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Review

Nutrient recovery and recycling from fishery waste and by-products

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ABSTRACT

The circular bio-based economy offers great untapped potential for the food industry as possible valuable products and energy can be recovered from food waste. This can promote more sustainable and resilient food systems in Europe in follow-up of the European Commission's Farm to Fork strategy and support the global transition to more sustainable agri-food systems with the common agricultural and fisheries policies. With its high nutrient content, waste and by-products originating from fish and seafood industry (including aquaculture) are one of the most promising candidates to produce alternative fertilising products which can play a crucial role to replace synthetic mineral fertilisers. Whereas several studies highlighted the opportunities to recover valuable compounds from fishery waste, study towards their potential for the production of fertilising products is still scarce. This study presents an extensive overview of the characteristics of fishery waste and by-products (i.e., fish processing waste, fish sludge, seafood waste/by-products), the state-of-the-art nutrient recovery technologies and recovered nutrients as fertilising products from these waste streams. The European Commission has already adopted a revised Fertilising Products Regulation (EU) 2019/1009 providing opportunities for fertilising products from various bio-based origins. In frame of this opportunity, we address the quality and safety aspects of the fishery waste-derived fertilising products under these criteria and highlight possible obstacles on their way to the market in the future. Considering its high nutrient content and vast abundance, fish sludge has a great potential but should be treated/refined before being applied to soil. In addition to the parameters currently regulated, it is crucial to consider the salinity levels of such fertilising products as well as the possible presence of other micropollutants especially microplastics to warrant their safe use in agriculture. The agronomic performance of fishery waste-derived fertilisers is also compiled and reported in the last section of this review paper, which in most cases perform equally to that of conventional synthetic fertilisers.

1. Introduction

The Circular Economy concept was introduced by the European Commission (EC) as a response to environmental and social problems following the rapid growth of human population (Chojnacka et al., 2020). Over recent decades, the developed and developing countries jointly achieved an extraordinary period of food crop productivity growth, characterised by food production rates increasing faster than the human population growth rate. Nonetheless, an estimated one third of the food is lost or wasted as flowing through supply chains (Santagata et al., 2021). Food waste is addressed in the EU Circular Economy Package, introducing a waste reduction target under the Farm to Fork Strategy within the European Green Deal (EC, 2020). In that sense, by-products from one production process are used as secondary raw materials in another, substituting raw materials with residual biomass, e.g. postharvest residues, residues from livestock production and slaughter or food processing.

The circular economy aims to promote the use of recycled products and to close the nutrient cycle loop by avoiding nutrient losses and detrimental environmental effects, while also reducing the dependency on fossil fuels (Egan et al., 2022). The production of fertilisers is highly energy consuming, which is based on fossil fuels (Nitrogen (N)-fertilisers on Haber–Bosch process) (Sigurnjak et al., 2019) or fossil ore deposits (phosphate rock - more than 85% of phosphorus (P) applied in agriculture comes from phosphate rock) (Ahuja et al., 2020; Chojnacka et al., 2020). In Europe, 46% of the total N applied to agricultural soil comes from mineral fertilisers (Duan et al., 2020), and intensive fertilisation can cause severe environmental problems such as nitrate contamination in groundwater and surface water, resulting in reduced biodiversity (by eutrophication) as well as reduced potability. It can also cause resource depletion in the form of natural gas used for fertiliser production, potentially increasing greenhouse gas (GHG) emissions

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(Andrade et al., 2022). Hence, a transition to sustainable agriculture is necessary not only to reduce the environmental impact of agricultural systems, but also to become more resilient to economic and societal challenges (Hendriks et al., 2021).

The production of recycled food waste-derived fertilisers is an interesting and promising approach to increase the economic and ecological sustainability of the fish industry. Upon the practical implementation of the Fertilising Products Regulation (EU) 2019/1009, the primary food production sector in the EU countries has to meet the policy changes in accordance with this legal framework, most importantly the EU Fertilising Product Regulation functionality specifications and compositional criteria. On the other hand, most farmers are not aware of the new policy content with the rapidly evolving legislative framework towards circularity. Resource recovery from fishery waste and by-products has gained quite a lot of attraction over the last few years and although numerous research and review papers have been published so far, no comprehensive review paper exists in the literature to the best of the authors' knowledge summarizing the quality and safety aspects of fertilising products derived from fishery waste in the technological, legislative (at the EU level) and agronomic frameworks except the review paper of Ahuja et al. (2020) with a focus on Norway. In this review paper, we aimed to highlight the characteristics of fishery waste products and most commonly used technologies to produce bio-based fertilising products from these secondary raw materials. We further discuss their compliance with European legislations and agronomic performance upon application to see their potential to replace synthetic mineral fertilisers in the market.

2. Fishery waste: emerging bio-based solutions

Global fishery production (including fish, crustaceans, molluscs, and other aquatic animals, excluding algae) has increased significantly in the last decades. It is estimated to have expanded with an annual growth rate of 3.3% and increased from 19 million tons in 1950 to 179 million tons (live weight equivalent) in 2018, then showed mere changes in 2019 and 2020 (FAO, 2020, 2022). In 2020, Asian countries accounted for 70% of the total fishery production followed by American and European producers, contributing to 12% and 10%, respectively. Fish capture and aquaculture from inland and sea are the two main sources for the production of fish and fishery waste streams. Aquaculture has faced an important increase from around 14.9 million tons in early 1990s to 82.1 million tons in 2018, corresponding to 46% of the total production (FAO, 2020). It was dominated by finfish (>54 million tons), molluscs (17.7 million tons) and crustaceans (9.4 million tons). The vast amount of fishery waste is generated during culturing, catching, and processing of fish. Conversion of fish to fishery waste is dependent on the fish species, generally accounting for 30–70% of the original fish (live weight) (Ahuja et al., 2020). Between 50–125 million tons of fishery waste were generated in 2018 and the amount would increase with respect to the increasing trend of fish production. Another important type of waste is fish sludge generated from aquaculture industry. Celis et al. (2008) estimated that around 1.4 tons of fish sludge produced from every ton of farmed salmon in Chile. In that sense, a huge amount of fishery waste is considered as a stable and nutrient-rich source for further bio-treatment to produce value-added products (Ahuja et al., 2020; Cooney et al., 2023). Considering the current nutrient dilemma globally, our aim concentrates on lower value-added fertilisers meeting lower standards rather than high cost food and feed.

Although intensively-increasing aquacultural production can support in meeting food demand, it generates huge volumes of wastewater, loading high content of organic matter and dissolved nutrients (e.g., ammonium and phosphate), thus may cause pollution to the surrounding environment, especially the nearby water body, and pose risks to aquatic organisms and human health (Chen et al., 2022; Teoh et al., 2022). Li, Z. et al. (2020) found that approximately one million tons of nitrogen (N) and 173 thousand tons of phosphorus (P) are discharged in water bodies through aquacultural waste effluent in China. In their study on a 40-ha pond aquaculture base, the aquaculture wastewater in the culture pond, prior to any treatment, exhibited average concentration of 44.8 mg/L for chemical oxygen demand (COD), 3.1 mg/L for total nitrogen (TN), 0.6 mg/L for ammonium nitrogen (NH_4^+-N) and 2.7 mg/L for nitrate nitrogen (NO_3^--N), requiring purification before discharge. Recovering these nutrients as fertilising products is an applicable way to solve this problem. Chen et al. (2022) reported that NH_4^+-N and P at concentration of 86.8 mg/L and 58.5 mg/L (from feed and fish faeces) in the aquaculture wastewater could be mostly recovered with approximately 60% NH_4^+-N and 92% P as struvite, after adding 0.5 g/L magnesium (Mg) contained composite to enhance struvite crystallisation. Teoh et al. (2022) found that membrane distillation worked in both water recycling and nutrient recovery, leading to more than 85% water recovery and five-fold condensed N, P, and potassium (K) in the retentate. The crystalized struvite, magnesium ammonium phosphate, and nutrient rich concentrate can be used as plant fertilisers.

A full understanding of nutrient content in fishery waste supports the alternatives of following treatment technologies and stands as a decisive criterion before the production and application of the final products as summarized in Fig. 1. To have an easy overview, the following subsections focus on three main fishery wastes (i) finfish processing waste, (ii) fish sludge, and (iii) seafood waste and/or by-products.

2.1. Finfish processing waste

In 2020, inland and marine finfish production reached more than 135 million tons, accounting for 76% of the total fishery production (excluding algae) (FAO, 2022). Finfish processing has several steps, beginning with size classification, then followed by removal of scales, carcass, fins by washing, and finally viscera removal for producing fillets, canned fish and other products (Villamil et al., 2017). Although fishery waste components vary depending on the fish species, general components of fishery waste from fish processing industry are: muscle-trimmings (15–20%), viscera (12–18%), bones (9–15%), heads (9–12%), scales (5%), skins and fins (1–3%) (live weight) (Martínez-Alvarez et al., 2015). Fish processing water is another huge volume of waste stream with high nutrient content. Muthukumaran and Baskaran (2013) found that the largest fish processing industry in Victoria state, Australia, produced around 9100 kL/year wastewater for 3500 tons of seafood, accounting for 70% of the total water usage. The neutral to light alkaline wastewater contained 410 mg/L Total Kjeldahl Nitrogen (TKN), 363 mg/L total P and 114 mg/L sulphur (S) and rich organic materials.

All kinds of fish processing waste have attracted attention from food and energy sectors due to their high proportion of protein and lipid contents (see Table 1). Protein content is high in all parts of various species of fish, most of which are higher than 10% of live weight. In general, fish heads have both high protein and lipid content (>10%); fish skin has the highest level of protein content compared to other residues, even more than 20% of live weight for some fish species. The fishery waste is characterised to be of high moisture, mostly ranging from 60% to 80%, which also means that the dried fishery waste has higher content of protein and lipids. The protein proportion of pollock and cod freeze dried stickwater can exceed 86% and the lipid content of viscera of European seabass (*Dicentrarchus labrax*) can be more than 50% of the total dry weight. Hydrolysates derived from fish processing waste are significant sources of N. For instance, the N content of cod viscera hydrolysates ranged from 11.5% to 12.8% (Aspmo et al., 2005). These findings clearly indicate that fish processing waste is a promising resource for N-rich fertiliser production.

The metal content of fish waste may limit the application of recovered products. Overall, fish contains micronutrients, such as copper (Cu) and zinc (Zn), and some potential toxic metals as well, including mercury (Hg), lead (Pb), cadmium (Cd) and arsenic (As). Makedonski et al. (2017) reported that Zn concentration of the fish muscle from Black Sea and from Mediterranean Sea coast was in the range of 9.8–22.9 mg/kg

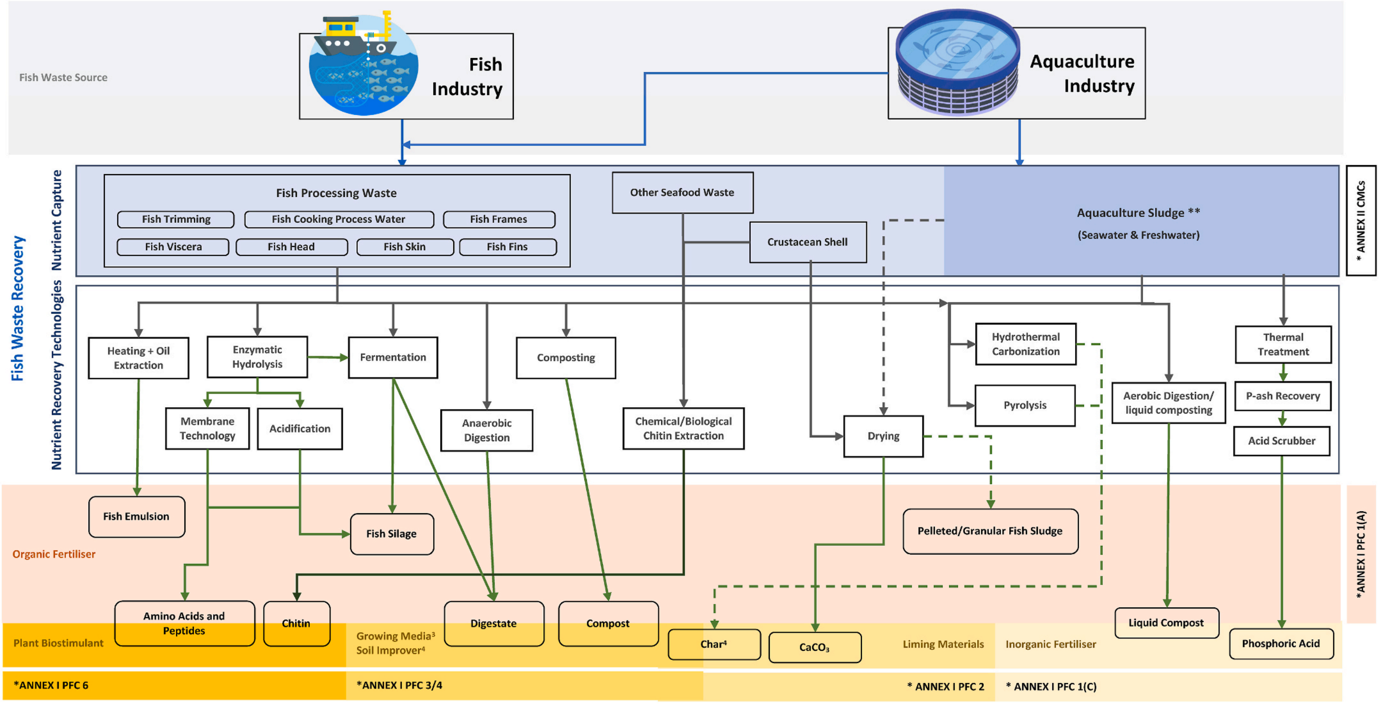

Fig. 1. Possible (but not limited to) routes to obtain alternative fertilising products from fishery waste and/or by-products and their potential function according to Regulation (EU) 2019/1009.
* Nutrient, pollutant and pathogen content limits are in compliance with Regulation (EU) 2019/1009 of the European Parliament and of the Council of June 5, 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003.
** Aquaculture/fish sludge is not included in ANNEX II component material.

and 16.1–31.4 mg/kg, respectively, while Cu content ranged from 0.23 mg/kg to 9.49 mg/kg in fish muscle from Marmara Sea. As for non-essential metals, fish muscle from Turkish Black Sea coasts had 0.02–0.24 mg/kg Cd; Pb level of fish muscle from middle Black Sea was 0.22–0.85 mg/kg in the study. The maximum concentration of Pb and Cd allowed in edible fish are 0.3 mg/kg and 0.5 mg/kg in food, respectively (European Commission, 2006), while these limit values are 120 mg/kg and 1.5 mg/kg for organic fertilisers according to the Fertilising Products Regulation (EU) 2019/1009 (see Section 4). The by-products from captured fish with comparatively higher content of metals can be then alternatively utilized for fertiliser production other than food.

2.2. Fish sludge

Fish sludge is an unignorable waste stream in aquaculture industry, which is composed of water, fish feed, faecal matter, biomass from dead fish and/or other species, based on the culturing species and aquaculture process. It is a potential source of nutrient supply for fertilising products due to its vast production and rich nutrient content. For example, every 1000 kg (live weight) catfish production from recirculating aquaculture system generates 70–420 L/day of sludge (Timmons and Ebeling, 2007). Approximately 14,000 tons P/year and 27,000 tons N/year are discharged to the marine environment from fish excrements and feed loss in Norway (Brod and Øgaard, 2021; Estevez et al., 2022; Hamilton et al., 2016). However, aquacultural fish production in Norway was just around 1.35 million tons in 2018, accounting for 1.65% of the world total aquacultural production (FAO, 2020). In global scale, aquaculture production rose from 21.8 million tons in 1990s to 87.5 million tons in 2020, accounting for 49% of the total production (FAO, 2022), which indicates the increasing generation of fish sludge and trends of nutrient losses.

The composition of various fish sludge types is given in Table 2, showing that different fish species exhibit a wide range of nutrient content in fish sludge. Even for same species, nutrient content vary most probably due to differences in feed supply. Fish feed or aquafeed, one of the main components of fish sludge, is an important external nutrient supply to the aquacultural system, reaching up to 40.1 million tons globally in 2018 (Alltech, 2019; Kong et al., 2020). The high percentage of unused fish feed further indicates the need to recover nutrients from fish sludge. Some estimated that around 7–10% of fish feed would be left in sediments and around 25–35% of the feed remain as suspended solids (Cerozi and Fitzsimmons, 2017; Strauch et al., 2018). In other studies, wasted fish feed has a higher proportion than the consumed part. For instance, Ballester-Moltó et al. (2017) estimated that the wasted feed ranged between 8.5% and 52.2%, while Edwards (2015) indicated that 2/3 of the feeds were voided. Hua and Bureau (2006) deemed that more than 50% N and 75% P of the total fish feed was lost and released to the environment. Fish feed, containing 0.9–1.5% P, is the only significant P input in aquaculture, of which 29.5% is recovered by fish, 69.8% is left in fish sludge, and 3.8% is released as soluble P (Yogev et al., 2020).

N and P recovery from fish sludge is necessary and significant in nutrient recycling but also in preventing eutrophication and acidification in aquatic ecosystems. Additionally, fish sludge has abundant K, calcium (Ca), Mg, sodium (Na), S and other micronutrients, like Zn and Cu, making it a promising substituting raw material for fertilising products (Estevez et al., 2022; Khiari et al., 2019; Monsees et al., 2017). Although recovery of nutrients from fish sludge has many disadvantages considering the environmental pollution and nutrient scarcity, contaminants within may also pose risks to the soil and related biota. Toxicological effects caused by pathogens and heavy metals in fish sludge derived fertilising products to soil and plants need monitoring and assessing (see Section 5).

Table 1
Composition of fish processing waste: viscera, head, skin, fish processing water and others (Values: mean ± SD).

Fish Processing Waste	Protein (%)	Lipids (%)	Moisture (%)	Ash(%)	Reference
Viscera*					
Yellowfin tuna (*Thunnus albacares*)	21.5 ± 0.5	5.08 ± 1.5	69.7 ± 2.3	4.46 ± 1.2	Ovissipour et al. (2012)
Catla (*Catla*)	8.52 ± 0.95	12.5 ± 1.45	76.3 ± 0.25	2.50 ± 0.04	Bhaskar et al. (2008)
Rainbow trout (*Onchorhynchus mykiss*)	15.0 ± 0.06	13.0 ± 0.76	71.7 ± 0.89	2.73 ± 0.89	Taheri et al. (2013)
Pink salmon (*Oncorhynchus gorbuscha*)	15.3 ± 0.40	2.00 ± 0.30	81.2 ± 0.70	1.70 ± 0.10	Bechtel (2003)
Alaskan pollock (*Theragra chalcogramma*)	15.2 ± 1.4	19.1 ± 1.3	63.5 ± 2.8	1.6 ± 0.1	
Pacific cod (*Gadus macrocephalus*)	13.0 ± 0.4	8.1 ± 2.5	76.5 ± 2.1	2.0 ± 0.1	
Black pomfret *(Parastromateus Niger)*	14.4 ± 0.50	3.90 ± 0.30	74.0 ± 0.50	3.40 ± 0.40	Nazeer and Sampath Kumar (2011)
Persian sturgeon (*Acipenser persicus*)	15.5 ± 0.25	15.7 ± 1.3	39.0 ± 0.0	5.76 ± 0.05	Ovissipour et al. (2009)
Cuttlefish *(Sepia officinalis)*	15.9 ± 0.25	4.92 ± 0.70	77.2 ± 0.10	2.01 ± 0.01	Kechaou et al. (2009)
Sardine (*Sardina pilchardus)*	15.8 ± 1.10	4.89 ± 0.11	77.5 ± 0.02	1.90 ± 0.00	
Cuttlefish *(Sepia officinalis)*	15.5 ± 0.25	4.78 ± 0.70	75.0 ± 0.10	1.95 ± 0.00	Kechaou et al. (2015)
Gilt-head seabream (*Sparus aurata*)	14.1 ± 0.92	10.6 ± 1.22	70.2 ± 2.0	1.6 ± 0.3	Valcarcel et al. (2020)
European seabass (*Dicentrarchus labrax*)	10.2 ± 0.22	15.0 ± 0.25	72.3 ± 0.9	0.5 ± 0.2	
Horse mackerel (*Magalaspis cordyla*)	15.1 ± 2.2	2.3 ± 2.1	81.2 ± 2.5	1.4 ± 0.4	Kumar et al. (2011)
Head					
Pink salmon (*Oncorhynchus gorbuscha*)	13.9 ± 1.0	10.9 ± 0.4	71.8 ± 1.5	3.4 ± 0.3	Bechtel (2003)
Alaskan pollock (*Theragra chalcogramma*)	15.2 ± 0.3	1.2 ± 0.5	79.9 ± 0.7	4.6 ± 0.2	
Pacific cod (*Gadus macrocephalus*)	16.4 ± 0.8	0.9 ± 0.3	80.2 ± 0.4	4.2 ± 0.2	
Herring (*Clupea harengus*)	13.1 ± 0.3	10.9 ± 0.6	72.4 ± 0.2	3.9 ± 0.3	Sathivel et al. (2003)
Atlantic salmon (*Salmo salar*)	15.0 ± 0.1	20.0 ± 0.4	67.8 ± 1.3	2.6 ± 0.6	Gbogouri et al. (2004)
Red salmon (*Oncorhynchus nerka*)	11.9 ± 0.7	14.5 ± 2.0	69.6 ± 2.7	4.0 ± 0.3	Sathivel et al. (2005)
Gilt-head seabream (*Sparus aurata*)	18.2 ± 0.94	9.89 ± 0.76	65.3 ± 1.2	6.4 ± 0.5	Valcarcel et al. (2020)
European seabass (*Dicentrarchus labrax*)	18.4 ± 1.03	14.5 ± 0.74	63.1 ± 1.5	7.2 ± 0.5	
Bluefin tuna (*Thunnus thynnus)*	12.1 ± 0.3	10.4 ± 0.7	69.4 ± 0.4	7.9 ± 0.5	Bougatef et al. (2012)
Skin					
Alaskan pollock (*Theragra chalcogramma*)	25.0 ± 2.9	0.4 ± 0.1	78.2 ± 2.9	0.7 ± 0.2	Bechtel (2003)
Pacific cod (*Gadus macrocephalus*)	24.5 ± 1.8	0.3 ± 0.1	78.1 ± 1.3	2.0 ± 0.5	
Bluefin leatherjacket (*Navodon septentrionalis*)	19.8 ± 0.76	3.08 ± 0.11		14.3 ± 0.24	Chi et al. (2015)
Fresh grass carp (*Ctenopharyngodon idella*)	22.6 ± 0.60	1.10 ± 0.30	64.1 ± 0.10	0.27 ± 0.02	Wasswa et al. (2007)
Skate (*Raja Kenojei*)	23.7	1.45	70.9	1.5	Lee et al. (2011)
Black carp (*Mylopharyngodon piceus*)	23.7 ± 0.01	0.56 ± 0.02	75.5 ± 0.73	0.40 ± 0.04	Wu et al. (2015)
Grass carp (*Ctenopharyngodon idella*)	31.31 ± 0.03	1.23 ± 0.03	66.2 ± 0.19	0.45 ± 0.03	
Silver carp (*Hypophthalmictuthys molitrix*)	26.7 ± 0.02	0.73 ± 0.01	71.7 ± 1.07	0.61 ± 0.02	
Bighead carp (*Hypophthalmichthys nobilis*)	24.3 ± 0.03	0.27 ± 0.01	75.4 ± 0.73	0.43 ± 0.05	
Frames					
Alaskan pollock (*Thneragra chalcogramma*)	16.3 ± 0.9	0.90 ± 0.4	80.9 ± 0.8	3.40 ± 0.50	Bechtel (2003)
Pacific cod (*Gadus macrocephalus*)	15.8 ± 1.0	0.60 ± 0.1	81.0 ± 1.0	3.90 ± 0.70	
Gilt-head seabream (*Sparus aurata*)	17.9 ± 0.65	14.6 ± 1.12	63.8 ± 1.9	5.60 ± 0.80	Valcarcel et al. (2020)
European seabass (*Dicentrarchus labrax*)	16.1 ± 0.75	16.8 ± 0.52	62.6 ± 2.0	5.20 ± 0.40	
Tuna	28.7 ± 0.16	11.3 ± 0.03	8.40 ± 0.10	44.1 ± 0.03	Abbey et al. (2017)
Fish processing water					
Yellow tuna (*Thunnus albacares*) cooking water	56.5 ± 0.6	1.0 ± 0.03	–	42.5 ± 0.5	Martínez-Montaño et al. (2021)
Pacific thread herring (*Opisthonema libertate*) stickwater	47.9 ± 0.4	3.3 ± 0.5	–	48.8 ± 0.1	
Salmon (*Oncorhynchus*) freeze dried stickwater	82.1 ± 0.76	1.80 ± 0.05	5.82 ± 0.17	10.6 ± 0.96	Bechtel (2005)
Pollock and cod freeze dried stickwater 1	86.2 ± 0.09	2.59 ± 0.14	3.41 ± 0.11	13.9 ± 0.16	
Pollock and cod freeze dried stickwater 2	70.5 ± 0.08	18.4 ± 0.42	4.54 ± 0.08	9.93 ± 0.11	
Pollock and cod freeze dried stickwater 3	76.2 ± 0.13	9.83 ± 1.8	4.68 ± 1.5	10.7 ± 0.91	

* Taken from the review paper of Villamil et al. (2017).

2.3. *Seafood waste and/or by-products*

Crustaceans and molluscs are two other major consumables from capture and aquaculture industry. In 2020, marine capture of crustaceans and molluscs reached 5.6 and 5.9 million tons, respectively, while farmed ones were 17.7 and 11.2 million tons (FAO, 2022). Zhan et al. (2022) estimated that more than 10 million tons of shell waste are generated from molluscs and crustaceans every year. Mollusc shells are composed of mineral part (95–99%) and organic fraction (0.1–5%), in which the mineral is typically made of highly ordered calcium carbonate aggregates, calcite (e.g., oyster shells) and/or aragonite (e.g., abalone and clam shells) (Checa, 2018; Zhan et al., 2022). These calcium carbonate crystals is a potential raw material to produce liming agent. Crustacean seafood, such as crab, shrimp and lobster corresponds to 6–8 million tons of shell waste every year (Yan and Chen, 2015). Crustacean waste is assembled from three fundamental components: chitin, minerals, and proteins. Yan and Chen (2015) summarized that protein (20–40%), calcium carbonate (20–50%) and chitin (15–40%) are three primary products harboured in shells and are of great value in fertiliser industry. Chitin is a nitrogenous polysaccharide compound and the second most abundant organic compound, regarded as another natural source of N (Singh et al., 2022). Chitin and chitosan, the acetylated chitin, not only supply N but also effectively contribute to stimulate plant yield and tolerance to environmental stresses (Shahrajabian et al., 2021). Other than the direct use of chitin or chitosan products as fertilisers, shell waste-based chitosan coatings with a thickener and coarser surface can provide the slow release of NPK elements contained in fertilisers (Rengga et al., 2018). In addition, the content of contaminants is considered low in shellfish wastes, making them an ideal source to generate bio-based fertilisers (Ahuja et al., 2021).

3. Nutrient recovery technologies and products from fishery waste and by-products

Various types of fish waste and/or by-products discussed above are potential candidates to be used as secondary resources for bio-based

Table 2

Composition of fish sludge (Values: mean ± SD).

Fish sludge (FS)	Units	pH	C:N	C	N	P	K	Reference
Tilapia sludge	% dry basis				4.5[3]	2.35	0.24	Khiari et al. (2019)
Freeze-dried tilapia sludge	mg/g; C,N%		8.8 ± 0.8	35.9 ± 1.6	4.10 ± 0.24[4]	30.37 ± 4.4		Monsees et al. (2017)
Tilpia sludge (liquid part)	ppm	6.5		9.9 ± 2.9[1]	33.1 ± 29[4]	43.9 ± 3.9	36.7 ± 6.3	Goddek et al. (2018)
Tilpia sludge (solid part)	ppm				363 ± 28[4]	133 ± 16.3	8.3 ± 2.7	
Catfish sludge (liquid part)	ppm	6.9		14.2 ± 0.8[1]	53.8 ± 24[4]	17.1 ± 5.7	16.6 ± 4.5	
Catfish sludge (solid part)	ppm				177 ± 45[4]	150 ± 25	27.0 ± 1.3	
Atlantic salmon sludge	mg/L			60.3–74.1[1]	2872–3573[4]	1350–1683	476	Gebauer (2004)
Land-based salmon sludge	C,N: %;	7.0	10.5	20.7[2]	1.10[3]	480[5]	30	Celis et al. (2008)
Lake salmon sludge	mg/kg	6.7	7.5	18.3[2]	1.35[3]	19.9	121	
FS	mg/kg DM;	5.8	2.8	10.27[2]	11[4]	3.12	1.07	Brod et al. (2017)
FS pellets	TN g/l g/kg	5.7	6.8	91[2]	75[4]	15	1.9	
FS granules		5.5		83.78[2]	68[4]	13.33	0.26	
Dried FS (hatchery)	C,N: %;	4.9		228[1]	4.56[4]	3.71		Estevez et al. (2022)
FS smolt (seawater)	mg/kg	6.1		66.9[1]	0.28[4]	0.34		
Brackish FS (Kadesh Barnea)	N,P: g/kg;	7.3	9.1 ± 0.8	398 ± 18	47.4 ± 3.4[4]	11.1 ± 1.2	2853 ± 40	Mirzoyan et al. (2008)
Brackish FS (R.A.M.)	K: mg/kg	7.0	10 ± 0.8	429 ± 19	38.7 ± 4.0[4]	19.1 ± 4.1	1691 ± 28	
Brackish FS (Beer Sheva Raw)		7.7	9.9 ± 1.9	318 ± 19	35.8 ± 2.7[4]	30.8 ± 3.0	1742 ± 27	
Brackish FS (Beer Sheva Treated)		7.1		194 ± 1				
Brackish water FS	TN g/kg	7.2		73 ± 3[2]	102 ± 9[3]			Mirzoyan et al. (2012)
FS (brackish water)		4.7		37[1]	0.51	0.09		Estevez et al. (2022)

[1] Chemical oxygen demand (COD).

[2] Organic matter (OM).

[3] Total nitrogen (TN).

[4] Total Kjeldahl nitrogen (TKN).

[5] Olsen-P, DM indicates to dry matter.

fertiliser production. Fish waste has high water content and contains a large amount of microbes, relating to infections, diseases and undesirable odours when unmanaged (Jayathilakan et al., 2012). To overcome these shortcomings, it is crucial to process further treatments on fish waste to condense nutrient content and reduce product volume before storage, transportation and application as fertilising products. Physical, chemical, (micro)biological and thermal treatments are widely used in dealing with organic-rich fishery waste, such as anaerobic digestion, fermentation, composting and pyrolysis. Each has its own advantages and drawbacks as summarized in Table 3.

Table 3

A summary of the most common nutrient recovery technologies for fishery waste.

Technology	Optimal conditions	Period	Advantages	Disadvantages	Fertilising product	Reference
Anaerobic digestion	pH: 6.5–7.5; T: Mesophile (20–43 °C) and thermophile (50–60 °C); C:N: 15-30	Days	Reduction of waste amount and odour; sustainable energy supply, a wide range of feedstock	High cost, long start-up process	Digestate	(Nie et al., 2021; Samoraj et al., 2022)
Fermentation		Days	Friendly to environment, low energy consumption, simple and inexpensive procedures, reduction of microbial proliferation, fish odour removal	Microorganism requirement, certain pH range	Peptides, amino acids, organic acids (e.g., lactic acid, acetic acid)	(Ghoreishi et al., 2023; Marti-Quijal et al., 2020; Rai et al., 2010)
Composting	pH: 5.5–8.0; T: Mesophile (20–40 °C) and thermophile (>40, 45–55 °C); C:N: 20-30	Weeks, Months	Reduction of volume, odour and GHG emission; elimination of pathogens, increasing nutrient capture, low initial capital investment	High cost for site preparation and equipment, the lengthy treatment period	Compost	(Ahuja et al., 2020; Illera-Vives et al., 2013)
Pyrolysis	T: 300–400 °C (slow pyrolysis)	Mins-Hours	Volume reduction, efficient at converting waste into useful products and energy, less noxious by-products and reduction of carbon emissions, a wide range of feedstock	Requiring pretreatment, high capital and investment cost, constant supply of waste	Biochar	(Bridgwater, 2012; Venderbosch and Prins, 2010)
Hydrothermal carbonization	T: 180–300 °C	Mins-Hours	Suitable for high-water content biomass, high conversion efficiency, elimination of pre-drying requirement,	High capital investment, difficult to collect the products and high requirements for equipment	Hydrochar	(Fu et al., 2019; Kannan et al., 2018)
Enzymatic hydrolysis		Mins-Days	A wide variety of available catalytic activities, greater pH and temperature stabilities	pH and temperature sensitive, critical storage condition for final products (under 0 °C), high expenses of enzymes	Fish protein hydrolysate	(Araujo et al., 2021; Bhaskar et al., 2008; Villamil et al., 2017)
Membrane filtration		–	Low Energy requirements, no chemical requirement, liable results	High equipment cost, clogging and damaging of membrane	Purified nutrients, size-separated protein hydrolysate	(Martínez-Montaño et al., 2021; Samoraj et al., 2022)
Drying		Hours-Days	Volume reduction	Energy and time consuming	Dried fishery wastes	(Ahuja et al., 2020, 2021; Brod et al., 2017)

3.1. Anaerobic digestion and digestate

Anaerobic digestion is a biological process in which anaerobic microbes decompose organic matter into biogas and digestate with little or no oxygen (Ahuja et al., 2020; Atelge et al., 2020). While biogas is a source of energy which can be further converted to heat and electricity or even upgraded into biomethane as a substitute for natural gas (Sikarwar et al., 2021), the by-product, digestate, has abundant bioavailable nutrients with good amendment and fertilising properties (Herrera et al., 2022; Pigoli et al., 2021; Samoraj et al., 2022). When proper operating parameters are set during anaerobic digestion, it enables the production of desired quality and quantity of end-products. The optimal pH ranges from 6.5 to 7.5, while a C:N ratio is often maintained between 15 and 30 (Samoraj et al., 2022). Mesophilic (20–43 °C) or thermophilic (50–60 °C) temperature conditions are generally used at industrial scale to balance energy delivery and digestion performance (Nie et al., 2021). Considering the high percentage of protein fractions in fishery waste, carbon-rich co-substrates should be added to ensure digestion efficiency of the feedstock.

Samoraj et al. (2022) showed that the liquid and solid fractions of fish waste digestate had condensed N, P and other nutrients, making them valuable fertilisers for crops. The liquid fraction of the digestate can be directly used on the field, but its high-water content is a challenge for storage and transportation. Estevez et al. (2014) found that ammonium N (NH_4^+-N), reaching up to 2300 mg/L, was the main form of N in the digestate derived from fish waste and other materials, representing 94% of the total N. High concentration of ammonium in the fertiliser can cause problems. NH_4^+-N in the topsoil increases the possibility of GHG and ammonia (NH_3) emissions. Manu et al. (2021) has reported that high concentration of NH_4^+-N (>700 mg/kg DM) has adverse and phytotoxic effects on some plants. Estevez et al. (2014) separated the digestate into two forms: the solid digestate (30% NH_4^+-N) was qualified as organic fertiliser and the liquid fraction (70% NH_4^+-N) was further treated to recover ammonium and phosphate through struvite precipitation. The recovery efficiency of the N and P were 87% and 60%, respectively. This struvite, containing around 57% of total N in the digestate derived from fish-contained feedstock mixture, can also be used as a slow-release fertilising product (Darwish et al., 2017). To valorise digestate, composting or pyrolysis can be further applied to produce more stable fertilisers (Samoraj et al., 2022). Depending on the soil type and/or final end-use requirements, various technologies can also be deployed to liquid or solid fraction of digestate to obtain more targeted fertilising products, e.g., stripping and scrubbing of liquid fraction to obtain ammonium salts (Sigurnjak et al., 2019).

3.2. Fermentation and fermented products

Fermentation is a similar anaerobic bacterial metabolism to anaerobic digestion which converts organic compounds into high (er) value products, such as short chain fatty acids, before ending up to biogas (Marti-Quijal et al., 2020; Rai et al., 2010). Fermentation is not only a traditional way to extend shelf-life of fish or to prepare fish sauce, but also used to improve the nutritional quality by producing amino acids and peptides (Marti-Quijal et al., 2020). The fermented products exhibit more nutrients than the raw materials, being applicable as fertilising products in agriculture. Kim et al. (2010) converted sliced fish waste into liquid fertiliser using proteolytic bacteria isolated from earthworm, resulting in 1.57% N and 0.14% P and 0.37% K, low concentrations of noxious heavy metals. However, further treatment, such as freeze-drying, is required to condense the nutrient content to make the fermented liquid product qualified as liquid organic fertiliser. According to the study of Aranganathan and SR (2016), liquid fertiliser derived from fermented trash fish (non-useable co-catch fish from fishing industry, which is too small for human consumption) waste contained 1.0% of total N, 0.39% P, 0.37% K, 56% organic carbon and abundant macronutrients, leading to better performance of tomato growth (height) after fertilised by the fermented products against conventional mineral fertilisers.

Many microorganisms are employed in the fermentation process to generate value added peptides as food or feed, but just few studies have considered to valorise fish waste as organic fertilisers via fermentation. Other than producing fertiliser, more attention and interest were given to biostimulant production. Biostimulants enhance plant growth by increasing nutrient use efficiency, stress tolerance of plants and bioavailability of nutrients in the soil. Many substances, such as humic acids, volatile fatty acids, protein hydrolysates, seed extracts and microorganisms, can be used as plant biostimulant (Busato et al., 2018; Gayathri et al., 2017; Ghoreishi et al., 2023).

3.3. Composting and compost

Composting is the aerobic biological decomposition of organic matter into a stable and humus-like product, regarding as an economically and environmentally viable solution to deal with organic-rich fish waste (Ahuja et al., 2020). During the process, the addition of microorganisms, such as bacteria and fungi, enhances and accelerates the decomposition of wastes, especially in the first thermophilic stage of composting (Wei et al., 2007). While others inoculated at the cooling phase to accelerate the degradation of organic matter by 7.58% and promote humus formation (Wu et al., 2020a, 2020b). It is a conventional and effective method to reduce the volume of fish waste. Simultaneously and inevitably, increased temperature and rapid decomposition lead to nutrient loss, especially by emission of the volatile components (C, N and S). The optimal C:N ratio of the compost substrate is between 20 and 30 (Ahuja et al., 2020). Carbon-rich materials are required during the composting process of fishery waste, because of its high protein content and low C:N ratio. Bulking agents, like piles, straws bark, crop hulls, crushed grass, are often added to speed up the aeration during composting and play as carbon sources for microorganisms (Ahuja et al., 2020; Illera-Vives et al., 2013).

The humus-like compost has high potential to be an organic fertiliser or growing medium depending on the nutrient content (Khiari et al., 2019). The final windrow compost derived from waste mixture (seaweed: fish waste: pine bark = 1:1:3) were hygienic and well-structured, and had rich organic matter and nutrients, plus low metal content, being qualified and classified as organic compost amendment according to EU ecolabeling scheme (Illera-Vives et al., 2013). Its total N accounted for more than 2% of compost, in which around 90% was organic N. The water soluble (1:5) ammonium (NH_4^+), nitrate (NO_3^-), phosphate and K were around 480, 108, 83 and 705 mg/L. Busato et al. (2018) used fish waste from tilapia and crushed grass (3:1) to produce compost, resulting in 176 mg g^{-1} TOC, 22.6 mg g^{-1} TKN, 180 mg g^{-1} P, 3.8 mg/g K and 110 mg g^{-1} Ca and many other nutrients.

To increase nutrient capture and conversion of waste, liquid composting (aerobic digestion) is also a sustainable approach to obtain liquid fertilisers via mineralization of fish waste (Khiari et al., 2019). Under optimal condition (pH 6.0 and 35 °C), the maximum NH_4^+–N concentration was around 145.1 mg/L in the liquid fertiliser. During liquid composting process, organic N is first converted into NH_4^+, then oxidized to nitrite (NO_2^-), subsequently to nitrate (NO_3^-). Sánchez-Monedero et al. (2001) reported that in their study the ratio of NH_4^+-N to NO_3^--N (<0.16) content was an indicator of the maturity of the compost, and NO_3^-–N content significantly increased electrical conductivity (EC) and decreased pH value. To reach the optimal nutrient recovery via composting, response surface methodology can be applied (Abdullah and Chin, 2010; Asadu et al., 2019). Similar to ammonia-rich digestate, compost with high ammonia content may lead to N loss. To prevent N emission, acidification is useful to keep ionized ammonium within the products.

3.4. Thermal treatment and char

Depending on the fish type, fish contains 8–15% carbohydrates, which make thermochemical conversion of fishery waste a possible method to recycle the waste into value-added solid char product (Kannan et al., 2018). Thermal treatments, like gasification (600–900 °C), pyrolysis (300–650 °C) and hydrothermal carbonization (180–260 °C), are options to deal with organic waste and generate char products (Kambo and Dutta, 2015), in which gasification focuses on syngas production for energy recovery but it is not covered in the context of this paper. Pyrolysis is the thermochemical decomposition of organic materials without oxygen or with inert gases at temperature ranging from 300 to 600 °C, from which a solid carbonaceous by-product is produced, called biochar (Fu et al., 2019). Depending on the operating conditions, like heating rate and vapour residence time, pyrolysis can be categorized into two main classes: fast and slow pyrolysis. Fast pyrolysis with high heating rates (hundreds to thousands °C/min, e.g., 1000 °C/s) and short reaction time (0.5–5 s, typically 2 s) leads to high liquid yields and comparatively low char yield (10–25%), while slow pyrolysis was regarded as the main pyrolysis process for biochar production, because of its higher solid yield (25–35%) due to longer reaction time (few minutes to hours) and lower heating rate (10–30 °C/min) (Brownsort, 2009; Kambo and Dutta, 2015; Mohan et al., 2006; Onay and Kockar, 2003). Hydrothermal carbonization focuses more on solid products with 45–70% typical product yield, and is more suitable for the carbonization of wet biomass feedstock ($\geq$50% moisture content), during which water is used as reaction medium and direct treatment of fishery waste is applicable at relatively low temperature (180–300 °C) (Fu et al., 2019; Kannan et al., 2018).

Biochar is a dry solid by-product via pyrolysis, while hydrochar is produced as a carbon-rich slurry (a mixture of solid and liquid) from hydrothermal carbonization; however, both char products can be called as biochar due to International Initiative guidelines (Kambo and Dutta, 2015). In general, biochar is considered as soil amendment to improve soil health and increase crop productivity. Biochar promotes soil aeration by its high surface area and porosity, enhances the cation exchange capacity, nutrient retention capacity and water holding capacity of soil by the functional groups at the surface (Kambo and Dutta, 2015). From this perspective, char products function as soil improver to maintain, improve or protect physicochemical properties and structure of the amended soil. Thermal treatment reduces the contents of volatile elements, like C and N, but condenses non-volatile components, like P and metals. In the study of Piccirillo et al. (2017), the cod fish bone biochar produced at 600 °C is composed of 2.5% N, 12.5% P and 23.8% Ca, while the one produced at 1000 °C has lower N content (2.3%) but Ca and P content reached up to 27.1% and 14.5%, respectively. That makes the fish bone biochar a potential alternative fertilising product to supply macronutrients. The problem with the biochar is that the available proportions of the nutrients are still unknown. Darwish et al. (2017) analysed the P content in animal bone ash and found that fishbones had higher P content (170 g/kg) than chicken and cow bone. Warren et al. (2009) reported that the cattle bone char with 13.4% total P had 11.5% neutral ammonium citrate extractable P, around 1500 mg/kg Olsen P and 244 mg/kg water extractable P. These three extractable fractions indicate the available P content to the soil and plants. When applying this bone char to the soil, the short-term study showed that even though the bone char was less effective in P supply than mineral P fertiliser, it elevated the yields of wheat and potatoes, maybe because of the Ca, Mg content and improvements of soil structure after char application (Siebers et al., 2014). It seems that the fishery waste-derived char products with high P content and other micronutrients can be an alternative to supply nutrients, but the function of fishery waste-derived biochar to the soil still needs investigation to have a better understanding of its P release pattern and impacts to the soil.

3.5. Enzymatic hydrolysis and hydrolysate

Enzymatic hydrolysis of protein fraction is the cleavage of peptide bonds between amino acids and consuming of water to generate free amino acids and low molecular weight peptides with the addition of exogenous enzymes (Araujo et al., 2021; Bhaskar et al., 2008; Rutherfurd and Gilani, 2009; Villamil et al., 2017). Proteases are the most important group of commercial enzymes, which is tested to be more suitable to produce fish protein hydrolysate (Arvanitoyannis and Kassaveti, 2008; Bhaskar et al., 2008; Singh et al., 2022). Alcalase is an alkaline protease produced from *Bacillus licheniformis*, and has been widely used and proven to be one of the best enzymes in generating fish protein hydrolysate (Araujo et al., 2021; Bhaskar et al., 2008; Ovissipour et al., 2009). Although the cost of enzymes is high, enzymatic hydrolysis has many advantages. Enzymatic hydrolysis avoids side reactions and nutritional value decrease compared to chemical hydrolysis (Araujo et al., 2021; Villamil et al., 2017). Generally, fish processing waste can generate N-rich compounds. Fish head yields the most oil and frame yields the least, whereas collagen is abundant insoluble protein in fish skin, head, frames and fins (Singh et al., 2022). Fish hydrolysate like other animal enzymatic hydrolysed protein is a soluble N source (Araujo et al., 2021; Bhaskar et al., 2008; Liaset et al., 2003) and can be used as a liquid fertilising product. Beckley et al. (2007) prepared a method to produce fish-based fertiliser through hydrolysis, in which environmental and operating parameters such as pH, temperature and reaction period were assessed, together with the application of pre-treatment and filtration. Accordingly, the liquid hydrolysate derived from fish processing waste was composed of 0.95% N, 1.16% P_2O_5, and 0.10% K_2O, and many other micronutrients, including 13 ppm Zn and 12.44 ppm Fe, proven to be able to stimulate plant growth. Fahlivi et al. (2015) treated fish viscera with 0.5% (*w/w*) alcalase, obtaining liquid fertiliser with 13.16% protein, 0.20% of lipid and 79.80% moisture content, resulting in high macronutrient content: 2.11% N, 0.22% P and 0.25% K. Liaset et al. (2000) enzymatically hydrolysed by-products from fish-filleting industry. The pre-treated supernatant of Atlantic cod frame without head had 4.33 g/kg N content before hydrolysis, resulting in an increased soluble N content 6.72 g/kg in the form of amino acids in the supernatant after 2.5 h alcalase treatment. The soluble N content of the freeze-dried fish protein hydrolysate increased to 128.32 g/kg after hydrolysis process via 2.5 h alcalase treatment and 8.5 h kojizyme treatment.

3.6. Other common technologies and products

3.6.1. Emulsion and fish emulsion

Fish emulsion is produced by heating fishery waste at least at 80 °C to extract oils and kill most of the pathogenic bacteria (Ahuja et al., 2020; Beckley et al., 2007). The solid material is pressed into a cake, which can be dried to produce fish meal, while the fish emulsion is the liquid residue that is pressed out of the fish cake. The chemical composition of fish emulsion is highly complex and composed of mainly water-soluble nutrient, including inorganic elements and mixtures of essential amino acids, as well as moderate or low amount of oil-soluble nutrients (Beckley et al., 2007; El-Tarabily et al., 2003). Fish emulsion can be stabilized by acidification with sulfuric, phosphoric or organic acids (Ahuja et al., 2020). In practice, fish emulsion not only supports the plant growth in a sandy soil as effective as an applied inorganic fertiliser, but also stimulates microbial activities in the rhizosphere (El-Tarabily et al., 2003).

3.6.2. Drying and dried products

In some cases, dried fishery waste can be directly used as soil amendment or an additive in fertiliser to improve nutrient input in the soil (Ahuja et al., 2021). However, high water content of fishery waste limits its application, so dewatering is a feasible option before further treatment or usage of these wastes. To solve this problem, filtration, drying and pelletizing are utilized to produce bio-based fertilisers (Brod et al., 2017). Drying techniques can be classified into several types, including freeze drying, spray drying and microwave oven drying, among which microwave showed the highest concentration of NH_4^+-N after drying (Ahuja et al., 2020, 2021). Since the drying method, temperature, duration and other unknown factors can affect the pH, total N, and NH_4^+-N concentrations of the dried products, it is necessary to think twice before drying based on the properties of the raw materials and the end-use of the products.

3.6.3. Membrane techniques and fish filtrates

Membrane techniques, such as ultrafiltration and nanofiltration, can be very efficient technologies to fractionate the different fractions of raw materials and fertilising products. Membranes can recover protein fractions obtained after hydrolysis of fishery by-products. For example, Pezeshk et al. (2019) successfully separated hydrolysate obtained from yellow fin tuna viscera into four molecular size fractions for further evaluation of the antioxidant property and antibacterial activity of each fraction by the help of membrane filtration. Membrane techniques are also able to apply into condensation of liquid digestate (Samoraj et al., 2022). Microfiltration, ultrafiltration and reverse osmosis function in concentrating and recovering protein fractions in the stickwater and fish cooking water produced from fish processing (Martínez-Montaño et al., 2021). Membranes can also help to remove salts from brine and enable water reuse. For fish sludge with high liquid content, membrane techniques can condense solid residues for further treatment.

To have an easy overview on the potential fertilising products generated by some above-mentioned technologies, Table 4 shows the fish waste and related final products with their nutrient content. Based on this overview, it is clear that the final products derived from same technologies may still differ due to multiple reasons such as the variety of raw waste material, addition of different reagents, and temperature. These factors eventually influence the final composition of the fertilising products.

4. Quality and safety assessment and regulatory compliance of alternative fertilising products derived from fishery waste and by-products at EU level

A wide variety of technologies facilitate nutrient recovery and recycling via converting fishery waste into high nutrients-contained fertilising products. The technologies can reduce or increase the contents of potential pollutants, like inactivating pathogens via composting (Samoraj et al., 2022) or concentrating heavy metals in char products through thermal treatment. In order to obtain safe and qualified fertilising products, the final products derived from fishery waste must be evaluated. In the processing of fishery waste, additives and manufacturing conditions vary due to different purposes of manufactures, resulting in various types of fertilising products. For example, the produced fertilising products differ in forms, such as liquid, semi-liquid and solid forms, or in matrixes, like inorganic and organic. According to the Regulation (EU) 2019/1009, EU fertilising products are categorized into seven Product Function Categories (PFCs) based on their function to the soil and/or plants: fertiliser, liming material, soil improver, growing medium, inhibitor, plant biostimulant and fertilising product blend.

4.1. Regulated parameters

Fertilising products derived from fishery waste and by-products are not yet included as a Component Material Category (CMC) in the Fertilising Products Regulation (EU) 2019/1009, while they will need to comply with the regulated parameters in terms of the product quality and potential environmental and human health effects to find their place in the market in the future. Possible EU regulations affecting the use of

Table 4

Potential fertilising products generated from various nutrient recovery technologies.

Potential fertilising product	Nutrient content	Waste material	Technology	Reference
Digestate	NH_4^+-N mg L^{-1}: 1390 ± 208; 1530 ± 230; 1970 ± 296	Chemically treated sludge: fish sludge = 9:1; 8:2; 7:3	Anaerobic digestion	Estevez et al. (2022)
Struvite	P 15.56%, C 8.73%, N 4.34% (Reagent: MgO); P 18.92%, C 15.92%, N 3.93% (Reagent: MgO + $NaHPO_4·12H_2O$)	Fish bone ash	Struvite precipitation	Darwish et al. (2017)
Liquid fertiliser	N 1.57%, P_2O_5 0.31%, K_2O 0.45%, Amino acids 5.71%	Fish wastes (mixture of viscera, heads, tails and bones)	Fermentation	Kim et al. (2010)
Organic liquid fertiliser	N 1.0%, P 0.39%, K 0.37%, C_{org} 56.31%	Marine trash fish	Fermentation	(Aranganathan and SR, 2016)
Compost	C_{org} 176 ± 14 mg g^{-1} TKN 22.6 ± 1.1 mg g^{-1} P 180 ± 8 mg g^{-1} K 3.8 ± 0.1 mg g^{-1} Humic acids 14.8 ± 0.4 mg g^{-1} Fulvic acids 10.2 ± 0.7 mg g^{-1} Humin fraction 72.5 ± 3.1 mg g^{-1}	Fish waste from tilápia: crushed grass = 3:1 (*w/w*, dry basis)	Composting	Busato et al. (2018)
Liquid fertiliser	NH_4^+: 145.1 mg/L (35 °C, pH = 6.0) 142.9 mg/L (35 °C, pH = 6.5)	Aquaculture solid waste from tilapia farming	Aerobic digestion (Liquid composting)	Khiari et al. (2019)
Biochar	N 6.3%, P 9.2%, Ca 17.7%; N 2.5%, P 12.5%, Ca 23.8%; N 2.3%, P 14.5%,.Ca 27.1%.	Cod fish bones	Pyrolysis (200 °C); Pyrolysis (600 °C); Pyrolysis (1000 °C).	Piccirillo et al. (2017)
Protein hydrolysate	Yield: 43 g $100g^{-1}$	Fish waste (heads, skins, bones, viscera, shells and small whole fishes)	Enzymatic hydrolysis	Araujo et al. (2021)
Protein hydrolysate	Yield: 6.04 g $100g^{-1}$ N: 14.25 g $100g^{-1}$ (N recovery rate: 63.12%)	Fish viscera of *Catla*	Enzymatic hydrolysis	Bhaskar et al. (2008)
Fish hydrolysate/ Hydrolysed fish fertiliser	N 0.95%, P_2O_5 1.16%, K_2O 0.10%	Fish processing waste (offal, fish frames, and heads, and potable water)	Enzymatic hydrolysis	Beckley et al. (2007)
Fish hydrolysate/Liquid fish silage	N 2.11%, P 0.22%, K 0.25%	Fish viscera (Cod)	Enzymatic hydrolysis	Fahlivi et al. (2015)
Fertiliser	N 2.9%,P 6.7%, K 0.1%; N 3.0%,P 1.6%, K 0.3%.	Fish sediment; Minced fish backs.	Drying	Ahuja et al. (2021)

fishery and aquaculture by-products for agronomic use are summarized and given in the **E-supplementary file**.

According to the Regulation (EU) 2019/1009, primary macronutrients (N, P, K), secondary macronutrients (Ca, Mg, Na, S) and organic carbon (C_{org}) values of the fertilising products need to meet the minimum values (see Table 5) to be qualified as fertilisers (PFC 1). Liming material (PFC 2) is composed of calcium or magnesium oxides, hydroxides, carbonates or silicates to correct soil acidity. Neutralising value, reactivity and grain size shall be determined on the basis of mass of a liming material. A soil improver (PFC 3) shall function to maintain, improve or protect properties and structure of the amended soil, as well as the biological activities within, while growing media (PFC 4) is to grow plants or mushrooms. An organic soil improver should contain more than 20% dry matter and at least 7.5% C_{org}. Inhibitor (PFC 5) aims to improve nutrient release pattern of the product through delaying or stopping microbial or enzymatic activities. Biostimulant (PFC 6) enhances the plant growth, such as improving the nutrient use efficiency or tolerance to abiotic stress. Finally, fertilising product blend (PFC 7) composes of more than one fertilising products mentioned above.

Fishery waste-derived fertilisers have potential risks to contain excessive pathogens, heavy metals, and other organic pollutants which may lead to unqualified products. Unprocessed slurry can contribute to pathogen and metal leaching during rainfall events (Nag et al., 2021). Similarly, the application of unqualified fishery waste-derived fertiliser with excess pathogens may pose a risk of pathogenic contamination to surface water and groundwater. The dissemination of pathogens in the food chain can then pose serious risks to human health (Seleiman et al., 2020). An estimation of more than 7.7 million pathogen infection-related deaths were recorded in the world in 2019, in which *Escherichia coli* accounted for more than 500 thousand deaths (Ikuta et al., 2022). It is necessary to monitor pathogens in the fishery waste-derived fertilisers before applying to the field. According to Regulation (EU) 2019/1009, pathogen control of fertilising products focuses on *Salmonella* spp. with the maximum value of the number of bacteria being absence in 25 g or 25 ml of fertilising products, *Escherichia coli or Enterococcaceae* being 1000 in 1 g or 1 ml, except for microbial plant biostimulants. Many researchers have paid attention to pathogen detection in their fertilising products. Fish powder produced from milled Tuna waste via 8 h-drying at 55 °C could destruct pathogens, like *Escherichia coli*, *Enterococcaceae,* and *Salmonella* (Abbey et al., 2017). Illera-Vives et al. (2013) noted that the composting process at 55 °C for more than 30 days could effectively reduce pathogens: *Salmonella* was not detected and number of *Escherichia coli* was very low in all piles of fish waste-derived compost.

Other contaminants, like heavy metals, can also influence the quality of derived fertilising products, due to their problematic characteristics to human and the environment (Piccirillo et al., 2017). Except for pathogens, there is minor variation between the limit values of seven PFCs, such as heavy metals Cd, Pb and Hg, as well as the maximal concentration limits of Cu and Zn (Table 6). Instead of total As and Cr, toxic forms, inorganic As (iAs) and hexavalent Cr (Cr(VI)) are taken into account when assessing the safety of fertilising products.

Fertilising products derived from fishery waste and by-products first need to be included in the CMCs of the Regulation (EU) 2019/1009 before being introduced as a raw material for fertilising production in the EU. Although fish sludge has not been defined as a component material for fertilising products in the regulation and is not permitted to be used in organic farming according to the Organic Materials Review Institute (Ahuja et al., 2020), it is a potential raw material for fertiliser production, being able to be applied in conventional agriculture or added as feedstock in organic fertiliser production not only in Norway but in the rest of Europe and the world (Brod et al., 2017).

4.2. *Other potential parameters*

Even though the salinity of fertilising products is not considered a critical parameter, the application of saline fertiliser, indicated by high electrical conductivity (EC), may influence the soil structure, soil water holding capacity, soil biodiversity and vegetation growth (Daliakopoulos et al., 2016; Illera-Vives et al., 2013). The salinity of seawater indicates the dissolved material within, in which Na^+, Mg^{2+}, Ca^{2+}, K^+, Cl^-, SO_4^{2-} contributes the most (Millero et al., 2008). High concentration of Na^+ can displace bivalent cations, like Ca^{2+} and Mg^{2+}, weakening bonds between soil particles, leading to easier dispersibility and erosion (Daliakopoulos et al., 2016). It is often crucial to assess the salinity of fertiliser and soil before and after the amendment of fertilising products. Yogev et al. (2020) demonstrated that fish sludge with moderate initial salinity (EC = 3.4 dS/m) was possible to be utilized as raw material for fertiliser production via anaerobic digestion. For example, the EC of a compost (derived from desalinated fish waste mixed with pine barks) can be around 2.5 dS/m (Illera-Vives et al., 2013). Crops vary in their tolerance to salts. Maize is sensitive to salinity, whereas potato, sunflower and sugar beet has high tolerance to salinity (moderately salt tolerance: 2–3 dS/m and considered tolerant: >3 dS/m) (Daliakopoulos et al., 2016). In that sense, the salinity of fertilising products should be taken into account before being applied to the soil based on the species of crops. Daliakopoulos et al. (2016) concluded that including indicators other than EC, like field symptoms, sodium adsorption ration and exchangeable sodium percentage, could reflect salinity of soil as well. Before applying fishery waste derived fertilising products in agriculture,

Table 5
Macronutrient and C_{org} requirements for fertilisers (PFC 1) according to the Regulation (EU) 2019/1009 (% by mass).

	Organic fertiliser				Organo-mineral fertiliser				Inorganic macronutrient fertiliser[1]			
	Solid		Liquid		Solid		Liquid		Solid		Liquid	
	Straight	Compound	Straight	Compound	Straight	Compound	Straight	Compound	Straight	Compound	Straight	Compound
N	2.5	1	2	1	2.5[2]	2[3]	2[3]	2[3]	10	3	5	1.5
P_2O_5	2	1	1	1	2	2	2	2	12	3	5	1.5
K_2O	2	1	2	1	2	2	2	2	6	3	3	1.5
Primary macronutrients		4		3		8		6				
CaO									12	1.5	6	0.75
MgO									5	1.5	2	0.75
Na_2O									1–40	1–40	1–40	0.5–20
SO_3									10	1.5	5	0.75
Macronutrients									18		7	
C_{org}	15		5		7.5		3					

'Straight' indicates that fertiliser products contains only one declared macronutrient, while 'Compound' refers to more declared macronutrients.

[1] Inorganic fertiliser with macronutrients met the threshold values is named as inorganic macronutrient fertiliser due to Regulation (EU) 2019/1009.

[2] 1% by mass out of total mass shall be organic nitrogen (N_{org}).

[3] 0.5% by mass out of total mass shall be organic nitrogen (N_{org}).

Table 6

Limit values for heavy metals, biuret, perchlorate, copper and zinc in fertilising products according to *Annex I* Product Function Categories (PFCs) of Regulation (EU) 2019/1009.

	mg/kg dry matter; biuret g/kg dry matter	Fertiliser				Liming material	Soil improver		Growing medium	Plant biostimulant	
		Organic fertiliser	Organo-mineral fertiliser	Inorganic fertiliser			Organic	Inorganic		Non-microbial	Microbial
				Inorganic macronutrient fertiliser	Inorganic micronutrient fertiliser[3]						
Heavy metals	Cd	1.5	3[1]/60[2]	3[1]/60[2]	200[3]	2	2	1.5	1.5	1.5	
	Cr (VI)	2	2	2		2	2	2	2	2	
	Hg	1	1	1	100[3]	1	1	1	1	1	
	Ni	50	50	100	2000[3]	90	50	100	50	50	
	Pb	120	120	120	600[3]	120	120	120	120	120	
	iAs	40	40	40	1000[3]	40	40	40	40	40	
Biuret ($C_2H_5N_3O_2$)		Not present	12	12							
Perchlorate (ClO_4^-)				50							
Cu&Zn	Cu	300	600	600		300	300	300	200	600	
	Zn	800	1500	1500		800	800	800	500	1500	

[1] P_2O_5 (% by mass) $< 5\%$.

[2] P_2O_5 (% by mass) $\geq 5\%$.

[3] Limit values of contaminants expressed in mg, in relation to the total micronutrient content expressed in kg (mg/kg of total micronutrient content, which means boron (B), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo) and zinc (Zn)). As content indicates total As content.

it is recommended to assess and monitor salinity of fertilisers and soil for a sustainable agro-ecosystem.

Last but not least, microplastics input from fishery waste-derived fertilisers might become a problem to the agro-ecosystem, because organic fertilisers are considered one of the major sources of microplastics in the soil agro-ecosystem (Gui et al., 2021; Okeke et al., 2022; Weithmann et al., 2018; Zhang et al., 2022). Microplastics (particle size < 5 mm) may negatively affect soil organisms' fitness, soil fertility and texture, thus decreasing crop yield (Li et al., 2019; Okeke et al., 2022). Moreover, microplastics can act as carriers for heavy metals and other organic pollutants, influencing pollutants' migration from the environment to the crops. However, Bian et al. (2022) found that the microplastics from the coating of the controlled-release fertiliser had limited impacts on soil structure and bacteria within in the 10-year term. This study also showed that the microplastics residues attracted relevant bacteria and functioned as specific habitat. Till now, the function of microplastics in the soil remains open for further investigation. Zhang et al. (2020) reported that the abundance of microplastics was around 550 items/kg in the soil dosed with 30 ton/ha sewage sludge compost after one year, and low quantities of microplastics was detected in earthworms in the amended soil. Zhang et al. (2022) estimated that the yearly input flux of microplastics due to organic fertiliser application reached up to 5.07 trillion items to soil in China. According to the study of Habib and Thiemann (2022), 1.5 million of primary microplastics is released to the marine environment every year and estimated load will reach 100–250 million tons by 2025, which means that fishery waste obtained from marine environment may contain significant amount of microplastics. Alfaro-Núñez et al. (2021) reported that microplastic-particles were detected in all marine organisms collected along the continental coast, including fish, squid and shrimp. Microplastics were detected in the gastrointestinal tract or gut of various fish species as well (Li, B. et al., 2020). In this study, the abundance of the microplastics ranged from 1.9 to 6.1 items in the fish, consisting of 86% of fibre and 14% of fragments. Since fresh fish sludge with high water content requires dewatering via mechanical filtration and drying before further use as a fertiliser or a feedstock for fertiliser production (Brod and Øgaard, 2021; Brod et al., 2017), the dehydration concentrates microplastics in the dried fish sludge. Although microplastics are not (yet) included in regulations as a decisive/regulative parameter, their vast presence in aquatic and terrestrial environments is already a remarkable sign to monitor their presence and prevalence in the fishery waste derived fertilising products and amended soils.

5. Agronomic performance of alternative fertilising products derived from fishery waste and by-products

The fertilising products derived from fishery waste have been widely used as a replacement or supplement for synthetic mineral fertilisers in various regions. The agronomic performance can be assessed and quantified by the yield, height and leaf parameters of the plants. Untreated fishery waste are mostly fresh fishery waste with limited or non-treatment before use, which exhibits low stability and non-uniformity, reflecting the limit of its direct usage of fish waste as fertiliser. Fishery waste-derived fertilising products are treated fishery waste via (but not limited to) earlier-mentioned technologies with high nutrient contents and more controlled quality.

5.1. *Agronomic performance of untreated fishery waste*

Without considering the regulations, fishery waste has been applied as fertilisers to promote crop growth in some areas for decades. In 1990s, fish (*Sardinella orita*) waste application in millet and groundnut farmland led to increased yield of millet from 0.29 ton/ha to 6 ton/ha and groundnut from 0.23 ton/ha to 2 ton/ha (Ndiaye et al., 2000). Since fish sludge is rich in nutrients, some studies directly used fish sludge to fertilise the soil. Certain attributes of fish sludge promoted lettuce growth, resulting in larger leaves, more leaves and higher leaf biomass compared to unfertilised plants (Lenz et al., 2021). Moreover, fish sludge-amended soil facilitated K uptake by lettuce and resulted in higher Ca and Mg content in leaf tissues. According to study of Celis et al. (2008), lake salmon sludge dosed at certain range could effectively offer N–P–K to ryegrass and reached higher yield of ryegrass. Application of 50 t/ha lake salmon sludge (equals to 60 kg total N/ha) corresponded to 5.33 kg/ha dry mass of annual ryegrass, while the pot amended with inorganic fertiliser (140 kg N/ha) resulted in 5.20 kg/ha.

Apart from N–P–K supply by shell wastes, some tried to utilize shell wastes as alternative sources for liming agents. Oyster shell can produce Ca-rich soil amendments to reduce the uptake of Cd and As by plants (Bi et al., 2020). The authors reported that application of 2% dose of dried and crushed oyster shell (2 mm) greatly lowered the bioavailable Cd and As in the soil, dropping the Cd content in edible part of vegetable Bok Choy from 2.80 to 0.048 mg/kg and decreasing As content from 1.73 to 0.47 mg/kg. This is most probably due to the brick-like layers of calcium carbonate of the oyster shells, working as a natural nanocomposite, between which thin layers of protein act as organic glue (Bi et al., 2020; H Silva et al., 2019). When oyster shell meal ($pH = 9.8$) was used as liming material, the pH of silt loam soil increased from 6.2 to 6.5 with the dosage of 3.4 ton/ha and to 6.9 with 16 ton/ha products, respectively (Lee et al., 2008).

5.2. Agronomic performance of fishery waste-derived fertilising products (treated/refined fishery waste)

In the last decade, fishery waste-based fertilisers have received more attention. Bio-based fertilising products derived from fishery waste has been proven to be useful to promote the growth of various crop plants. For instance, liquid fertiliser fermented from trash fish can significantly promote the tomato growth (Aranganathan and SR, 2016). Tomato plant recorded its highest height to 54.2 cm from 10% liquid fertiliser amend pot, while just 38.6 cm from 10% diammonium phosphate ($(NH_4)_2HPO_4$) amended soil and 33.5 cm from the control (no fertiliser addition) after 30 days. However, the trash fish fermented liquid fertiliser did not function well as foliar spraying at the later stage of growth. Tomato plants sprayed with 10% liquid fertiliser and 10% $(NH_4)_2HPO_4$ corresponded to 57 and 94 leaves in 60 cm × 60 cm plot, respectively, while the control plot presented 61 number of leaves. This may be attributed to the immediate release of nutrients of chemical fertiliser, allowing a quick and abundant nutrient supply to leaves (Aranganathan and SR, 2016). The diameters of leaves had no big difference from three plots, being 3.3 cm, 3.1 cm and 3.2 cm, respectively.

Fish protein hydrolysates, chitin and chitosan are often considered biostimulants for organic farming, because they are characterised to benefit nutrient delivery to plants, strengthen plant defense systems against environmental stresses, thus promote plant growth and increase fruit phytochemical parameters of plants (García-Santiago et al., 2021; Shahrajabian et al., 2021). García-Santiago et al. (2021) applied fish protein hydrolysate as N sources for grape tomatoes, achieving higher leaf dry weight, fruit numbers and total yields with 120% organic nutrient solution compared to conventional fertilisers. Beckley et al. (2007) found that turf grass fertilised with fish hydrolysate fertiliser harvested double biomass compared to that of non-fertilised control and 35% more than the treatment amended with mineral fertiliser solution. Their study also showed that fish waste-based liquid fertiliser greatly promoted root growth, resulting in 130% higher root biomass than that of control. Fish waste co-composted with seaweed and pine bark was applied as organic amendment in ecological agriculture after maturity, hygiene and phytotoxicity tests (Illera-Vives et al., 2013). Despite the enriched nutrients in the compost, humic acids were able to promote lettuce growth via increasing root biomass and length, and to increase 64% water use efficiency after humic acid addition during the growing period (Busato et al., 2018). In another study (Abbasi, 2013), fish emulsion was reported to promote crop growth and also function in influencing microorganisms' activities. Diluted fish emulsion (0.1% or 2000 L/ha) application increased potato tuber yield 7–20%, of which 20–83% were at marketable level for the first three years. It also consistently reduced potato scab (soilborne disease) severity by 44–53% and increased soil bacteria numbers at the same period.

Nowadays, many companies have seen the potential of fishery waste-based fertiliser and sell commercial fertilising products. Ahuja et al. (2020) mentioned that 154 commercial fish-fertiliser products have been allowed by Organic Materials Review Institute. They summarized 25 commercially available fish-based fertilising products from the North America, most of which were hydrolysed fish fertiliser and fish emulsion. These products were tested on many crop species like tomatoes, cabbage, leek, yellow squash and radish. In Europe, a Norwegian company, Grønn Gjødsel AS, sells hybrid N fertiliser derived from fish meal and blood meal for conventional agriculture (GRØNN, 2023). There are two pelleted products (size: 2–4 mm) generated via long-period composting at high temperature to ensure pasteurisation, the product 'Hybrid N' with 20% N, 4% P and 8% K and the product 'Hybrid K' with11% N, 5% P and 17% K, and many other nutrients like Ca, Mg, S and Zn. 'Hybrid K' is recommended to be used for grain, grass, meadow and vegetables.

6. Conclusions and prospects

Nutrient recovery and recycling through the utilization of bio-based fertilising products derived from fishery waste and by-products fit perfectly well to the targets of Farm to Fork strategy which aims to reduce nutrient losses to the environment from both organic and mineral fertilisers by at least 50% by 2030 (EC, 2020). Where current regulations control the use of fertilising products derived from fishery waste, exemptions could be made to allow easier valorisation and open the way of single market for these products. Commercial agriculture applies value to a fertiliser based on its nutrient content, while the implications of a low fertiliser nutrient level means low market value. When side streams and by-products from fishery and aquaculture industries are manufactured into fertilisers, they may contain low levels of the primary macronutrients (N, P and K) but high levels of contaminants, which limit their profit and marketability. The choice of nutrient recovery technology therefore highly depends on the characteristics of raw waste material as well as on the requirements of the final product. Due to high protein and lipid content of fish processing waste, recovery of amino acids and peptides and/or production of fish emulsion come forward among other recovery technologies. Fish sludge has a great potential as well due to its high nutrient content and vast production, while its direct application is not favourable considering possible contaminants such as heavy metals, salinity, microplastics, and therefore relevant processing and monitoring are required. Seafood waste and by-products, namely crustacean and mussel shells, can also provide an alternative route to mainly obtain N-fertilisers, biochar/hydrochar as growing medium and calcium carbonate as liming agent. The existing literature shows that fertilisers derived from fishery waste perform equal or even superior to conventional synthetic fertilisers.

Further research is still needed in a life cycle perspective, both environmental, economic and social, to showcase the benefits and drawbacks of these nutrient recovery technologies and recovered products against the current practice which is using synthetic mineral fertiliser in most cases. With the winning concepts presented in this review paper (secondary raw material + nutrient recovery technology + recovered products), scale-up to operational level should be tested to validate the feasibility of replacing synthetic mineral fertilisers in the market.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119266.

References

Abbasi, P.A., 2013. Establishing suppressive conditions against soilborne potato diseases with low rates of fish emulsion applied serially as a pre-plant soil amendment. J. Indian Dent. Assoc. 35 (1), 10–19. https://doi.org/10.1080/07060661.2012.740076.

Abbey, L., Glover-Amengor, M., Atikpo, M.O., Atter, A., Toppe, J., 2017. Nutrient content of fish powder from low value fish and fish byproducts. Food Sci. Nutr. 5 (3), 374–379. https://doi.org/10.1002/fsn3.402.

Abdullah, N., Chin, N., 2010. Simplex-centroid mixture formulation for optimised composting of kitchen waste. Bioresour. Technol. 101 (21), 8205–8210. https://doi.org/10.1016/j.biortech.2010.05.068.

Ahuja, I., Dauksas, E., Remme, J.F., Richardsen, R., Løes, A.-K., 2020. Fish and fish waste-based fertilizers in organic farming–With status in Norway: a review. Waste Manag. 115, 95–112. https://doi.org/10.1016/j.wasman.2020.07.025.

Ahuja, I., Ween, O., Ebbesvik, M., Kvande, I., Boer, A.d., Ahlin, J.P., 2021. Fish Waste as Fertiliser-Effect of Drying Methods on Fish Waste and Supplementing Fish Waste with Other Residual Raw Materials to Form an Organic Fertiliser.

Alfaro-Núñez, A., et al., 2021. Microplastic pollution in seawater and marine organisms across the tropical eastern pacific and galápagos. Sci. Rep. 11 (1), 6424. https://doi.org/10.1038/s41598-022-07504-w.

Alltech, 2019. 2019 Global Feed Survey.

Andrade, E.P., et al., 2022. Selection and application of agri-environmental indicators to assess potential technologies for nutrient recovery in agriculture. Ecol. Indicat. 134, 108471 https://doi.org/10.1016/j.ecolind.2021.108471.

Aranganathan, L., SR, R.R., 2016. Bioconversion of marine trash fish (MTF) to organic liquid fertilizer for effective solid waste management and its efficacy on Tomato growth. Manag. Environ. Qual. Int. J. https://doi.org/10.1108/MEQ-05-2015-0074.

Araujo, J., Sica, P., Costa, C., Márquez, M., 2021. Enzymatic hydrolysis of fish waste as an alternative to produce high value-added products. Waste and Biomass Valorization 12 (2), 847–855. https://doi.org/10.1007/s12649-020-01029-x.

Arvanitoyannis, I.S., Kassaveti, A., 2008. Fish industry waste: treatments, environmental impacts, current and potential uses. Int. J. Food Sci. Technol. 43 (4), 726–745. https://doi.org/10.1111/j.1365-2621.2006.01513.x.

Asadu, C.O., et al., 2019. Survey on solid wastes management by composting: optimization of key process parameters for biofertilizer synthesis from agro wastes using response surface methodology (RSM). Artificial Intelligence in Agriculture 3, 52–61. https://doi.org/10.1016/j.aiia.2019.12.002.

Aspmo, S.I., Horn, S.J., Eijsink, V.G., 2005. Use of hydrolysates from Atlantic cod (Gadus morhua L.) viscera as a complex nitrogen source for lactic acid bacteria. FEMS (Fed. Eur. Microbiol. Soc.) Microbiol. Lett. 248 (1), 65–68. https://doi.org/10.1016/j.femsle.2005.05.021.

Atelge, M., et al., 2020. Biogas production from organic waste: recent progress and perspectives. Waste and Biomass Valorization 11 (3), 1019–1040. https://doi.org/10.1007/s12649-018-00546-0.

Ballester-Moltó, M., Sanchez-Jerez, P., Cerezo-Valverde, J., Aguado-Giménez, F., 2017. Particulate waste outflow from fish-farming cages. How much is uneaten feed? Mar. Pollut. Bull. 119 (1), 23–30. https://doi.org/10.1016/j.marpolbul.2017.03.004.

Bechtel, P.J., 2003. Properties of different fish processing by-products from pollock, cod and salmon. J. Food Process. Preserv. 27 (2), 101–116. https://doi.org/10.1111/j.1745-4549.2003.tb00505.x.

Bechtel, P.J., 2005. Properties of stickwater from fish processing byproducts. J. Aquat. Food Prod. Technol. 14 (2), 25–38. https://doi.org/10.1300/J030v14n02_03.

Beckley, M., Robinson, P., Ormsby, W., Neale, M., 2007. Process of Preparing Soil Additive of Fertilizer from Fish. Google Patents.

Bhaskar, N., Benila, T., Radha, C., Lalitha, R.G., 2008. Optimization of enzymatic hydrolysis of visceral waste proteins of Catla (Catla catla) for preparing protein hydrolysate using a commercial protease. Bioresour. Technol. 99 (2), 335–343. https://doi.org/10.1016/j.biortech.2006.12.015.

Bi, D., Yuan, G., Wei, J., Xiao, L., Feng, L., 2020. Conversion of oyster shell waste to amendment for immobilising cadmium and arsenic in agricultural soil. Bull. Environ. Contam. Toxicol. 105 (2), 277–282. https://doi.org/10.1007/s00128-020-02906-w.

Bian, W., et al., 2022. The long-term effects of microplastics on soil organomineral complexes and bacterial communities from controlled-release fertilizer residual coating. J. Environ. Manag. 304, 114193 https://doi.org/10.1016/j.jenvman.2021.114193.

Bougatef, A., Balti, R., Haddar, A., Jellouli, K., Souissi, N., Nasri, M., 2012. Protein hydrolysates from bluefin tuna (Thunnus thynnus) heads as influenced by the extent of enzymatic hydrolysis. Biotechnol. Bioproc. Eng. 17 (4), 841–852. https://doi.org/10.1007/s12257-012-0053-y.

Bridgwater, A.V., 2012. Review of fast pyrolysis of biomass and product upgrading. Biomass Bioenergy 38, 68–94. https://doi.org/10.1016/j.biombioe.2011.01.048.

Brod, E., Øgaard, A.F., 2021. Closing global P cycles: the effect of dewatered fish sludge and manure solids as P fertiliser. Waste Manag. 135, 190–198. https://doi.org/10.1016/j.wasman.2021.08.041.

Brod, E., Oppen, J., Kristoffersen, A.Ø., Haraldsen, T.K., Krogstad, T., 2017. Drying or anaerobic digestion of fish sludge: nitrogen fertilisation effects and logistics. Ambio 46 (8), 852–864. https://doi.org/10.1007/s13280-017-0927-5.

Brownsort, P.A., 2009. Biomass Pyrolysis Processes: Performance Parameters and Their Influence on Biochar System Benefits. http://hdl.handle.net/1842/3116.

Busato, J.G., et al., 2018. Recycling of wastes from fish beneficiation by composting: chemical characteristics of the compost and efficiency of their humic acids in stimulating the growth of lettuce. Environ. Sci. Pollut. Control Ser. 25 (36), 35811–35820. https://doi.org/10.1007/s11356-017-0795-3.

Celis, J., Sandoval, M., Barra, R., 2008. Plant response to salmon wastes and sewage sludge used as organic fertilizer on two degraded soils under greenhouse conditions. Chil. J. Agric. Res. 68 (3), 274–283. https://doi.org/10.4067/S0718-58392008000300007.

Cerozi, B.d.S., Fitzsimmons, K., 2017. Phosphorus dynamics modeling and mass balance in an aquaponics system. Agric. Syst. 153, 94–100. https://doi.org/10.1016/j.agsy.2017.01.020.

Checa, A.G., 2018. Physical and biological determinants of the fabrication of molluscan shell microstructures. Front. Mar. Sci. 5, 353. https://doi.org/10.3389/fmars.2018.00353.

Chen, X., et al., 2022. Spontaneous nutrient recovery and disinfection of aquaculture wastewater via Mg–coconut shell carbon composites. J. Hazard Mater. 426, 128119 https://doi.org/10.1016/j.jhazmat.2021.128119.

Chi, C.-F., et al., 2015. Purification and identification of three novel antioxidant peptides from protein hydrolysate of bluefin leatherjacket (Navodon septentrionalis) skin. Food Res. Int. 73, 124–129. https://doi.org/10.1016/j.foodres.2014.08.038.

Chojnacka, K., Moustakas, K., Witek-Krowiak, A., 2020. Bio-based fertilizers: a practical approach towards circular economy. Bioresour. Technol. 295, 122223 https://doi.org/10.1016/j.biortech.2019.122223.

Cooney, R., de Sousa, D.B., Fernández-Ríos, A., Mellett, S., Rowan, N., Morse, A.P., Hayes, M., Laso, J., Regueiro, L., Wan, A.H.L., Clifford, E., 2023. A circular economy framework for seafood waste valorisation to meet challenges and opportunities for intensive production and sustainability. J. Clean Prod. 392, 136283. https://doi.org/10.1016/j.jclepro.2023.136283.

Daliakopoulos, I., et al., 2016. The threat of soil salinity: a European scale review. Sci. Total Environ. 573, 727–739. https://doi.org/10.1016/j.scitotenv.2016.08.177.

Darwish, M., Aris, A., Puteh, M.H., Jusoh, M.N.H., Abdul Kadir, A., 2017. Waste bones ash as an alternative source of P for struvite precipitation. J. Environ. Manag. 203, 861–866. https://doi.org/10.1016/j.jenvman.2016.02.033.

Duan, Y., et al., 2020. Mapping and Characterization of CNP Flows and Their Stoichiometry in Main Farming Systems in Europe.

EC, 2020. Farm to Fork Strategy. https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en#modal.

Edwards, P., 2015. Aquaculture environment interactions: past, present and likely future trends. Aquaculture 447, 2–14. https://doi.org/10.1016/j.aquaculture.2015.02.001.

Egan, A., Saju, A., Sigurnjak, I., Meers, E., Power, N., 2022. What are the desired properties of recycling-derived fertilisers from an end-user perspective? Cleaner and Responsible Consumption 5, 100057. https://doi.org/10.1016/j.clrc.2022.100057.

El-Tarabily, K.A., Nassar, A.H., Hardy, G.E.S.J., Sivasithamparam, K., 2003. Fish emulsion as a food base for rhizobacteria promoting growth of radish (Raphanus sativus L. var. sativus) in a sandy soil. Plant Soil 252 (2), 397–411. https://doi.org/10.1023/A:1024729620154.

Estevez, M.M., Sapci, Z., Linjordet, R., Morken, J., 2014. Incorporation of fish by-product into the semi-continuous anaerobic co-digestion of pre-treated lignocellulose and cow manure, with recovery of digestate's nutrients. Renew. Energy 66, 550–558. https://doi.org/10.1016/j.renene.2014.01.001.

Estevez, M.M., Tomczak-Wandzel, R., Kvamme, K., 2022. Fish sludge as a Co-substrate in the anaerobic digestion of municipal sewage sludge-maximizing the utilization of available organic resources. EFB Bioecon. J., 100027 https://doi.org/10.1016/j.bioeco.2022.100027.

European Commission, E., 2006. Commission Regulation (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs. Off. J. Eur. Union 364, 5–24.

Fahlivi, M., Campus, F.I., Jónsson, Á., 2015. Physicochemical Characteristics of Liquid Fertilizer from Fish Viscera. United Nations University, Indonesia.

FAO, 2020. The State of World Fisheries and Aquaculture 2020: Sustainability in Action. https://doi.org/10.4060/ca9229en. Rome.

FAO, 2022. The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation FAO. https://doi.org/10.4060/cc0461en. Rome, Italy.

Fu, M.-M., Mo, C.-H., Li, H., Zhang, Y.-N., Huang, W.-X., Wong, M.H., 2019. Comparison of physicochemical properties of biochars and hydrochars produced from food wastes. J. Clean. Prod. 236, 117637 https://doi.org/10.1016/j.jclepro.2019.117637.

García-Santiago, J.C., et al., 2021. Effects of fish-derived protein hydrolysate, animal-based organic fertilisers and irrigation method on the growth and quality of grape tomatoes. Biol. Agric. Hortic. 37 (2), 107–124. https://doi.org/10.1080/01448765.2021.1891458.

Gayathri, M., Shunmugam, S., Thajuddin, N., Muralitharan, G., 2017. Phytohormones and free volatile fatty acids from cyanobacterial biomass wet extract (BWE) elicit plant growth promotion. Algal Res. 26, 56–64. https://doi.org/10.1016/j.algal.2017.06.022.

Gbogouri, G., Linder, M., Fanni, J., Parmentier, M., 2004. Influence of hydrolysis degree on the functional properties of salmon byproducts hydrolysates. J. Food Sci. 69 (8), C615–C622. https://doi.org/10.1111/j.1365-2621.2004.tb09909.x.

Gebauer, R., 2004. Mesophilic anaerobic treatment of sludge from saline fish farm effluents with biogas production. Bioresour. Technol. 93 (2), 155–167. https://doi.org/10.1016/j.biortech.2003.10.024.

Ghoreishi, G., Barrena, R., Font, X., 2023. Using green waste as substrate to produce biostimulant and biopesticide products through solid-state fermentation. Waste Manag. 159, 84–92. https://doi.org/10.1016/j.wasman.2023.01.026.

Goddek, S., et al., 2018. Nutrient mineralization and organic matter reduction performance of RAS-based sludge in sequential UASB-EGSB reactors. Aquacult. Eng. 83, 10–19. https://doi.org/10.1016/j.aquaeng.2018.07.003.

GRØNN, 2023. Conventional Fetilisers Overivew. https://www.gronngjodsel.no/wp-content/uploads/2021/12/Konvensjonell-gjodsel-eng.pdf.

Gui, J., Sun, Y., Wang, J., Chen, X., Zhang, S., Wu, D., 2021. Microplastics in composting of rural domestic waste: abundance, characteristics, and release from the surface of macroplastics. Environ. Pollut. 274, 116553 https://doi.org/10.1016/j.envpol.2021.116553.

H Silva, T., Mesquita-Guimarães, J., Henriques, B., Silva, F.S., Fredel, M.C., 2019. The potential use of oyster shell waste in new value-added by-product. Resources 8 (1), 13. https://doi.org/10.3390/resources8010013.

Habib, R.Z., Thiemann, T., 2022. Microplastic in the marine environment of the Red Sea–A short review. The Egyptian Journal of Aquatic Research. https://doi.org/10.1016/j.ejar.2022.03.002.

Hamilton, H.A., et al., 2016. Investigating cross-sectoral synergies through integrated aquaculture, fisheries, and agriculture phosphorus assessments: a case study of Norway. J. Ind. Ecol. 20 (4), 867–881. https://doi.org/10.1111/jiec.12324.

Hendriks, C.M., et al., 2021. Replacing mineral fertilisers for bio-based fertilisers in potato growing on sandy soil: a case study. Appl. Sci. 12 (1), 341. https://doi.org/10.3390/app12010341.

Herrera, A., et al., 2022. Environmental performance in the production and use of recovered fertilizers from organic wastes treated by anaerobic digestion vs synthetic mineral fertilizers. ACS Sustain. Chem. Eng. 10 (2), 986–997. https://doi.org/10.1021/acssuschemeng.1c07028.

Hua, K., Bureau, D., 2006. Modelling digestible phosphorus content of salmonid fish feeds. Aquaculture 254 (1–4), 455–465. https://doi.org/10.1016/j.aquaculture.2005.10.019.

Ikuta, K.S., et al., 2022. Global mortality associated with 33 bacterial pathogens in 2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 400 (10369), 2221–2248. https://doi.org/10.1016/S0140-6736(22)02185-7.

Illera-Vives, M., Seoane Labandeira, S., López-Mosquera, M., 2013. Production of compost from marine waste: evaluation of the product for use in ecological agriculture. J. Appl. Phycol. 25 (5), 1395–1403. https://doi.org/10.1007/s10811-013-9997-3.

Jayathilakan, K., Sultana, K., Radhakrishna, K., Bawa, A.S., 2012. Utilization of byproducts and waste materials from meat, poultry and fish processing industries: a review. J. Food Sci. Technol. 49 (3), 278–293. https://doi.org/10.1007/s13197-011-0290-7.

Kambo, H.S., Dutta, A., 2015. A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. Renew. Sustain. Energy Rev. 45, 359–378. https://doi.org/10.1016/j.rser.2015.01.050.

Kannan, S., Gariepy, Y., Vijaya Raghavan, G., 2018. Optimization of the conventional hydrothermal carbonization to produce hydrochar from fish waste. Biomass Conversion and Biorefinery 8 (3), 563–576. https://doi.org/10.1007/s13399-018-0323-9.

Kechaou, E.S., Bergé, J.-P., Jaouen, P., Ben Amar, R., 2015. Optimization of common cuttlefish (Sepia officinalis) protein hydrolysate using pepsin by response surface methodology. J. Aquat. Food Prod. Technol. 24 (3), 270–282. https://doi.org/10.1080/10498850.2013.773116.

Kechaou, E.S., et al., 2009. Enzymatic hydrolysis of cuttlefish (Sepia officinalis) and sardine (Sardina pilchardus) viscera using commercial proteases: effects on lipid distribution and amino acid composition. J. Biosci. Bioeng. 107 (2), 158–164. https://doi.org/10.1016/j.jbiosc.2008.10.018.

Khiari, Z., Kaluthota, S., Savidov, N., 2019. Aerobic bioconversion of aquaculture solid waste into liquid fertilizer: effects of bioprocess parameters on kinetics of nitrogen mineralization. Aquaculture 500, 492–499. https://doi.org/10.1016/j.aquaculture.2018.10.059.

Kim, J.K., Dao, V.T., Kong, I.S., Lee, H.H., 2010. Identification and characterization of microorganisms from earthworm viscera for the conversion of fish wastes into liquid fertilizer. Bioresour. Technol. 101 (14), 5131–5136. https://doi.org/10.1016/j.biortech.2010.02.001.

Kong, W., Huang, S., Yang, Z., Shi, F., Feng, Y., Khatoon, Z., 2020. Fish feed quality is a key factor in impacting aquaculture water environment: evidence from incubator experiments. Sci. Rep. 10 (1), 1–15. https://doi.org/10.1038/s41598-019-57063-w.

Kumar, N.S., Nazeer, R., Jaiganesh, R., 2011. Purification and biochemical characterization of antioxidant peptide from horse mackerel (Magalaspis cordyla) viscera protein. Peptides 32 (7), 1496–1501. https://doi.org/10.1016/j.peptides.2011.05.020.

Lee, C.H., Lee, D.K., Ali, M.A., Kim, P.J., 2008. Effects of oyster shell on soil chemical and biological properties and cabbage productivity as a liming materials. Waste Manag. 28 (12), 2702–2708. https://doi.org/10.1016/j.wasman.2007.12.005.

Lee, J.K., Jeon, J.-K., Byun, H.-G., 2011. Effect of angiotensin I converting enzyme inhibitory peptide purified from skate skin hydrolysate. Food Chem. 125 (2), 495–499. https://doi.org/10.1016/j.foodchem.2010.09.039.

Lenz, G.L., Loss, A., Lourenzi, C.R., Luiz de Alcantara Lopes, D., Siebeneichler, L.d.M., Brunetto, G., 2021. Lettuce growth in aquaponic system and in soil fertilized with fish sludge. Aquacult. Res. 52 (10), 5008–5021. https://doi.org/10.1111/are.15372.

Li, B., Su, L., Zhang, H., Deng, H., Chen, Q., Shi, H., 2020. Microplastics in fishes and their living environments surrounding a plastic production area. Sci. Total Environ. 727, 138662 https://doi.org/10.1016/j.scitotenv.2020.138662.

Li, Q., Wu, J., Zhao, X., Gu, X., Ji, R., 2019. Separation and identification of microplastics from soil and sewage sludge. Environ. Pollut. 254, 113076 https://doi.org/10.1016/j.envpol.2019.113076.

Liaset, B., Julshamn, K., Espe, M., 2003. Chemical composition and theoretical nutritional evaluation of the produced fractions from enzymic hydrolysis of salmon frames with Protamex™. Process Biochem. 38 (12), 1747–1759. https://doi.org/10.1016/S0032-9592(02)00251-0.

Liaset, B., Lied, E., Espe, M., 2000. Enzymatic hydrolysis of by-products from the fish-filleting industry; chemical characterisation and nutritional evaluation. J. Sci. Food Agric. 80 (5), 581–589. https://doi.org/10.1002/(SICI)1097-0010.

Makedonski, L., Peycheva, K., Stancheva, M., 2017. Determination of heavy metals in selected black sea fish species. Food Control 72, 313–318. https://doi.org/10.1016/j.foodcont.2015.08.024.

Manu, M., Li, D., Liwen, L., Jun, Z., Varjani, S., Wong, J.W., 2021. A review on nitrogen dynamics and mitigation strategies of food waste digestate composting. Bioresour. Technol. 334, 125032 https://doi.org/10.1016/j.biortech.2021.125032.

Marti-Quijal, F.J., Remize, F., Meca, G., Ferrer, E., Ruiz, M.-J., Barba, F.J., 2020. Fermentation in fish and by-products processing: an overview of current research and future prospects. Curr. Opin. Food Sci. 31, 9–16. https://doi.org/10.1016/j.cofs.2019.08.001.

Martínez-Alvarez, O., Chamorro, S., Brenes, A., 2015. Protein hydrolysates from animal processing by-products as a source of bioactive molecules with interest in animal feeding: a review. Food Res. Int. 73, 204–212. https://doi.org/10.1016/j.foodres.2015.04.005.

Martínez-Montaño, E., et al., 2021. Biochemical and antioxidant properties of recovered solids with pH shift from fishery effluents (sardine stickwater and tuna cooking water). Waste and Biomass Valorization 12 (4), 1901–1913. https://doi.org/10.1007/s12649-020-01147-6.

Millero, F.J., Feistel, R., Wright, D.G., McDougall, T.J., 2008. The composition of standard seawater and the definition of the reference-composition salinity scale. Deep Sea Res. Oceanogr. Res. Pap. 55 (1), 50–72. https://doi.org/10.1016/j.dsr.2007.10.001.

Mirzoyan, N., McDonald, R.C., Gross, A., 2012. Anaerobic treatment of brackishwater aquaculture sludge: an alternative to waste stabilization ponds. J. World Aquacult. Soc. 43 (2), 238–248. https://doi.org/10.1111/j.1749-7345.2012.00554.x.

Mirzoyan, N., Parnes, S., Singer, A., Tal, Y., Sowers, K., Gross, A., 2008. Quality of brackish aquaculture sludge and its suitability for anaerobic digestion and methane production in an upflow anaerobic sludge blanket (UASB) reactor. Aquaculture 279 (1–4), 35–41. https://doi.org/10.1016/j.aquaculture.2008.04.008.

Mohan, D., Pittman Jr., C.U., Steele, P.H., 2006. Pyrolysis of wood/biomass for bio-oil: a critical review. Energy Fuels 20 (3), 848–889. https://doi.org/10.1021/ef0502397.

Monsees, H., Keitel, J., Paul, M., Kloas, W., Wuertz, S., 2017. Potential of aquacultural sludge treatment for aquaponics: evaluation of nutrient mobilization under aerobic and anaerobic conditions. Aquaculture Environment Interactions 9, 9–18. https://doi.org/10.3354/aei00205.

Muthukumaran, S., Baskaran, K., 2013. Organic and nutrient reduction in a fish processing facility–A case study. Int. Biodeterior. Biodegrad. 85, 563–570. https://doi.org/10.1016/j.ibiod.2013.03.023.

Nag, R., et al., 2021. Quantitative microbial human exposure model for faecal indicator bacteria and risk assessment of pathogenic Escherichia coli in surface runoff following application of dairy cattle slurry and co-digestate to grassland. J. Environ. Manag. 299, 113627 https://doi.org/10.1016/j.jenvman.2021.113627.

Nazeer, R., Sampath Kumar, N., 2011. Purification and identification of antioxidant peptide from black pomfret, Parastromateus Niger (Bloch, 1975) viscera protein hydrolysate. Food Sci. Biotechnol. 20 (4), 1087–1094. https://doi.org/10.1007/s10068-011-0147-x.

Ndiaye, M., Yamoah, C.F., Dick, R.P., 2000. Fish by-product as a soil amendment for millet and groundnut cropping systems in Senegal. Biol. Agric. Hortic. (BAH) 17 (4), 329–338. https://doi.org/10.1080/01448765.2000.9754853.

Nie, E., He, P., Zhang, H., Hao, L., Shao, L., Lü, F., 2021. How does temperature regulate anaerobic digestion? Renew. Sustain. Energy Rev. 150, 111453 https://doi.org/10.1016/j.rser.2021.111453.

Okeke, E.S., et al., 2022. Microplastics in agroecosystems-impacts on ecosystem functions and food chain. Resour. Conserv. Recycl. 177, 105961 https://doi.org/10.1016/j.resconrec.2021.105961.

Onay, O., Kockar, O.M., 2003. Slow, fast and flash pyrolysis of rapeseed. Renew. Energy 28 (15), 2417–2433. https://doi.org/10.1016/S0960-1481(03)00137-X.

Ovissipour, M., Abedian, A., Motamedzadegan, A., Rasco, B., Safari, R., Shahiri, H., 2009. The effect of enzymatic hydrolysis time and temperature on the properties of protein hydrolysates from Persian sturgeon (Acipenser persicus) viscera. Food Chem. 115 (1), 238–242. https://doi.org/10.1016/j.foodchem.2008.12.013.

Ovissipour, M., Abedian Kenari, A., Motamedzadegan, A., Nazari, R.M., 2012. Optimization of enzymatic hydrolysis of visceral waste proteins of yellowfin tuna (Thunnus albacares). Food Bioprocess Technol. 5 (2), 696–705. https://doi.org/10.1007/s11947-010-0357-x.

Pezeshk, S., Ojagh, S.M., Rezaei, M., Shabanpour, B., 2019. Fractionation of protein hydrolysates of fish waste using membrane ultrafiltration: investigation of antibacterial and antioxidant activities. Probiotics and antimicrobial proteins 11 (3), 1015–1022. https://doi.org/10.1007/s12602-018-9483-y.

Piccirillo, C., Moreira, I., Novais, R., Fernandes, A., Pullar, R., Castro, P., 2017. Biphasic apatite-carbon materials derived from pyrolysed fish bones for effective adsorption of persistent pollutants and heavy metals. J. Environ. Chem. Eng. 5 (5), 4884–4894. https://doi.org/10.1016/j.jece.2017.09.010.

Pigoli, A., et al., 2021. Thermophilic anaerobic digestion as suitable bioprocess producing organic and chemical renewable fertilizers: a full-scale approach. Waste Manag. 124, 356–367. https://doi.org/10.1016/j.wasman.2021.02.028.

Rai, A.K., Swapna, H., Bhaskar, N., Halami, P., Sachindra, N., 2010. Effect of fermentation ensilaging on recovery of oil from fresh water fish viscera. Enzym. Microb. Technol. 46 (1), 9–13. https://doi.org/10.1016/j.enzmictec.2009.09.007.

Rengga, W., Mubarok, M., Cahyarini, N., 2018. Utilization of shrimp shell waste as matrix controller by using ionotropic gelation method in slow release fertilizer based on environmental conservation. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing, 012036. https://doi.org/10.1088/1755-1315/171/1/012036.

Rutherfurd, S.M., Gilani, G.S., 2009. Amino acid analysis. Current protocols in protein science 58 (1), 11–19. https://doi.org/10.1002/0471140864.ps1109s58, 11-11.19. 37.

Samoraj, M., et al., 2022. The challenges and perspectives for anaerobic digestion of animal waste and fertilizer application of the digestate. Chemosphere 295, 133799. https://doi.org/10.1016/j.chemosphere.2022.133799.

Sánchez-Monedero, M., Roig, A., Paredes, C., Bernal, M., 2001. Nitrogen transformation during organic waste composting by the Rutgers system and its effects on pH, EC and maturity of the composting mixtures. Bioresour. Technol. 78 (3), 301–308. https://doi.org/10.1016/S0960-8524(01)00031-1.

Santagata, R., Ripa, M., Genovese, A., Ulgiati, S., 2021. Food waste recovery pathways: challenges and opportunities for an emerging bio-based circular economy. A systematic review and an assessment. J. Clean. Prod. 286, 125490 https://doi.org/10.1016/j.jclepro.2020.125490.

Sathivel, S., et al., 2003. Biochemical and functional properties of herring (Clupea harengus) byproduct hydrolysates. J. Food Sci. 68 (7), 2196–2200. https://doi.org/10.1111/j.1365-2621.2003.tb05746.x.

Sathivel, S., Smiley, S., Prinyawiwatkul, W., Bechtel, P.J., 2005. Functional and nutritional properties of red salmon (Oncorhynchus nerka) enzymatic hydrolysates. J. Food Sci. 70 (6), c401–c406. https://doi.org/10.1111/j.1365-2621.2005.tb11437.x.

Seleiman, M.F., Santanen, A., Mäkelä, P.S., 2020. Recycling sludge on cropland as fertilizer–Advantages and risks. Resour. Conserv. Recycl. 155, 104647 https://doi.org/10.1016/j.resconrec.2019.104647.

Shahrajabian, M.H., Chaski, C., Polyzos, N., Tzortzakis, N., Petropoulos, S.A., 2021. Sustainable agriculture systems in vegetable production using chitin and chitosan as plant biostimulants. Biomolecules 11 (6), 819. https://doi.org/10.3390/biom11060819.

Siebers, N., Godlinski, F., Leinweber, P., 2014. Bone char as phosphorus fertilizer involved in cadmium immobilization in lettuce, wheat, and potato cropping. J. Plant Nutr. Soil Sci. 177 (1), 75–83. https://doi.org/10.1002/jpln.201300113.

Sigurnjak, I., et al., 2019. Production and performance of bio-based mineral fertilizers from agricultural waste using ammonia (stripping-) scrubbing technology. Waste Manag. 89, 265–274. https://doi.org/10.1016/j.wasman.2019.03.043.

Sikarwar, V.S., Pohořelý, M., Meers, E., Skoblia, S., Moško, J., Jeremiáš, M., 2021. Potential of coupling anaerobic digestion with thermochemical technologies for waste valorization. Fuel 294, 120533. https://doi.org/10.1016/j.fuel.2021.120533.

Singh, S., et al., 2022. Sustainable Processes for Treatment and Management of Seafood Solid Waste. Science of The Total Environment, 152951. https://doi.org/10.1016/j.scitotenv.2022.152951.

Strauch, S.M., et al., 2018. Commercial African catfish (Clarias gariepinus) recirculating aquaculture systems: assessment of element and energy pathways with special focus on the phosphorus cycle. Sustainability 10 (6), 1805. https://doi.org/10.3390/su10061805.

Taheri, A., Anvar, S., Ahari, H., Fogliano, V., 2013. Comparison the Functional Properties of Protein Hydrolysates from Poultry By-Products and Rainbow Trout (Onchorhynchus Mykiss) Viscera.

Teoh, G.H., Jawad, Z.A., Ooi, B.S., Low, S.C., 2022. Simultaneous water reclamation and nutrient recovery of aquaculture wastewater using membrane distillation. J. Water Proc. Eng. 46, 102573 https://doi.org/10.1016/j.jwpe.2022.102573.

Timmons, M.B., Ebeling, J.M., 2007. Recirculating Aquaculture. Cayuga Aqua Ventures, Ithaca, NY.

Valcarcel, J., Sanz, N., Vázquez, J.A., 2020. Optimization of the enzymatic protein hydrolysis of by-products from seabream (Sparus aurata) and seabass (Dicentrarchus labrax), chemical and functional characterization. Foods 9 (10), 1503. https://doi.org/10.3390/foods9101503.

Venderbosch, R., Prins, W., 2010. Fast pyrolysis technology development. Biofuels, bioproducts and biorefining 4 (2), 178–208. https://doi.org/10.1002/bbb.205.

Villamil, O., Váquiro, H., Solanilla, J.F., 2017. Fish viscera protein hydrolysates: production, potential applications and functional and bioactive properties. Food Chem. 224, 160–171. https://doi.org/10.1016/j.foodchem.2016.12.057.

Warren, G.P., Robinson, J.S., Someus, E., 2009. Dissolution of phosphorus from animal bone char in 12 soils. Nutrient Cycl. Agroecosyst. 84 (2), 167–178. https://doi.org/10.1007/s10705-008-9235-6.

Wasswa, J., Tang, J., Gu, X.-h., Yuan, X.-q., 2007. Influence of the extent of enzymatic hydrolysis on the functional properties of protein hydrolysate from grass carp (Ctenopharyngodon idella) skin. Food Chem. 104 (4), 1698–1704. https://doi.org/10.1016/j.foodchem.2007.03.044.

Wei, Z., Xi, B., Zhao, Y., Wang, S., Liu, H., Jiang, Y., 2007. Effect of inoculating microbes in municipal solid waste composting on characteristics of humic acid. Chemosphere 68 (2), 368–374. https://doi.org/10.1016/j.chemosphere.2006.12.067.

Weithmann, N., Möller, J.N., Löder, M.G., Piehl, S., Laforsch, C., Freitag, R., 2018. Organic fertilizer as a vehicle for the entry of microplastic into the environment. Sci. Adv. 4 (4), eaap8060.

Wu, D., et al., 2020b. Reconstruction of core microbes based on producing lignocellulolytic enzymes causing by bacterial inoculation during rice straw composting. Bioresour. Technol. 315, 123849 https://doi.org/10.1016/j.biortech.2020.123849.

Wu, J., Wei, Z., Zhu, Z., Zhao, Y., Jia, L., Lv, P., 2020a. Humus formation driven by ammonia-oxidizing bacteria during mixed materials composting. Bioresour. Technol. 311, 123500 https://doi.org/10.1016/j.biortech.2020.123500.

Wu, X., Cai, L., Zhang, Y., Mi, H., Cheng, X., Li, J., 2015. Compositions and antioxidant properties of protein hydrolysates from the skins of four carp species. Int. J. Food Sci. Technol. 50 (12), 2589–2597. https://doi.org/10.1111/ijfs.12927.

Yan, N., Chen, X., 2015. Sustainability: don't waste seafood waste. Nature 524 (7564), 155–157. https://doi.org/10.1038/524155a.

Yogev, U., Vogler, M., Nir, O., Londong, J., Gross, A., 2020. Phosphorous recovery from a novel recirculating aquaculture system followed by its sustainable reuse as a fertilizer. Sci. Total Environ. 722, 137949 https://doi.org/10.1016/j.scitotenv.2020.137949.

Zhan, J., Lu, J., Wang, D., 2022. Review of shell waste reutilization to promote sustainable shellfish aquaculture. Rev. Aquacult. 14 (1), 477–488. https://doi.org/10.1111/raq.12610.

Zhang, L., Xie, Y., Liu, J., Zhong, S., Qian, Y., Gao, P., 2020. An overlooked entry pathway of microplastics into agricultural soils from application of sludge-based fertilizers. Environ. Sci. Technol. 54 (7), 4248–4255. https://doi.org/10.1021/acs.est.9b07905.

Zhang, S., et al., 2022. Occurrence and Distribution of Microplastics in Organic Fertilizers in China. Science of The Total Environment, 157061.