouse gases such as carbon dioxide and methane. The waste produced by the fish processing industry is shown in Table 1.

**Common approaches used by fish manufacturing facilities:** Fish sorting, cleaning, scaling, and washing are among the steps involved. This process includes Deheading, gutting, fin-cutting, steak-slicing, filleting, separating the flesh from the bones, packing, labelling, and distribution.

**Table 1. Illustrates the products of fish utilized in processing and waste generated (Biswajit, 2020).**

| S.No | Name of the product | Waste generated (%) |
|---|---|---|
| 1. | Cuttles fillets | 50 |
| 2. | Cuttles rings | 50 |
| 3. | Fish fillets | 70 |
| 4. | Fish sticks | 30 |
| 5. | Cuttles whole | 30 |
| 6. | Squid tubes | 50 |
| 7. | Whole and gutted fish | 10 |


**Fig. 1. Illustrates the fish waste processing steps (Jayathilakan, 2012)**

**Step-1: Stunning:** The first and most important stage in processing fish is stunning, as prolonged pain in fish leads to the creation of undesirable chemicals in the animal's tissues. Low oxygen levels in the blood and muscles cause lactic acid buildup, which paralyzes the nervous system. A stunned fish moves violently and produces such a loud noise that its vertebrae and blood vessels crack. Red patches appear in the backbone muscles and the skin's surface (ByKowski & Dutkiewicz, 1996; Erikson, 2012).

After capture, some wild fish remain alive until they are euthanized using $CO_2$ (Erikson et al., 2012). According to Robb et al. (2002), exposure to CO2-saturated narcosis causes fish to exhibit strong aversion behaviors lasting three to five minutes. This immersion alters the blood's pH, impairing brain function (Poli et al., 2005). $CO_2$ narcosis also increases lactic acid production (Roth et al., 2002; Mohan, 2018). $CO_2$ stunning is considered the most distressing method for fish as it creates an acidic and hypoxic environment, triggering panic and escape behaviors. This rapid loss of phosphagen energy hastens the onset of rigor mortis. In aquaculture, fish are sometimes immediately submerged in near-freezing cold water. To manage the amount of waste collected from every Canadian province, the temperature is kept low to prevent the fish from dying prematurely.

**Step-2: Grading:** The second stage of fish processing involves grading fish according to size and species. Both manual and mechanical methods can be used to grade fish. In comparison to fish that have achieved a condition of rigor mortis, mechanical methods are more accurate when grading fish before or after rigor. Automated grading equipment is six to ten times more efficient than manual grading (Shahidi, 2019; Vidotti, 2003; Espe, 1999). Low manufacturing costs and better fish products after the production process are the main benefits of the automated system (Tatterson et al., 1974).

**Step-3: Slime Removal**: Fish secrete mucus on the surface of their bodies to shield themselves from potentially dangerous conditions. Mucus secretion ceases before rigor mortis. The combination of fish mucus and seawater provides ideal conditions for bacterial growth. In seafood processing, anaerobic bacteria can absorb sulfur compounds from the water to create mucus in skin, and flesh. Consequently, continuous washing is necessary to eliminate the mucus. Certain species, such as eels, produce significant amounts of mucus. Trout and other freshwater fish can be soaked in a solution of two cups of soda, followed by rinsing in a cylindrical tumble dryer (Granata, 2012).

**Step-4: Scaling:** The fish processing process involves scaling, which is one of the most challenging and labor-intensive steps. Remove any bacteria or pathogens that may have been present on the scales to keep the fish fresh while it is chilled or frozen. Manual descale can be achieved by using either a razor blade or a stiff brush. Certain fish species, like perch, tile fish, carp, and catfish, have difficult-to-remove scales. The sea fish are first blanched in boiling water for three to six seconds. After that, they are mechanically shrunk using a portable, tiny machine in a motion perpendicular to the body's long axis. When compared to hand tools, electric scales are more effective in completely eliminating tartar and reducing time significantly.

**Step-5: Washing:** Fish should be washed primarily to clean and get rid of microbial buildup. The water ratio, water quality, and kinetic energy of the water run all affect how well fish are cleaned. A 1:1 fish-to-water ratio is advised. However, when processing fresh water fish, the amount of water utilized doubles in order to use the recommended drinking water (Gildberg, 1992). Belt rings, vertical drums, and horizontal drums are used in the washing process. Fish fillets and whole, headless, and gutted fish can be washed in motorized washing machines in approximately a minute or two. According to Disney et al., (1977) cleaning the product does not physically harm it. Water is sprayed under pressure during the continuous washing procedure. Waste tanks are used to collect the dirty water.

**Step-6: De-heading:** The fish's head is usually considered an inedible component since it accounts for 20% of its weight (Ichimura et al., 2003). Fish can be manually or mechanically topped. simpler manual cutting at a low cost. Fish bigger than 20 to 40 cm can be mechanically de-Dheaded. Fish can be cut in three ways: counter, straight, and circular. Most fish processing facilities use manual removal because it results in less flesh loss. When cutting around the gills, circular cut sand results in the least amount of flesh loss. The spine of the fish is cut both perpendicular and at a 45-degree angle. Typically, this cut is used when meat without bones is the final product and fillets without skin.

**Step-7: De-Gutting**: The process of gutting a fish entails removing its internal organs and cleaning its kidney tissue, blood, and peritoneum out of its body cavity. The fish is gutted by cutting it lengthwise and removing its internal organs on a table that is covered in a non-absorbent material and can be easily cleaned. The table is regularly disinfected and rinsed. The cost of fish processing is increased by using various mechanical de- gutting machines that are available for trout, eels, and other species (Gildberg, 1993). According to Ichimura *et al.,* (2003), the internal organs make up between 5 and 8% of the fish's weight.

## 3. FISH WASTE MANAGEMENT AND ITS COMPOSITION

The production, treatment, specification, control, prevention, handling, reuse, and final disposal of fish waste are the primary themes of fish waste management (shown in Fig. 2). Over the past 30 years, various directives under the European Union's auspices have been initiated to address waste management from aquaculture and the environmental impacts of fisheries (Arvanitoyannis, 2014). With the increasing utilization of by-products, implementing fishery policy guidelines is crucial. However, when designing the optimal waste management system, it is important to consider the costs and anticipated benefits.

Waste processed by aquaculture and related industries poses a serious threat to the ecosystem. Therefore, it is crucial to employ the right technologies to reduce pollution. The primary goal of fishery management is to convert these wastes into valuable materials while recovering important resources before disposal (Uddin, 2010).

Fish produce different kinds of waste depending on their species, age, sex, nutritional state, time of year, and overall health. Fish contain 15–30% protein, 0–25% fat, and 50–80% moisture on average. Solid fish waste includes the head, tail, skin, intestines, and carcass. Additionally, fish waste is rich in monounsaturated acids, oleic acid, and palmitic acid (22%). (Shown in Table 2)

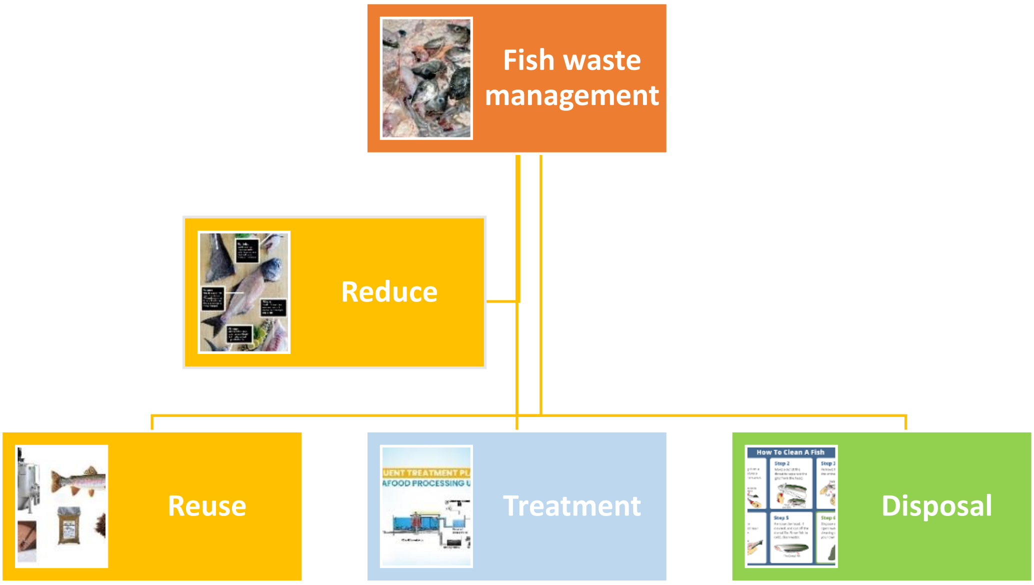


**Fig. 2. Block flow diagram (BFD) of the process of fish waste management (FAO, 2020)**

**Table 2. Depicts the composition and percentage of fish waste (Rahimi, 2017)**

| FISH WASTE | PERCENTAGE |
|---|---|
| Muscle trimmings | 15-20% |
| Skin and fins | 1-3% |
| Bones | 9-15% |
| Heads | 9-12% |
| Viscera | 12-18% |
| Scales | 5%-22% |

## 4. APPLICATION OF SPOILED FISH AND FISH WASTE CURRENTLY

We are using different fish waste to generate various products like fish silage, fish meal, fish sauce, protein hydrolysate, fish oil, and fish oil biodiesel. (shown in Fig. 3)

**Fish silage:** Fish silage is made from entire fish and is a liquid product. It's a fantastic source of protein because it's high in protein and biologically important for animal feed. When there is acid present, enzymes work to liquefy this substance. Enzymes that break down fish protein into smaller soluble molecules and stop bacterial spoiling are accelerated by the acidic media, which also serves as a catalyst. Free amino acids can be produced by protein hydrolysis found in fish silage. This process yields a source of amino acids that can be used for protein production (Poli, 2005; Vidotti, 2003).

**Fishmeal:** Fishmeal is a dehydrated powder made from fish filleting wastes or entire fish that is unfit for human consumption. The raw materials are shipped either fresh or preserved in sodium nitrate or formaldehyde and then delivered to the processing companies (Hussein, 1991). There are six phases involved in making fish meal: heating, pressing, separating, evaporating, drying, and grinding. The protein in the fish coagulates and ruptures the fat deposits when it is cooked. This releases water and oil. After that, the fish is squeezed to extract a significant amount of liquid from the raw material. To separate the oil from the water, the liquid is collected. The water, commonly referred to as stick water, evaporates and turns into a viscous syrup with 30–40% solids.

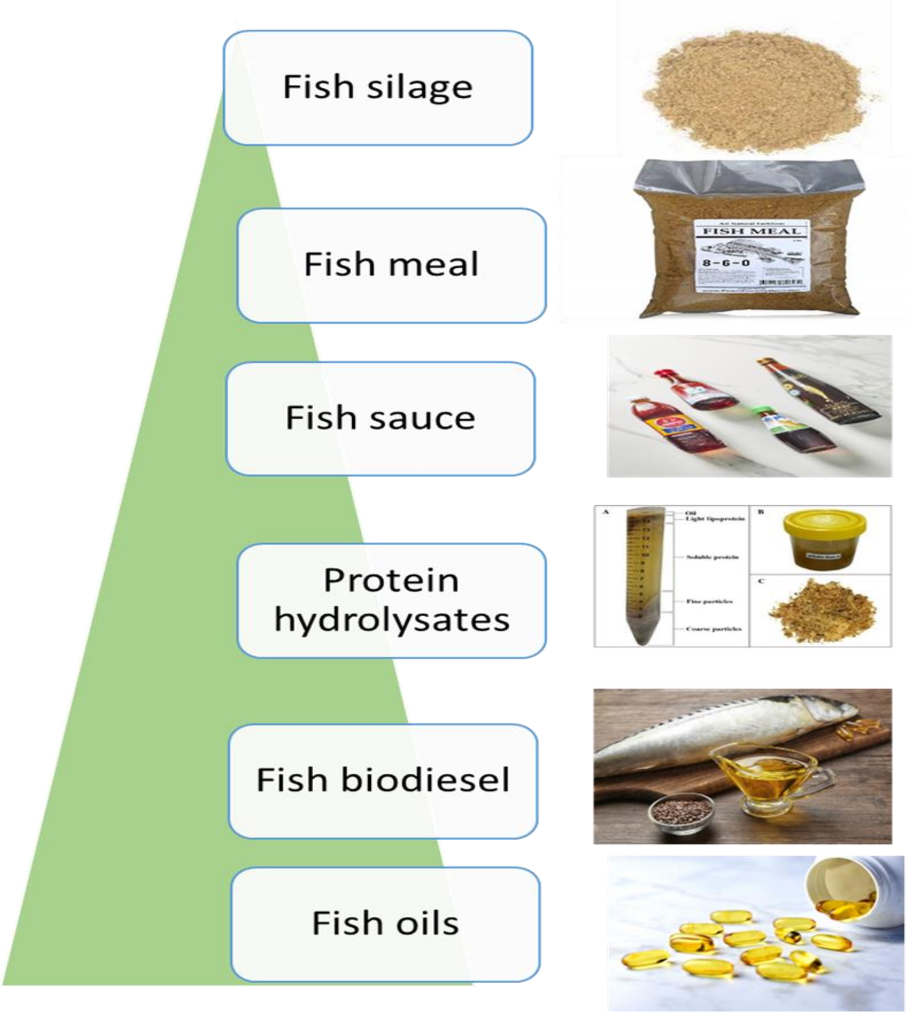


**Fig. 3. Depicts Prospects and the application of enhanced extraction techniques for resource recovery from fish waste (Thirukumaran. 2022)**

**Fish sauce:** Small pelagic fish or leftovers from salt fermentation are used to make this sauce. Fish that has been mixed in a 3:1 ratio with salt ink and kept at 30 degrees Celsius for six months is ideal for this process. After that, the bottom of the tank is emptied of the amber protein solution. Because it contains all of the essential amino acids, it is highly nutritious. Its functions range from boosting insulin secretion to acting as an inhibitor and as the antiotensin-1 converting enzyme [ACE]. Numerous studies have discovered that fermented fish sauce from salmon, sardines, and anchovies has ACE inhibitory action. Gly-trp, ile-trp, and val-trp, three ACE peptides, were discovered in fermented fish sauce.

**Fish protein hydrolysate:** According to Kim and Wijesekara (2010), bioactive peptides consisting of particular lengths of amino acids can be prepared by enzymatic hydrolysis of fish proteins using the right enzymes, such as alcalase, pronase, collagenase, pepsin, papain, protamex, bromelain, chymotrypsin, and trypsin. The primary benefit of enzymatic protein hydrolysis is that it does not result in racemization during digestion and permits the measurement of sensitive residues like glutamine and aspartgine, which are typically eliminated by acid and alkali hydrolysis.

**Fish oil and Biodiesel:** The raw fish material primarily comprises three components: solid (free fat dry matter), oil, and water. Numerous tools and techniques have been developed to extract fish oil to increase production and quality. Many reviews, patents, and experimental articles have been published; these insights not only clarify technical issues but also highlight the profitability of the process, which should ideally be scalable to an industrial level (Rubio-Rodríguez, 2010). Conventional lipid extraction techniques use organic solvents including methanol, hexane, petroleum ether, and chloroform and depend on the hydrophobicity of the lipids (Fiori, 2012; Adeoti, 2014). The fish processing sector is the source of large amounts of fish oil production. This byproduct has the potential to be a renewable energy source. Fish oil's high hydrogen and low carbon content have led to a number of studies being done on its fuel-related properties. It has a greater flash point and a much lower kinematic viscosity (Yahyaee, 2013). Bio-oil is a good fuel for diesel engines because of its specific properties. It has a better heating value than regular diesel fuel and is of higher quality than waste vegetable oil that has been methyl esterified. Diesel engines could use fish waste-derived biodiesel, primarily at low temperatures.( Jayasinghe, 2012)

## 5. FISH DEBRIS AMID THE ERA OF THE REGENERATIVE BIOLOGICAL ECONOMY

Because of the massive increase in population over the past 20 years and the ensuing heavy reliance on non-renewable resources, the environment has suffered, and sustainable approaches are becoming more and more important. Under this situation, it is crucial for the next generation to employ alternative resources in place of fossil fuels and to develop sustainable renewable processes. Because the entire notion of sustainability depends on the circularity of all required materials, the shift from a linear to a circular economy is currently a crucial component of resource management in an environmentally responsible manner. The achievement of resource and environmental sustainability depends on the circular bioeconomy, which is an essential component of the circular economy.

The bioeconomy mimics or uses biologically derived materials and processes in order to achieve an effective utilization of resources (Mohan, 2020). The use of waste streams and renewable biological resources to create value-added products including feed, food, feedstock, bio-based products, and bioenergy is included in the European Commission's definition of the bioeconomy (Commission, E. 2020). With this strategy, there is an increase in the inflow of renewable resources, a decrease in the anthropogenic consumption of raw materials with a fossil origin, and a less negative impact on the environment.

The principal benefits of the circular bioeconomy are: zero waste; resource valuation; greater public and business awareness; political backing; and stakeholder and policy maker involvement. Thus, one of the main goals of the bio-waste valorization approach is to bring circularity into the bioeconomy. The scientific community is working very hard in this area, mostly focused on recovering resources from biological waste, with government support.

## 6. FISH BY-PRODUCTS: SOURCES OF HIGH-ADDED-VALUE COMPOUNDS

The nutritional makeup of fish by-products is comparable to that of fish fillet and other food products meant for consumption, making them a valuable source of proteins, fatty acids, and minerals. Proteins from fish are higher in nutrients than those from other plant sources. Research on many fish species has shown that the skin is the main source of protein, the intestines, head, and bones are rich sources of lipids, and the calcium content of trimmings and bones is high (Kandyliari et al., 2020; Wani, 2024). Furthermore, according to Abbey et al. (2017), the mean value of all fish by-products, determined using dry weight, ranges from 49.22 to 579.92% for protein content, 21.79 to 30.16% for ash content, and 7.16 to 19.10% for fat content.

## 7. FISH WASTAGE AND SUSTAINABILITY

An estimated 179 million tons of fish were produced worldwide in 2018, of which 156 million tons were used for human consumption and 22 million tons were used to produce fish oil and animal feed (Venkata Mohan, 2016). Large volumes of leftovers and byproducts from fish farming and processing can have a detrimental impact on the environment. Additional effluents are produced by flushing the offal away and cleaning the apparatus with spray water. Fish waste is routinely discarded back into the ocean, where it consumes more oxygen and nutrients and alters the ecosystem, or it is sold for a low price and used as fertilizer or animal feed. Some of this waste can be successfully turned into high-value, marketable items as opposed to being ignored or disposed of in landfills or the open ocean.

Despite a recent research from the Food and Agriculture Organization (2020) suggesting that marine fishery resources are deteriorating, the amount of wild species used to manufacture fish meal decreased from over 30 million tons in 1994 to approximately 18 million tons in 2018. The aquaculture sector and the implementation of sound waste management techniques were blamed for this decrease. Regarding the fisheries and aquaculture sectors, SDG 14, "Conserve and sustainably use the oceans, seas, and marine resources for sustainable development," holds significance. But SDG 12, "Responsible consumption and production," is strongly related to how fish waste is handled and how it contributes to the provision of jobs, food, and nutrition.

Let's now discuss the economic aspect of the recovery. According to Mozaffarian (2011) and Finco (2016), the market for omega 3 FAs was estimated to be worth 28 billion euros, or roughly $30 billion USD, in 2015, while the price of fish oil reached 2800 USD/ton. As long as the process of valorization is carried out utilizing sustainable standards, fish waste can be utilised as a promising tool to meet the expanding market demand and maximise the economic potential of this special resource.

## 8. OBSTACLES AND PROSPECTS FOR THE FUTURE

The aquaculture sector produced effluent in addition to sustainable resources. In light of the growing population, their increased need for food, and the effects of climate change, managing the industry will be difficult unless scarce resources and wastewaters are carefully managed (Troell et al., 2014; Boyd et al., 2020). Consumers and industry can produce more sustainably with improvements in nutrient resource recovery, such as the collection and processing of wastewaters and by-products (Han et al., 2019; Lu et al., 2019; Singh, 2017), as well as the optimization of feeding composition (Turchini et al., 2019; Deng, 2021) and formulations (Willer & Aldridge 2019).

Seafood by-product processing needs to be carefully controlled in order to reduce microbial deterioration, maintain high nutritional value, and guarantee a fresh product (Jennings et al., 2016; Olsen et al., 2014). By-product recovery can be boosted by better management of oxidative stability and the dispersion of unwanted odor, as in the refinement of fish oil (Simat et al., 2019). In the future, aquaculture will need to produce higher yields with lower waste. Conversely, this calls for less waste, pollution, and inputs while also necessitating sustainable practices, higher revenues, and efficient utilization of resources (Campanati et al., 2021).

## 9. CONCLUSION

From this, we can infer that controlling fish waste and addressing the negative effects of fish disposal contaminate the environment and keep nutrients from leaving the food chain. The products produced quantitatively by fish feces must be safely released into the environment to avoid entering water bodies and causing an excess of nutrients to build up and eventually cause eutrophication. Sustainability is promoted by fish waste products. Furthermore, fish waste and byproducts are a simple source of important compounds that don't require a lot of additives.

However, one must take into account the possible risks associated with the presence of contaminants before beginning any disposal operations. Fish waste can be treated using a variety of methods, such as B. mechanics, biotechnology, ultrasound- or microwave-assisted extraction technologies. These methods are effective at treating fish waste and lowering the pollution that results from the buildup of fish waste. By doing this, we can eventually contribute to the sustainability of nature by lowering the amount of contaminants in the environment. Waste is a vital resource that can benefit the environment, economy, society, and health just as much as fish itself. It should not be viewed as less important than fish itself. In order to fully comprehend the feasibility and potential of bringing fish processing waste closer to the production of commodities with added value for the growth of human civilization, additional research and public education is therefore required.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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