Fish Waste to Fish Meal: Potential, Sustainability and Emerging Issues Related to Microplastics and Regulations

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ABSTRACT

Massive growth in global fisheries and aquaculture production driven by the development of fishing technologies and exerted by the world population pressure has resulted in a remarkable increase in fish waste. The annual average discard amount was estimated to be 7.3 million t for the period from 2016 to 2020. The discard from marine capture commercial fisheries globally is a major concern in terms of environmental sustainability and cost of disposal. Production of fish meal is considered a practicable solution for the utilization of these wastes in a sustainable manner with a significant economic return due to the increasing demand from aquaculture and livestock industries, and occasionally for the utilization as a high-quality organic fertilizer. Fish meal is enriched with a protein source and could be utilized as a feed ingredient due to its excellent amino acid profile, excellent digestibility, high palatability, lack of anti-nutritional factors, and large acceptance by farmers. Due to climate change, habitat degradation and overfishing, wild fish catches used for fish meal are in decline, thus necessitating the increased utilization of fish waste to produce fish meal. However, the inclusion of microplastics in the fish meal and legal and regulatory issues, i.e., intra-species mixing, contamination with endangered fish species, and illegal, unreported, and unregulated fishing, need to be taken into account while utilizing the fish waste to produce fish meal. The review suggests that the utilization of fish waste for fish meal is vital for the future expansion of the fish meal industry, and also for the subsequent expansion of aquaculture and livestock industries in a sustainable manner while driving a circular economy and ensuring environmental sustainability.

Keywords: Aquaculture, Environmental sustainability, Fish meal quality, Fish waste, Livestock production

INTRODUCTION

Fish meal is a catch-all term for a nutrient-dense feed additive that is mostly used in aquaculture and domestic animal diets, but is also sometimes utilized as a high-quality organic fertilizer. Since the late 1800s, fish meal has been utilized as an animal feed addition as a good source of high-quality protein and minerals. In the last 50 years, its use has expanded substantially (Dorea, 2006). The key nutritional advantages of fish meal are its high protein content and high amino acid profile, as well as its high digestibility and lack of anti-nutritional elements (Jackson and Shepherd, 2010). Fish meal normally comprises 60–72% protein, 10–20% ash, and 5–12% fat (Shepherd and Jackson, 2013). These nutritional properties of fish meal stimulate rapid animal development and boost egg, milk, meat, and farmed fish production (Jackson and Shepherd, 2010).

In 2020, total fisheries and aquaculture output surpassed 214 million t (FAO, 2022c). The key drivers of this rise are a mix of strong demand caused by growing incomes and urbanization, coupled with increased fish production, advances

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in post-harvest technologies, and distribution networks that will extend fish commercialization. The rise of fish processing has led to an increase in by-products, which may account for up to 70% of processed fish (Roda *et al*., 2019). According to the latest available data from the Food and Agriculture Organization of the United Nations (FAO), the global discard rate for marine capture commercial fisheries was estimated to be 10.3% in 2020. The annual average discard amount was estimated to be 7.3 million t for the period from 2016 to 2020 (FAO, 2022a). Shrimp fisheries recorded the largest total volume and the highest share of trash, accounting for 62% of discards (Kelleher, 2005).

According to the FAO (2020), around 9.84% (or 18 million t) of the global fish supply was used to generate fish meal and fish oil in 2018. An increasing proportion of fish meal, estimated to be approximately 27% of overall fish meal production, is generated from by-products of fish processing, which were once typically wasted or utilized as direct feed, in silage, or in fertilizers, while 73% is produced from by-catch fish. Furthermore, the proportion of catch fisheries production turned into fish meal is expected to drop slightly during the next decade. However, the overall amount of fish meal produced in 2030 is predicted to be 1% greater than in 2018, owing to a rise in production from fish waste and by-products of the processing sector. The percentage of total fish meal made from fish waste is anticipated to increase from 22% to 28% between 2018 and 2030 (FAO, 2020). The fish meal produced from whole fish and fish by-products is given in the following graph (Figure 1).

Currently, Peru is the global leader in fish meal production, accounting for 1.1 million t (about 20% of global fish meal supply), followed by Vietnam and European Union nations. Latin America has the biggest proportion of fish used for conversion into fish meal and fish oil, followed by Asia and Europe (Figure 2). In 2020, China's fish meal imports were 1.43 million t, with Peru accounting for more than 45%, a significant edge over other producing countries. Currently, the price of fish meal in Europe is between 1,400 and 1,600 USD·t^{-1}. Prices for fish meal and fish oil have remained relatively constant, with minimal fluctuations through early 2021 (FAO, 2022b).

According to the International Fish meal and Fish Oil Organization (IFFO), the use of fish meal in aquaculture has been significantly expanding since 1960. In 2020, the aquaculture sector consumed 78% of all fish meal generated globally. Aside from that, fish meal is used in the raising of pigs, poultry and for other purposes (Figure 3). Salmon farming had become one of the largest users of fish meal by the 2000s, and utilization by that sector has plateaued at roughly 400,000 t per year. However, the shrimp farming industry, which requires more than 1 million t of fish meal each year, was the greatest user of fish meal in 2020. Considering that the worldwide fish

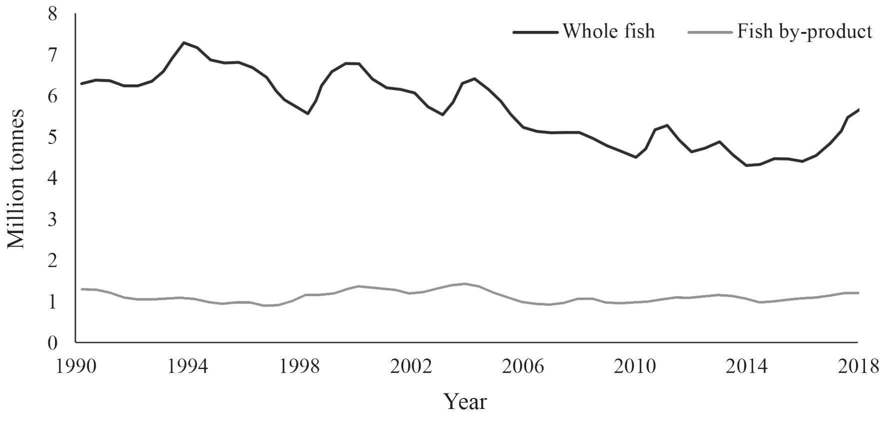

Figure 1. World fish meal production (Million tonnes) 1990–2018. Source: FAO (2020)

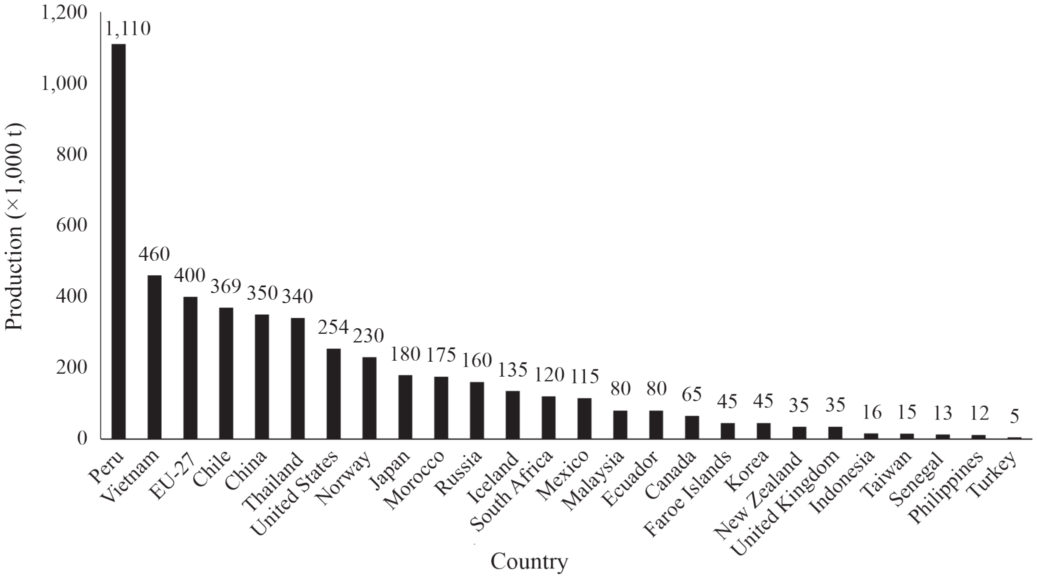

Figure 2. Estimates of fish meal production by countries in 2020. Source: FAO (2022a)

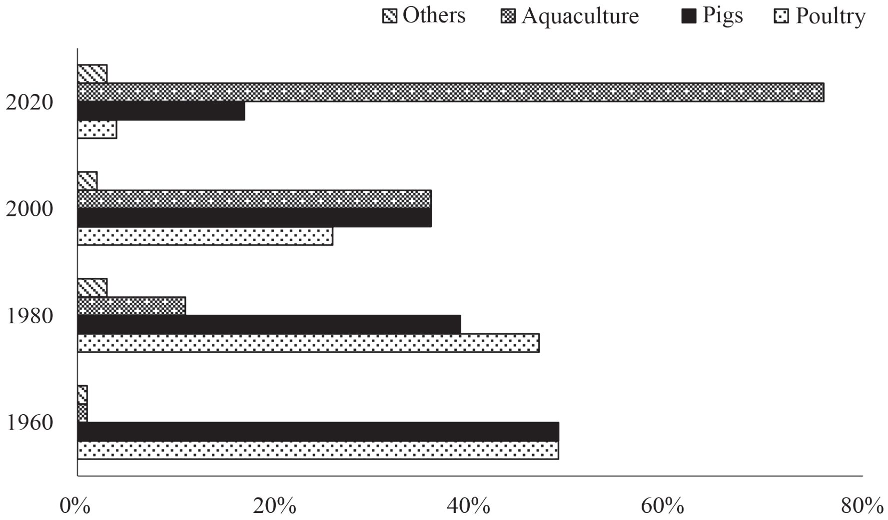

Figure 3. Fish meal utilization by different sectors. Source: IFFO (2022b)

meal supply is around 5 million t, and aquaculture accounts for over 4 million t of that, shrimp currently account for approximately 25% of all fish meal used in aquaculture (IFFO, 2022b). In 2019, approximately 25% of the fish meal used in aquaculture was used to feed crustaceans, 15% to feed salmon and trout, 17% to feed marine fish, and 21% to feed freshwater species. The remainder was distributed among tilapias, cyprinids, and eels (European Commission, 2021).

The objective of this review is to provide a comprehensive overview regarding the potential for converting fish waste into fish meal, with a focus on sustainability and emerging issues. The review explores the current state of knowledge regarding the environmental and economic benefits of using fish waste as a raw material for fish meal production. It also examines the challenges of microplastics in fish waste and relevant regulations. Overall, this review aims to provide valuable insights for researchers, policymakers, and industry stakeholders interested in promoting sustainable practices in the fish meal industry.

FISH WASTE: ENVIRONMENTAL IMPACTS

Fish waste was formerly used for a variety of purposes, including direct feeding to aquaculture species, livestock, pets, and fur-producing animals, and the creation of silage and fertilizers; some fish waste was also disposed of in landfills. Other species captured unintentionally (by-catch) are either kept and sold or thrown overboard with the offal from fish processing at sea because of their low value (at least in the local context) (Garcia *et al*., 2003). In certain circumstances, the rejected component is known as a discard. Even sport anglers discard a considerable number of non-target and target fish on the bank when fishing (FAO, 2022b). Significant amounts of landed fish are lost or discarded between landing and eating, which is a significant economic and environmental concern in most fish distribution networks (Coppola *et al*., 2021).

The amount of organic material produced may be significant due the discards (Garcia *et al*., 2003). The discharge of organic wastes has the potential to alter the composition and variety of benthic communities (Arvanitoyannis and Kassaveti, 2008). In turn, this increases the food supply for bottom-feeding organisms and, if concentrated for long enough, may lead to local anoxia in the seafloor environment (Garcia *et al*., 2003). The quantity of offal produced by at-sea surimi manufacture in the North Pacific shelf and upper slope is especially significant because the procedure used removes less than half of the wet weight from the entire catch, with the rest wasted. In the North Sea, 6.5 to 12.5% of all groundfish caught is thrown overboard at sea. Some of this is consumed by marine gulls, but some becomes accessible to benthic scavengers. An increase in the number of discards has been linked to an increase in the population of dogfish (*Scyliorhinus canicula*) in the fisheries of northern Spain and *Raja radiata* in the shrimp fisheries region of Greenland (Garcia *et al*., 2003). Diverse species of seabirds make use of discards and offal as trophic resources, and it is believed that the availability of food has caused some species' populations to grow as a direct consequence of the availability of discards (Votier *et al*., 2004). However, Grémillet *et al*. (2008) believe that, at least for gannets, fisheries waste is essentially junk food and has a detrimental influence on chick development rate.

Organic processing wastes may be easily broken down by microbes. Thus, the biological oxygen demand increases and the concentration of oxygen in the water falls accordingly. Depletion of oxygen due to excessive organic loading from discards has been seen in New Zealand Hoki (*Macruronus novaezelandie*) fisheries in the Northeastern Atlantic (Goñi, 1998). The breakdown of proteins and other nitrogenous compounds that results from the anaerobic decomposition of organic matter results in the release of hydrogen sulfide, ammonia, and methane, all of which have the potential to be harmful to the ecosystem, are toxic to marine organisms in low concentrations, and can deprive aquatic life of oxygen that is necessary for survival (Islam *et al*., 2004). Eutrophication is characterized by changes in ecosystem structure brought on by an abundance of plant life due to nutrients produced from decaying organic waste, as well as a lack of oxygen. The organic and inorganic contaminants found in partially degraded industrial effluents that reach coastal waterways are many and varied (Islam *et al*., 2004).

Fish populations may initially grow near the location of discharge due to a combination of factors, including an increase in food and nutrient availability and the complexity of the surrounding environment. However, increased nutrient levels are associated with an increase in the risk of algal bloom development, toxin generation, and a decline in dissolved oxygen levels. Increased phytoplankton biomass and widespread declines in benthic and fish species diversity are two long-term effects (Bonsdorff *et al*., 1997). Species of fish that drink water contaminated with algal toxins succumb in huge numbers. It is now well established that eutrophication causes substantial changes in the species diversity, structure, and function of marine ecosystems across large areas. A rise in phytoplankton biomass and productivity is a common result of eutrophication (Riegman, 1995). Changes in phytoplankton composition have been documented, with diatoms giving way to dinoflagellates and smaller phytoplankton, particularly nanoplankton, dominating (Kimor, 1992). Herbivorous copepods are being outcompeted by small, gelatinous zooplankton in zooplankton communities (Zaitsev, 1992). In addition, macroalgae and filamentous algae flourish in eutrophic environments. Unfortunately, this is a common annoyance that may have negative effects on benthic fauna, fish nursery and feeding, aesthetics, leisure, and tourism (Riegman, 1995). The loss of recreational water use infrastructure is another potential problem produced by the massive discharge of processing wastes and associated debris, which in turn alters the structure, diversity, trophic structure, and food web of benthic and fish communities due to hypoxia (Riegman, 1995). The spatial and temporal scale of effects from wastes generated during seafood processing may vary depending on the kind and quantity of the wastes generated. However, the effects are felt most keenly at the community level, since wastes from processing industries are often generated year-round, leaving little time for the environment to recover. It's more probable that adverse effects may occur when waste from many processing facilities is dumped into the same area (Islam *et al*., 2004).

To mitigate the environmental implications of fish waste, it should be transformed into sustainable and usable products via the employment of modern technology. Fish by-products and by-catch are good sources of protein, fatty acids, and minerals. Skin is the most important protein source in fish species; trimmings and bones are high in calcium; and the head, guts, and bones are high in lipids (Kandyliari *et al*., 2020). Due to their high quantity of collagen, peptides, chitin, polyunsaturated fatty acids (PUFAs), enzymes, and minerals, fish by-products are becoming a sustainable supply of high-value bio-compounds for biotechnological and pharmaceutical applications with high market value (Rinaudo, 2006; Granito *et al*., 2018; Abuine *et al*., 2019; Nasri, 2019; Shahidi *et al*., 2019; Shavandi *et al*., 2019; Karkal and Kudre, 2020; Coppola *et al*., 2021). Furthermore, fish wastes might be used to make fish meal, fish oil, fish silage, fertilizer, and biodiesel/biogas as feasible solutions to fish waste concerns.

FISH WASTE MANAGEMENT

As discussed earlier, fish waste is a major environmental issue that arises from the fishing and aquaculture industries. Fish waste can cause severe environmental impacts such as water pollution, degradation of aquatic ecosystems, and depletion of fish populations. However, fishery discards or manufacturing by-products may be used to make new products. With food shortages, restricted fisheries, and a growing awareness of sustainability, using all resources is moral and economic (Islam *et al*., 2021). Over the years, various methods have been developed to manage fish waste and by-products, and these methods can be broadly categorized into four main approaches: composting, anaerobic digestion, recycling, and further processing of fish waste.

Composting is a procedure that includes the breakdown of fish waste to generate a nutrient-rich soil supplement that can be utilized in agriculture. This amendment may be used to improve the quality of the soil. Composting fish waste was discovered to be an effective way for handling fish waste in small-scale aquaculture systems, according to research carried out by Radziemska *et al*. (2019). According to the findings of the research, composting fish waste decreased the overall amount of nitrogen and phosphorus included in the trash while simultaneously producing a stable and risk-free soil amendment.

Through a process known as anaerobic digestion, fish waste is broken down in the absence of oxygen, resulting in the production of biogas. This biogas has the potential to be utilized as a source of renewable energy. Anaerobic digestion was identified as a potentially useful approach to the management of fish waste in research that was carried out by Salam *et al*. (2009). According to the findings of the research, anaerobic digestion not only offered a method for the disposal of fish waste but also generated biogas, which had the potential to be utilized as a source of renewable energy.

The process of recycling entails transforming discarded fish by-products into valuable products such as fish meal, fish oil, and fish silage (Islam *et al*., 2021). The recycling of fish waste into fish meal was shown to be a successful way for controlling fish waste in the aquaculture sector. This practice not only lowers the environmental effect of fish waste but also provides a reliable supply of protein for the feed used in aquaculture (Miles and Chapman, 2006). Furthermore, fish silage is a method that involves the preservation of fish waste by adding acid or salt to the waste to prevent spoilage. In a study by Islam *et al*. (2021), the production of fish silage from fish waste was found to be a viable option for managing fish waste in the fisheries and aquaculture sectors. The study reported that fish silage production reduced the negative environmental impacts of fish waste and provided a potential source of income for fishers.

Utilization and further processing of fish waste are dependent on the local conditions and the structure of the industry. For food, feed, technical and pharmaceutical purposes, fish waste may be processed into proteins, amino acids, peptides, collagen, oil, minerals, enzymes, flavors, and other compounds (Ghaly *et al*., 2013). Treated fish waste has been found valuable for many applications: dietetic products (chitosan), natural pigments (after extraction), food-packaging applications (chitosan), cosmetics (collagen), enzyme isolation, Cr immobilization, soil fertilizer and moisture maintenance in foods (hydrolysates) (Arvanitoyannis and Kassaveti, 2008). Fish wastes are rich in enzymes like proteases, triglycerides, lipases, chitinases, and alkaline phosphatases that can be used for various seafood-related applications (Mathew *et al*., 2022). These marine enzymes have novel properties like the ability to tolerate high salinity and low temperatures, making them very useful for food applications (Mathew *et al*., 2022).

Overall, the literature suggests that composting, anaerobic digestion, recycling and further processing are effective methods for managing fish waste. These methods not only reduce the negative environmental impacts of fish waste but also offer potential economic benefits by creating new revenue streams and reducing costs associated with waste disposal.

FISH MEAL PRODUCTION

Fish waste to fish meal

While we have discussed several fish waste management techniques above, it is important to note that fish meal production is one of the most effective methods for utilizing the fish waste. The substantial quantities of landed fish that are lost or thrown away between landing and eating pose a serious economic and environmental concern in most fish distribution networks. It is of the utmost importance to underline that the current increase in consumption is driven not just by a shift in production but also by a range of other factors, including the decrease of waste (Coppola *et al*., 2021). One out of every four fish caught is discarded as bycatch (FAO, 2020). Furthermore, depending on the level of processing and the species of fish, the amount of waste created during processing ranges from 20 to 80% (Dorea, 2006). Fish by-products and by-catches are now economically feasible for widespread use in animal feeds due to sophisticated and effective fishing methods and the rise of the fishing industry (Dorea, 2006). As a result, fish meal manufacturing is a generally recognized and sustainable solution to this problem.

There are two distinct types of fish meals: those that are produced from entire fish that have been taken for the express purpose of being processed into fish meal, and those that are produced from the waste products of fisheries and used to provide food for humans (Dorea, 2006). Fish meal may be created from almost any kind of fish; however, it is mainly created from wild-caught, small-bodied marine fish that are too oily and boney to consume. A small quantity of fish meal is produced from by-catch from other fisheries and by-products made through the preparation of different marine products intended for direct human consumption (e.g., fish filleting and cannery operations) (Miles and Chapman, 2006).

More than 13% of the world's raw material used for fish meal conversion comes from the by-products of filleting pelagic fish like mackerel and herrings as well as demersal fish like hake and pollock. Another 5% is derived from tuna trimmings and offal, 3.5% from salmon by-products, and 3% from pangasius off-cuts. In addition, tilapia is the farmed fish that currently contributes the least amount of raw material to fish meal, accounting for just 1.9% of the total (IFFO, 2022a) (Figure 4).

The nutritional content of fish meal varies greatly due to differences in source material, processing methods and circumstances utilized (Mathew, 2010). There are numerous techniques for producing high-quality fish meal, however the fundamental principle is to separate the solids from the oil and water. Fish meal is produced by cooking, squeezing, drying, and grinding the fish (Mathew, 2010). It is common practice to omit the pressing step when there is no oil that has to be extracted, as is the case with lean fish. In general, 100 kg of raw material yields around 21 kg of fish meal (Miles and Chapman, 2006). According to the type of fish waste used in the production of fish meal, it is mainly divided into the dry rendering process and wet rendering process. Only lean or non-oily fish such as silver bellies, jewfish, scaenids, ribbon fish, sole, anchoviella, shark corpses, fish offal, and filleting waste is appropriate for the dry rendering or dry reduction process (Mathew, 2010). During this step, the moisture content is reduced until it reaches 10%, and it is then ground into a powder (Zynudheen and Binsi, 2019).

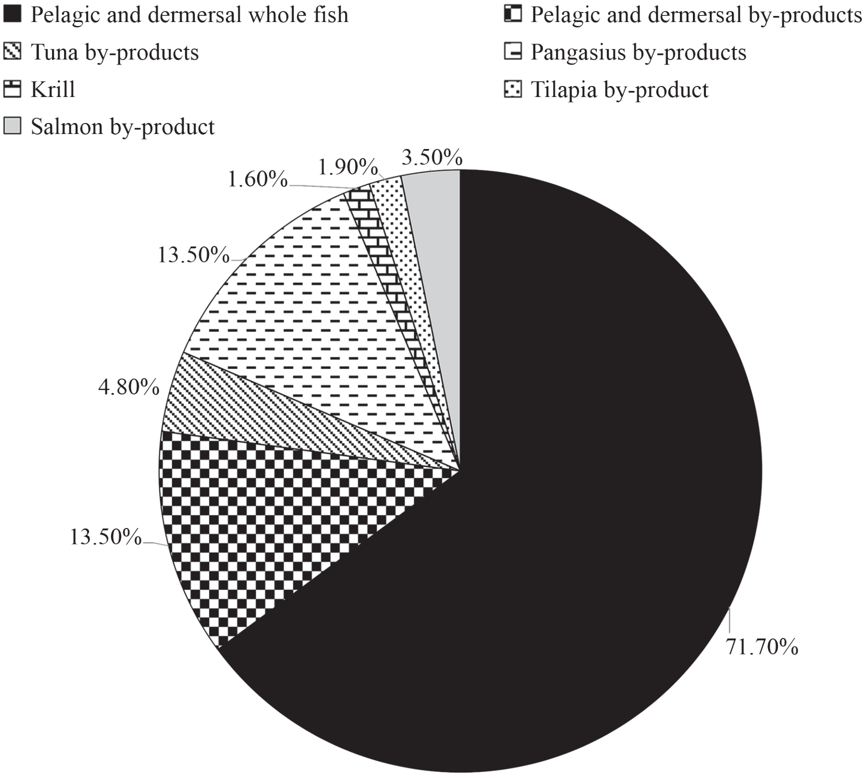

Figure 4. World fish meal production by species, Source: IFFO (2022a).

Nutritional profile of fish meal

Crude protein content in high-quality fish meal ranges from 60 to 70% by weight (Miles and Chapman, 2006; Khan *et al*., 2012). Fish meal's amino acid profile is a major selling point as a dietary protein supplement (Hall, 2010). Cereal grain and other plant concentrate proteins often have incomplete amino acid profiles and are deficient in some essential amino acids, including lysine and methionine. In contrast to the sulfur-containing amino acids methionine and cystine, the amino acids lysine and tryptophan are abundant in soybean and other legume meals, which are staples in the feeds of common farm animals (Miles and Chapman, 2006). Overall, the protein digestibility of fish meal is more than 95%. The digestibility of plant proteins generally ranges from 77 to 96% (Miles and Chapman, 2006).

Fish meal is preferred over plant-derived proteins in aquaculture diets because it has no nutritional inhibitors or anti-nutritional components (Romarheim *et al*., 2005). Chemicals included in fish meal increase the feed's palatability and attractiveness. This quality makes the food easier to swallow and lessens the loss of nutrients during digestion. Glutamic acid, a non-essential amino acid, is thought to be one factor in fish meal's palatability (Miles and Chapman, 2006). There are two distinct categories of lipids found in fish: oils that are liquid at room temperature and solid fats. In spite of the fact that most of the oil is removed during processing, the amount of lipid that is left behind is typically between 6 and 10% by weight. However, this number may range anywhere from 4 to 20% (Miles and Chapman, 2006). Lipids from fish are rich in beneficial polyunsaturated fatty acids, including omega-3 and omega-6 fatty acids, and are easily absorbed by the bodies of all animals. The omega-3 fatty acids found in the greatest quantities in fish meal and fish oil include linolenic acid, docosahexaenoic acid, and eicosapentaenoic acid (Hall, 2010). Fish are the primary consumers of the fatty acids docosahexaenoic acid and eicosatetraenoic acid, which are generated by algae and zooplankton. Fish meal and fish oil have a more favorable ratio of omega-3 to omega-6 fatty acids than the majority of other meals (Miles and Chapman, 2006).

Fish meal is a fantastic source of energy and provides a healthy balance of fatty acids. Calories in fish meal are directly proportionate to the quantity of protein and oil it contains, as fish meal contains very little carbohydrate (Hall, 2010). Several factors, including the fish's species, physiology, sex, reproductive stage, age, diet, and processing method, influence the quantity and quality of oil in fish meal (Miles and Chapman, 2006). Lipids included in fish meal and fish oil are readily absorbed by fish, shrimp, poultry, swine, and ruminants including cows, sheep, and goats. In these creatures, 90% or more of the lipids are digestible (Miles and Chapman, 2006). Fish lipids are highly digestible and may be converted into usable energy quickly. In order to protect animals from the free radicals that are continually being produced on a molecular level in animal cells, high-quality fish meal contains antioxidants or compounds that reduce this risk (Laohabanjong *et al*., 2009). When lipids, particularly polyunsaturated fatty acids, are exposed to oxygen, a process known as oxidation takes place, which results in the production of heat. This causes the lipids to simply deteriorate and become rancid. Due to the high PUFA content of the oil, fish meal must be preserved with antioxidants in order to retain its energy content (Laohabanjong *et al*., 2009).

Typically, the mineral content of superior fish meal varies between 17 to 25% (Khan *et al*., 2012). More ash indicates an increase in minerals, including calcium, phosphorus, and magnesium. The majority of fish meal ash is composed of calcium and phosphorus (Hall, 2010). Phosphorus found in fish meal is easily absorbed by most animals, unlike plant-based phosphorus. Monogastric animals cannot absorb phosphorus from plants because it is mostly found in the plant's cells in an organic form called phytate (Miles and Chapman, 2006). It is possible for ruminants like cows, sheep, and goats to utilize phosphorus in phytate due to the microbial community that lives in their rumen. There is a large amount of variation in the vitamin content of fish meal, which may be attributed to a number of different variables. These factors include the source and composition of the fish meal manufacturing technology, in addition to the freshness of the product. Fish meal has a relatively low concentration of fat-soluble vitamins since this process, which removes fat-soluble vitamins, is part of the oil extraction process. Fish meal is a good source of the B-complex vitamins, such as riboflavin, cobalamin, niacin, pantothenic acid, choline and pantothenic acid (Miles and Chapman, 2006; Hall, 2010).

Furthermore, the nutrient profile of fish meals produced from different fish species varies. The crude protein, crude fat, ash, phosphorus, moisture content, and amino acid profile vary according to the type of fish utilized, area of fish catch, life stage of fish utilized, and processing methods (Table 1) (Guo *et al*., 2020). Other than fish meal, there are several other meals used by farmers including soy meal, blood meal, chicken meal, rendered meat meal which possess different nutrition profiles as shown in Table 2.

Table 1. Proximate and amino acid content of fish meals produced from different fish by-products.

Component	**Menhaden**	**Anchovy**	**Salmon**	**Hydrolyzed salmon**
Crude protein %	62.77	68.3	64.6	66.2
Crude fat %	10.5	7.57	10.6	3.04
Ash %	18.2	15.8	16.03	17.3
Moisture %	9.6	8.53	9.14	7.7
Phosphorus %	2.82	2.32	2.7	1.47
Amino acids				
Alanine	3.98	4.14	4.22	3.8
Arginine	3.75	3.81	3.81	3.51
Aspartic acid	5.6	5.87	5.0	5.36
Cysteine	0.51	0.65	0.46	0.54
Glutamic acid	8.02	8.01	7.06	7.36
Glycine	4.57	3.82	6.45	4.37
Histidine	1.31	1.78	1.40	1.52
Isoleucine	2.39	2.89	2.25	2.67
Leucine	4.34	4.83	3.79	4.14
Lysine	4.68	5.10	3.93	4.75
Methionine	1.67	1.65	1.49	1.51
Ornithine	0.06	0.06	0.19	0.07
Phenylalanine	2.48	2.68	2.17	2.3
Proline	2.88	2.36	2.17	2.3
Serine	2.42	2.28	2.31	2.26
Taurine	0.71	0.69	0.89	0.38
Threonine	2.54	2.76	2.38	2.53
Tryptophan	0.62	0.76	0.55	0.57
Tyrosine	1.46	2.05	1.88	2.34
Valine	2.82	3.47	2.87	3.08

Note: *Adopted and modified from Guo *et al*. (2020)

Table 2. Crude protein and essential amino acid content in fish meal and meals from other sources.

Item	Crude protein	Essential amino acid, g·100 g^{-1} crude protein											
		Arg	His	Iso	Leu	Lys	Met	Cys	Phe	Tyr	Thr	Try	Val
Fish meal	64.6	5.70	2.41	4.74	7.74	7.91	3.02	0.94	4.12	3.33	4.37	1.18	5.43
Rendered meat meal	54.0	6.67	2.11	2.96	7.11	5.69	1.48	1.11	4.02	2.59	3.65	0.65	4.93
Poultry by-product meal	64.1	6.15	1.95	3.14	6.07	5.18	1.73	1.01	3.53	2.43	3.40	0.75	3.92
Blood meal	77.1	4.33	6.56	1.18	14.25	9.13	1.28	1.41	6.93	2.94	5.25	1.4	9.14
Soybean meal	47.5	7.33	2.69	4.55	7.71	6.36	1.41	1.56	5.03	3.83	3.89	1.37	4.78
Linseed meal	33.6	8.84	2.02	4.64	6.13	3.69	1.76	1.76	4.67	3.07	3.75	1.55	5.18
Canola meal	35.6	6.21	2.7	4.02	7.25	5.84	2.08	2.56	4.02	3.17	4.47	1.26	5.11
Cottonseed meal	42.4	10.05	2.62	3.04	5.78	3.89	1.58	1.63	4.65	2.90	3.16	1.27	4.15
Sunflower meal	42.2	6.94	2.18	3.41	5.47	2.84	1.94	1.56	3.93	2.44	3.15	1.04	4.12

Note: *Adopted and modified from: Cho and Kim (2011)

SUSTAINABILITY OF FISH WASTE-BASED FISH MEAL

The feed conversion ratio (FCR), fish-in: fish-out ratio (FIFO), the forage-fish dependency ratio (FFDR), and lifecycle assessment analysis (LCA) are the four metrics typically employed in the examination of aquafeed performance and sustainability (IFFO, 2022c). FCR, the ratio between weight of feed input and weight gained by an animal or fish, is the traditional metric of livestock production efficiency. It is also known as the economic feed-conversion ratio (eFCR), which accounts for feed waste and mortalities, and the biological feed-conversion ratio (bFCR), which excludes non-consumed feed and production losses from the calculation. The feed conversion ratio of the fish meal varies based on the raw material source utilized, seasonality, age, reproductive condition, and processing method used in fish meal manufacturing, which impacts protein and oil content (Hall, 2010). The weight of captured live fish should be converted to fish meal for use in aquaculture to generate a unit weight of the live fish product, which is referred to as the FIFO ratio. The comparative units might be kilogram (or tonnes) of wild-caught fish per kilogram (or tonnes) of live-weight farmed fish (IFFO, 2022c).

FFDR calculates the environmental effect of aquaculture feed by combining eFCR with the amount of incorporation of forage fish marine elements in the feed (not by-products) and their yield ratio (Hall, 2010). LCA is a significantly more sophisticated computation that considers environmental implications such as possible global warming, cumulative energy usage, abiotic resource use, potential ozone depletion, consumptive water use, and land use. Due to better technology, nutritional understanding, and feed-management practices, IFFO discovered an improving trend across all four measures between 2000 and 2020. According to IFFO statistics, eFCR, FIFO, and FFDR have been decreasing throughout the years, demonstrating the effectiveness of the fish meal used in the aquaculture business (Table 3). According to IFFO, feed is now more precisely designed to satisfy the demands of specific species, and nutrients are given more effectively. The collection and analysis of LCA data for the marine ingredients business are still ongoing, but preliminary findings indicate that the environmental footprint of fish meal and fish oil is mostly driven by fuel usage during fishing operations. Most forage (small pelagic) fisheries have very low fuel usage per tons of capture because of high-volume captures per unit effort and the prevalence of purse-seine fishing (IFFO, 2022b).

The resource sustainability for fish meal production must be considered in order to measure production efficiency. Heat is a valuable resource

Table 3. IFFO data (eFCR, FIFO and FFDR) over recent decades in the aquaculture sector.

Species	eFCR for years			FIFO for years			FFDR for years		
	2000	2010	2020	2000	2010	2020	2000	2010	2020
Crustaceans	1.31	1.22	0.93	1.61	0.83	0.45	1.29	0.62	0.31
Marine fin fish	1.48	1.20	0.96	2.21	0.98	0.75	1.77	0.74	0.52
Salmonids	1.54	1.50	1.27	3.03	1.87	0.93	2.43	1.40	0.64
Eels	1.22	0.89	0.82	2.86	1.51	1.34	2.29	1.13	0.93
Cyprinids	0.44	0.39	0.30	0.09	0.03	0.01	0.08	0.02	0.01
Tilapias and other cichlids	1.54	1.36	1.35	0.63	0.25	0.11	0.50	0.19	0.08
Freshwater fish	1.14	1.06	1.02	0.71	0.44	0.29	0.57	0.33	0.20
Turtles and frogs	0.90	0.75	0.73	1.34	0.85	0.73	1.07	0.63	0.50
Total fed aquaculture	0.81	0.799	0.732	0.47	0.28	0.19	0.38	0.15	0.13

Note: Source: IFFO (2022c)

in the fish meal production process, since several steps including the numerous separation steps require that the material be heated to a high temperature. The amount of fuel consumed varies on the technique used to dry the fish meal, with indirect heating using less fuel because the fuel is only needed to create steam. Fuel oil usage might be lowered from 49 to 35 L·1,000 kg^{-1} of raw material using the best available technology (UNEP, 2000). A modern facility requires 30 KWh of electricity use per ton of raw material, and 35 kg of fuel oil use (UNEP, 2000).

Because fish meal manufacturing is a method of removing moisture from raw materials, water is used sparingly in the process, with the bulk of the water coming from the usage of saltwater to unload the fish from the ship to the plant. If the most advanced technology is used, the potential for an increase in wastewater pollution load might be reduced from 30 to 22 kg of chemical oxygen demand per 1,000 kg of raw material dumped, and from 12 to 9 kg of chemical oxygen demand per 1,000 kg of raw material processed (Figure 5) (UNEP, 2000). The processing of fish meal results in the release of effluents into the atmosphere, the majority of which are composed of water vapor generated during the process of extracting water from raw materials as they move through the plant, most notably in the evaporators. These effluents are a characteristic of the fish meal manufacturing industry. These vapors also convey smells that may disturb neighbors; therefore, their removal has become an industry standard procedure. The most effective strategies for odor control include using freshly caught fish, centralizing exhausts for convenience of treatment, drying indirectly rather than directly to reduce aerosol formation in flue gases, plant location, and familiarity with prevailing climatic variables like wind direction and velocity (Hall, 2010).

Scrubbing, high-temperature combustion, chemical inactivation, catalytic combustion, and adsorption onto active carbon are some of the flue gas odor-reduction techniques that are available (FAO, 1986). Fish that are judged unfit for direct human eating are used in the fish meal process, which completely reduces the fish so that no by-products are produced. Fish oil separation is a primary goal of the process, and while much of it ends up in aquaculture feeds, it is also intended for direct human consumption through the production of margarine or in health goods such as omega-3 fatty acid capsules, which might be regarded as by-products. The goals of sustainable development and cleaner manufacturing, which have been discussed in relation to traditional fishery performance indicator processes, are closely related, and this is also true for the production of fish meal (Hall, 2010).

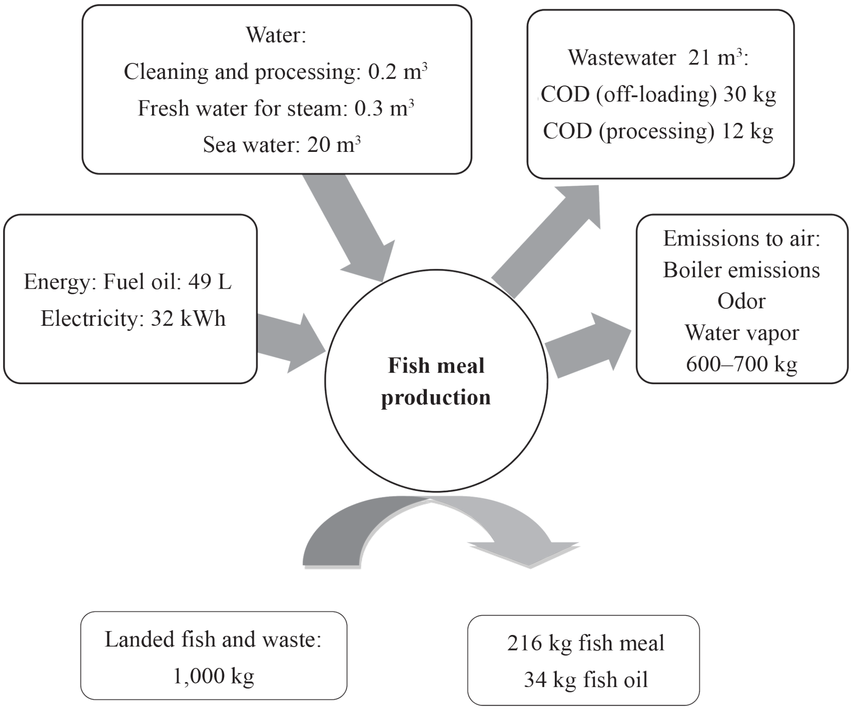

Figure 5. Inputs and outputs for fish meal and fish oil production using average technology. Source: UNEP (2000)

PROBLEMS ASSOCIATED WITH FISH MEAL PRODUCTION

Recent studies have shown that because of the fast rise of contamination and pollution due to plastics in coastal areas, microplastics are increasingly prevalent in fish meal (Tanaka and Takada, 2016). A portion of microplastics (less than 5 mm) is known as the residual leftovers of microplastics (MP) or polymers (Hanachi *et al*., 2019). Primary microplastics are microplastics that are developed from polymers that are produced as little particles of plastic (Andrady, 2011). Secondary microplastics are generated when these polymers are formed as pieces of bigger plastics, such as resin pellets, cosmetic scrubbers, or blasting abrasives. The relationship between the rate of microplastic ingestion and their existence in feedstuffs is another factor supporting the growing microplastic accumulation in freshwater fish bodies, even though fish often reject ingesting free microplastics from their environment (Parker *et al*., 2021). The physiology of fish, the culture environment, and consumer health are all significantly impacted by the introduction of microplastics into aquaculture ponds. For instance, several studies found microplastics in the fish gastrointestinal system, body tissue, gills, and skin, also affected the fish's ability to feed and develop, and caused metabolic problems, respiratory failure or gill infections, decreased fecundity, and neurological damage (Mahamud *et al*., 2022). Additionally, because of their collective large surface area, microplastics allegedly let harmful microbes assemble hazardous chemicals in aquatic water bodies (Xu *et al*., 2020). Therefore, studies identified microplastic accumulation in the fish meal and fish oil produced in several parts of the world (Thiele *et al*., 2021).

MPs are primarily introduced into the human body through the consumption of fish and mussels (Prata *et al*., 2020). The majority of evidence revealed MPs in the GI tracts of wild and farmed fish (Zazouli *et al*., 2022) and thus, it was hypothesized that removing the GI tract from fish during processing might minimize MP exposure in humans (Toussaint *et al*., 2019). It has been noted, however, that removing the GI tract from fish does not totally minimize the possibility of human exposure to MPs (Karami *et al*., 2017). Fish meal is a crucial component of the food chain since it is used to feed a variety of animals, including poultry, pigs, and fish in aquaculture. A recent study found MPs in approximately 73.3% of Bangladesh's freshwater fishes such as *Labeo rohita, Labeo bata, Labeo calbasu, Cyprinus carpio, Oreochromis mossambiscus, Anabas testudineus,* and *Heteropneustes fossilis*, which are well-known aquaculture species (Parvin *et al*., 2021).

In the case of microplastics, recent studies have shown that they may have negative impacts on the organisms and ecosystems found in marine environments; nevertheless, there are still many information gaps. For instance, it is not yet known how microplastics gather and transit through food webs, how they interact with other pollutants, or how they influence the health of people who eat seafood that is polluted with microplastics. All of these questions remain unanswered. As a result, the emphasis of future research may shift to addressing these knowledge gaps and devising innovative strategies for monitoring and reducing the effects of microplastic contamination.

The possibility of accidental inclusion of endangered species in fish meal is a second problem. The Japanese eel and bluefin tuna, which are endangered species (Pike *et al*., 2020), each has a 0.63% probability of being included in fish meal (Ido and Kaneta, 2020). Such incidence may have occurred as a result of using fish from IUU (illegal, unreported, and unregulated) fishing for fish meal. Due to a lack of IUU traceability rules, an analysis showed that between 24 to 36% of wild-catch fish was imported to European Union nations in 2015 (Pramod *et al*., 2017). It is anticipated that removing IUU fishing, which may include endangered species, from the overall catch would not have a negative impact on the fishery's sustainability or productivity (Pramod *et al*., 2017). Aquaculture will become more responsible as a result of strict restrictions that are urgently needed to limit the trade of endangered or IUU fish products (Ido and Kaneta, 2020).

According to Barange *et al*. (2009), many species of pelagic fishes are mostly utilized for fish meal. This group of fishes is more vulnerable to climate change since they are heavily reliant on inter-annual, environmentally driven recruitment changes. The availability of certain wild-caught, fast-growing, and short-lived pelagic fish, which are prevalent in subtropical and temperate regions, is the primary factor that drives the industrial production of fish meal. They are bony fish that are high in oil content but have a limited market for human consumption (Pauly *et al*., 2005). Furthermore, El Nino events have caused projected changes in ocean circulation patterns, resulting in a decrease in production of pelagic fishes such as Peruvian anchovies and sardines (Pike and Barlow, 2003). Similarly, fluctuations in the North Atlantic Ocean's winter index (Schmittner *et al*., 2003) altered Sandeel production. Thus, these climatic changes have ultimately resulted in a decrease in the supply of raw materials required for the production of fish meal. Climate model studies have showed that by the 2050s, worldwide fisheries income may decline by 35%, which is more than the predicted decline in catches (Lam *et al*., 2016). According to the FAO, the proportion of fish stocks that are at ecologically sustainable levels has fallen from 90% in 1974 to 65.8% in 2017 (FAO, 2020). Overfishing, or fishing above a stock's maximum sustainable level, may endanger marine biodiversity by causing the extinction of both target and non-target species and the creation of dead zones. The decline in fish catches has put human health in danger (Golden *et al*., 2016).

FISH WASTE AND BLUE ECONOMY

The "Blue Economy", as defined by the United Nations, is an ocean economy that strives to promote human wellbeing and social fairness while significantly lowering environmental risks and ecological constraints (UN, 2014). Two different concepts were put up as support for the Blue Economy Hypothesis. To begin, the efficacy of nature, in which the blue economy imitates the natural ecosystem and functions effectively in line with what nature gives, without degrading the environment but rather improving it. This is termed "the efficiency of nature". The second concept is known as "zero waste", and it implies that garbage produced by one source may be used as a source of food or energy by another source. This makes it possible for the living systems of an ecosystem to become sustainable and balanced (Rani and Cahyasari, 2015). The sustainability indexes such as FCR, FIFO, FFDR, and LCA discussed in the sustainability of fish waste processing above, also provide evidence that utilization of fish waste is a possible option towards the blue economy of a nation. The fish wastes and by-catches from the fishery industry are going to waste and creating severe environmental pollution in coastal areas. Blue Economy also seeks to boost economic development, social inclusion, and the enhancement of traditional ocean-related livelihoods, while supporting the sustainability of oceans and coastal areas (Wenhai *et al*., 2019). Therefore, the utilization of fish waste produced by the fishery industries would be a great support for economic growth, protection of the marine environment, and promoting sustainability.

CONCLUSION

The disposal of by-products and by-catches from fishery industries pose severe environmental and health-related threats. Fish meal production is considered as a widely acceptable and sustainable solution for the fisheries discards. It has been found that fish meal is enriched with excellent nutrient profiles that satisfy the nutrient requirements of aquaculture and livestock. However, fish meal production shows a declining trend globally due to several factors, whereas a sustainable and continuous supply of fish meal to the industries is essential. However, the inclusion of microplastics in the fish meal and legal or regulatory issues are major concerns that need to be taken into account while promoting the conversion of fish waste to fish meal. Therefore, it is recommended that regulations and restrictions should be in place to control the quality and the legal requirement of fish meal production. Furthermore, fish meal production plays a key role in driving circular economy by reducing the environmental problems and by generating additional income, which is important for the socio-economic development of the stakeholders and the nations. This review establishes a clear linkage/model between fisheries discards, fish meal, aquaculture and livestock production that drives the circular economy while contributing to environmental health and sustainability. Strengthening the linkage with further research and development is needed for the future expansion of the industries involved with this linkage.

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