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# Sustainable production of biofuels and bioderivatives from aquaculture and marine waste

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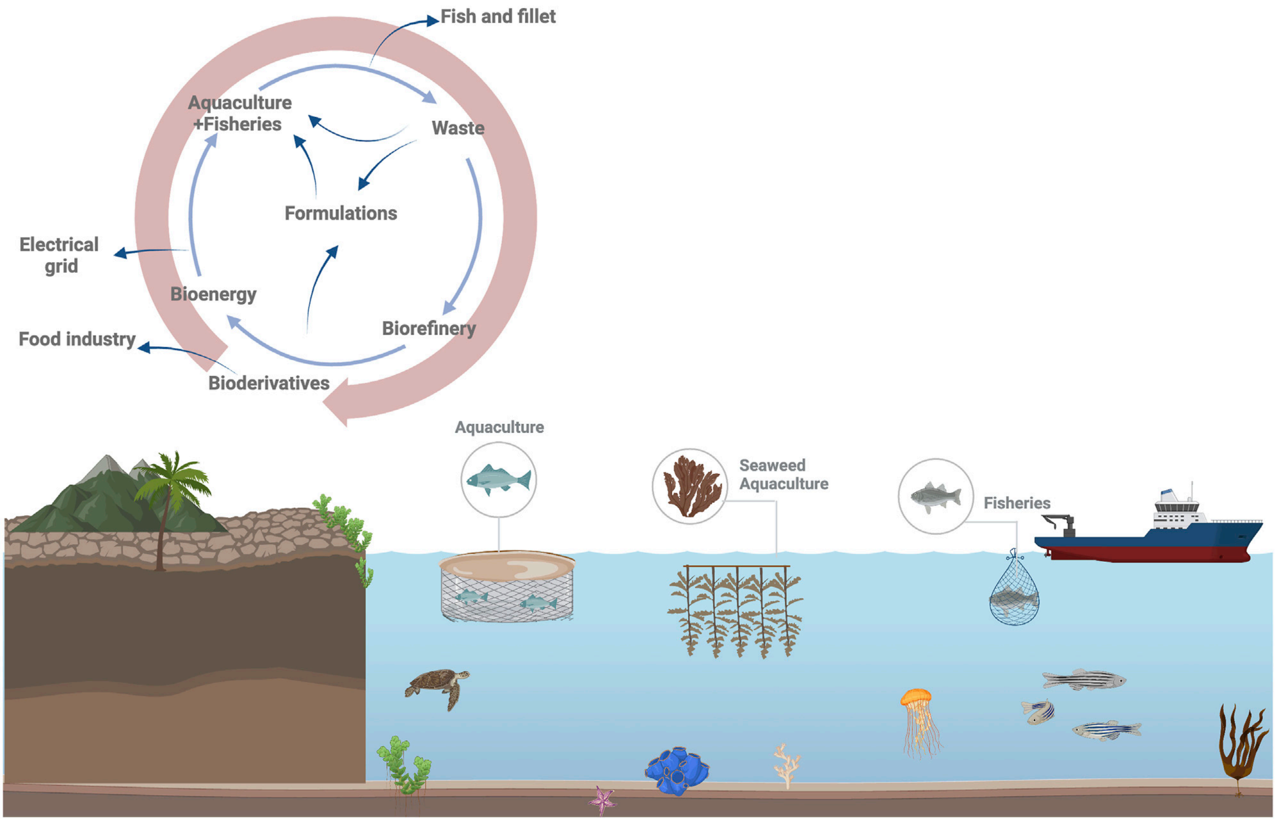
The annual global fish production reached a record 178 million tonnes in 2020, which continues to increase. Today, 49% of the total fish is harvested from aquaculture, which is forecasted to reach 60% of the total fish produced by 2030. Considering that the wastes of fishing industries represent up to 75% of the whole organisms, the fish industry is generating a large amount of waste which is being neglected in most parts of the world. This negligence can be traced to the ridicule of the value of this resource as well as the many difficulties related to its valorisation. In addition, the massive expansion of the aquaculture industry is generating significant environmental consequences, including chemical and biological pollution, disease outbreaks that increase the fish mortality rate, unsustainable feeds, competition for coastal space, and an increase in the macroalgal blooms due to anthropogenic stressors, leading to a negative socio-economic and environmental impact. The establishment of integrated multi-trophic aquaculture (IMTA) has received increasing attention due to the environmental benefits of using waste products and transforming them into valuable products. There is a need to integrate and implement new technologies able to valorise the waste generated from the fish and aquaculture industry making the aquaculture sector and the fish industry more sustainable through the development of a circular economy scheme. This review wants to provide an overview of several approaches to valorise marine waste (e.g., dead fish, algae waste from marine and aquaculture, fish waste), by their transformation into biofuels (biomethane, biohydrogen, biodiesel, green diesel, bioethanol, or biomethanol) and recovering biomolecules such as proteins (collagen, fish hydrolysate protein), polysaccharides (chitosan, chitin, carrageenan, ulvan, alginate, fucoidan, and laminarin) and biosurfactants.

KEYWORDS

**biofuels, bioderivatives, aquaculture, marine waste, circular economy**




GRAPHICAL ABSTRACT

## 1 Introduction

The demand for fish meat is increasing, however, capture fisheries production remains static or is diminishing, depending on the species in question, during the last decades. The aquaculture industry has been recognised to have a critical role in food production, so it is growing at the fastest rate in the world. Up today, the aquaculture industry produces 48% of the total fish produced and it is estimated that by 2030 the demand for aquaculture will reach 57% of the total global production (OECD-FAO, 2021). This industry involves cultures of fish or aquatic organisms, either in freshwater or marine culture. It is commonly associated with fish farming since it is the most relevant one for human consumption, but it also covers other forms of aquatic animal and plant production, such as crustaceans, molluscs, algae and seaweed, and others (Ahmad et al., 2021). Nevertheless, the fast growth of the aquaculture industry and its intensive activities are creating a negative impact on the environment caused of the excessive release of nutrients into the sea, causing eutrophication of coastal areas and other aquatic systems (Sarà et al., 2018). The excessive formation of algae decreases the oxygen level in the water and increases the level of toxins in the water due to their degradation affecting the mortality rate of the wild population (Van Osch et al., 2017; Mangano et al., 2019). Oliviera et al. (2021) reported that more than 10 million fish die annually around the world for environmental factors which directly affect the increase of infectious agents and parasites. The high mortality generates a massive amount of low-value waste that is difficult to recycle due to restricted legislation.

The significant environmental issues caused by intensive aquaculture increased the interest in alternative sustainable practices, such as integrated multi-trophic aquaculture (IMTA) (Alexander et al., 2016; Sarà et al., 2018). Integrated multi-trophic aquaculture aims to incorporate the production of aquaculture species of different trophic levels under a circular economy approach, minimising energy losses, environmental deterioration and valorising the waste products (Buck et al., 2018). This novel system uses algae to capture nutrient and inorganic solid waste and convert them into feed, fertiliser and possible substrate to produce biofuel (Correia et al., 2020). The use of this novel aquaculture concept could reduce the fish mortality both for the aquaculture and for the wild fish up to 5.5% which is closer to mortality rates on egg-laying hen farms. It has been calculated for Norwegian farmers that reach the level of mortality mentioned above, it could generate an annual saving of over $892 million USD (Just Economy, 2021).

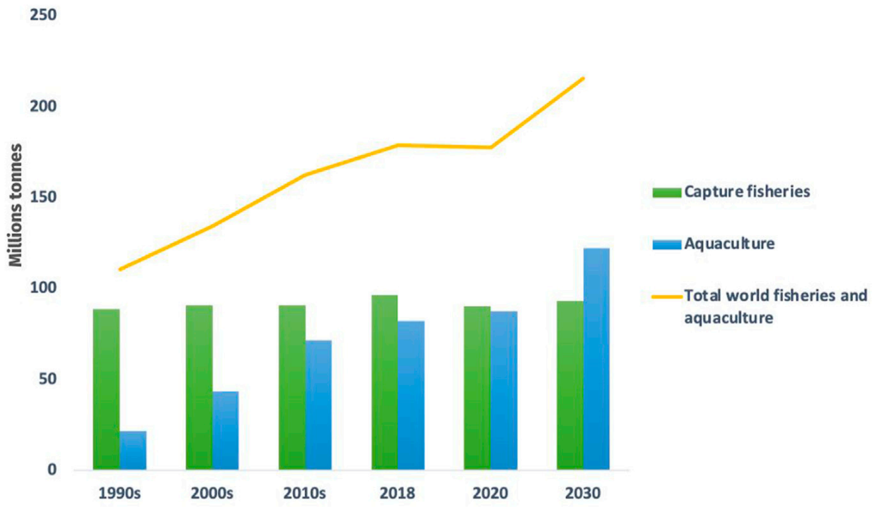



FIGURE 1
Global capture fisheries and aquaculture production, 1990–2030 Adapted from FAO, 2022b.

Despite the environmental benefits of integrated multi-trophic aquaculture (IMTA), aquaculture and the fisheries industry produce a large amount of waste which is not included in the circular economy of the process and takes into account dead fish, algae waste, and all the waste generated by fish manufactured (e.g., viscera, skin, bonds, and heads). The transformation of waste products into biofuel and bioderivatives will help to further reduce the carbon footprint of the aquaculture industry (4-75Kg$CO_2$/Kg protein), replacing the utilization of fossil fuel resources. In 2018, world fish production reached about 179 million tonnes with a total first sale value estimated at USD 401 billion, 82.1 million tonnes of that fish production, which is the largest in aquaculture industry, of which 82 million tonnes, valued at USD 250 billion, came from aquaculture production, followed by aquatic algae production, dominated by seaweed, with 32.4 million tonnes produced (Figure 1).

These two products had a total farmgate value of USD 263.6 billion. Of the total global fish production, about 88% was used for human consumption, equivalent to an estimated annual supply of 20.5 kg *per capita* (FAO, 2020). Considering that 50%–60% of the whole organism is wasted annually, we generate a waste stream of 134 million tons/yr. While the waste generates from fish mortality is difficult to quantify due to the main factors that affect the value. Oliviera et al. (2021) reported that in Norway, the salmon industry generated 50 million tonnes per year of dead fish in 2018, while in Scotland 8.3 million tonnes per year. A recent report published by Just Economy (2021) focuses on the main aquaculture industry in Norway, Scotland, Chile and Canada reported that the fish mortality due to different causes is the main cost for the salmon aquaculture industry (15,539 MUSD). The mortality also generate of Environmental and social costs which account for 19,195 MUSD.

With respect to the waste represented by the fisheries and aquaculture, it is estimated that 35% of the global harvest is either lost or wasted every year, meaning that in the year of 2018 about 28.7 million tonnes of the aquaculture production were lost, which translates to the loss of USD 87.5 billion. In most regions of the world, total fish loss and waste lies between 30%–35%. With the rapid growth of this industry and the expansion of fish processing, the number of by-products obtained from aquaculture has also increased (Khawli et al., 2019), these may represent up to 70% of processed fish (FAO, 2020). In the past, these by-products were treated as marine waste, used directly as feed for aquaculture, livestock, or employed to produce fish oil, fertilizer, pet food and fish silage, most of these recycled products possess low economic value allowing only a minimal amount of the capital invested in the aquaculture production to be recovered. However, this waste can now be used more efficiently as a source of marine biomass with a great diversity of biotechnological applications. Recent studies have identified a number of bioactive compounds from remaining fish muscle proteins, collagen and gelatin, fish oil, fish bone, internal organs and shellfish and crustacean shells. These bioactive compounds can be extracted, purified, transformed, and exploited as a consequence of the improved processing technologies varying from simple to complex techniques. Such compounds may include the preparation and isolation of bioactive peptides, polyphenols, polysaccharides, oligosaccharides, fatty acids, enzymes and biopolymers for biotechnological applications (Kim and

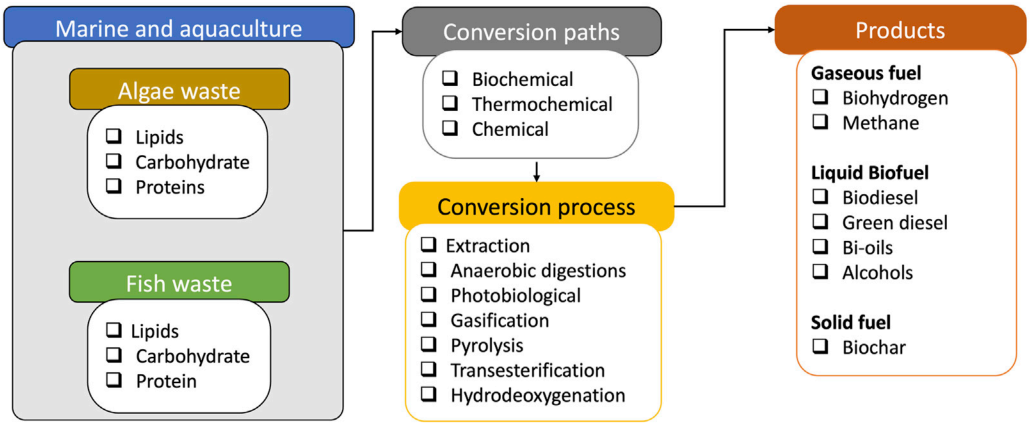



FIGURE 2
Schematic description of marine waste and fish waste products conversion path and products.

Mendis, 2006; Khawli et al., 2019; Rudovica et al., 2021) such as the synthesis of biofuels, biosurfactants, biochar and other bioproducts. Global food loss and waste is one of the main concerns regarding sustainable development, for this reason, it is the focus of Sustainable Development Goal (SDG) Target 12.3, which aims at halving wastage by 2030 (FAO, 2020). The most extensively used and promising alternative to achieve this SDG goal is the use the exploitation of marine biomass and valorisation of seafood by-products either directly or by the extraction of bioproducts, leading to more environmentally sustainable uses of marine resources and higher economic benefits, in line with the circular economy concepts (Rudovica et al., 2021) that can provide a continued supply of aquatic products beneficial for human consumption without harming existing ecosystems or exceeding the ability of the planet to renew the natural resources required for aquaculture production.

Regarding the aquatic algae production, algae play a very important role in many ecosystems, providing food and shelter for many different species of aquatic animals. However, when uncontrolled growth occurs, their impact on the ecosystem can be harmful. The excessive growth of marine algae is called "algal blooms" there are several factors that contribute to algal blooms, including limiting nutrients, climate change, and pollution. Although some blooms occur naturally, others are caused by human intervention. Algae bloom affects not only ecological balances but also fundamental economic activities in the territory, such as fishing and tourism, potentially even affecting public health (Jena and Hoekman, 2017). Beach wrack is another concerning algae bloom, it consists of organic material like seagrass or seaweed biomass which accumulates on beaches due to the action of waves, tides, and non-periodical water level fluctuations. Despite the natural origin of most of this material and its significant ecological role, beach wrack often becomes an environmental issue if accumulated in excessive amounts (Rudovica et al., 2021). Although the negative impact that algal blooms can have on an ecosystem and the environment due to their overproduction and degradation, they could represent a solution and resource if they are collected and reused for the production of biofuel (The Climate Institute, 2017).

Indeed, algae waste from marine and aquaculture is a sustainable and optimal solution for producing third-generation fuel. Seaweeds (*U. lactuca*) collected from the beach could become profitable as it gathers in blooms that need to be removed from beaches. Thus, harvest cost is cheap, and it may even attract a gate fee. Allen et al. (2015) reported that the potential Gross energy yields can be on the order of 186 GJ $ha^{-1}$ $yr^{-1}$, which is higher than the first-generation liquid biofuel like ethanol (135 GJ $ha^{-1}$ $yr^{-1}$) produced from sugarcane or biodiesel (120 GJ $ha^{-1}$ $yr^{-1}$) from palm oil.

Algae biomass has enormous potential to also high-value products like nutraceuticals, proteins and other functional ingredients (Jena and Hoekman, 2017). This review aims to highlight the importance of using marine and aquaculture waste and assessing current technologies to convert this waste into high-value products in line with new sustainability trends in industries such as the circular economy by using what was once waste and converting it into new valuable products for human use.

## 2 Bio-based circularity economy: Exploring the impact fish-aquaculture-marine waste conversion into products

The circular bio-based economy target to reuse all types of sustainable sourced biomass and degradable waste from

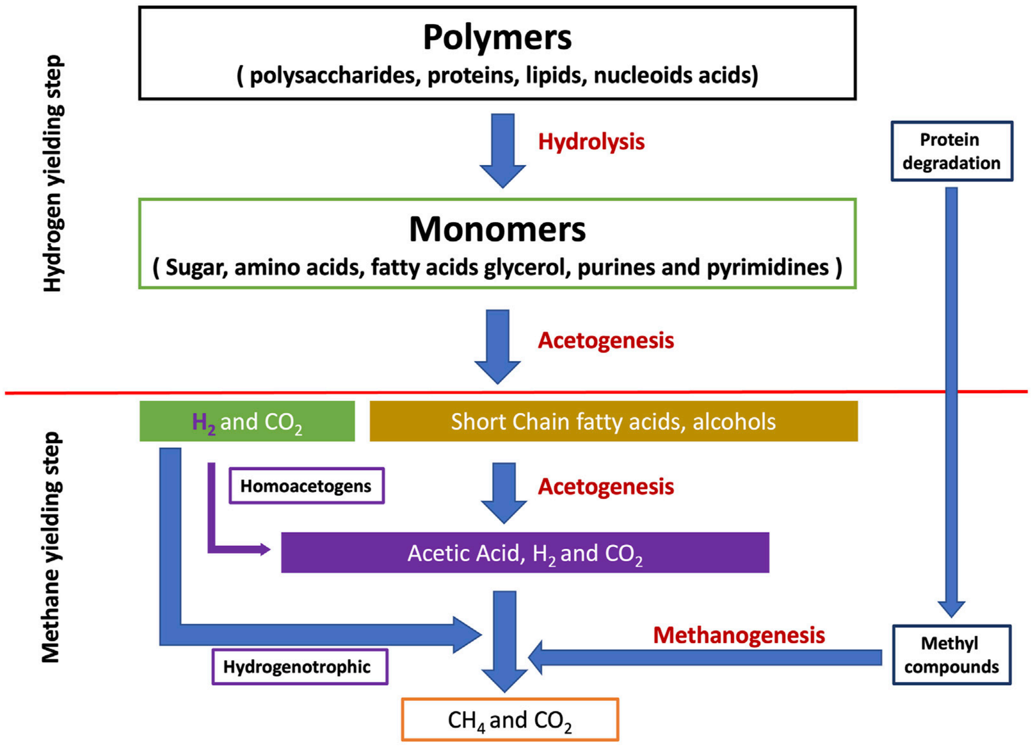



FIGURE 3
Schematic description of metabolic mechanisms of anaerobic digestion.

many sectors and transforming it into a wide-spectrum of high value products including biofuels, biomaterials, bioactive compounds, among others (Vishwakarma et al., 2022).

The circular economy has gain momentum by returning materials and waste into sources towards making a sustainable and zero-waste environment. The global energy demand is estimated to increase approximately 28% by the year 2040 and there is much interest in biofuels production under sustainable circular bioeconomy because they are eco-friendly and are preferred for their carbon neutral character, production flexibility from several and versatile sources and renewability (Ranjbari et al., 2022).

The use of the biofuels as an alternative to fossil fuel and technologies for its production is improving day by day. The main source of biofuels is the organic matter called biomass, it could be plants, waste, farming residue, waste from sewage, manure, *etc.* Recently, the biofuels from crops and plants have been taken relevance. Additional to plants, algae, microalgae seaweeds and seagrass founded to be potential reserves and solution in the energetic transition. The suitable biofuels production from third and fourth generation is not competing with land and food leading to lot benefits in transport sector (Priya et al., 2021).

The rapid growth of aquaculture sector has resulted in massive waste, residuals products and environmental concerns has been conflicted also with the amount of water utilised (Azwar et al., 2022). Considering that 35% of the global harvest in fisheries and aquaculture is lost as waste every year, there is a gap of opportunities to valorise and minimize the total discarded. The sociological and environmental impact complain to construct regulatory frameworks, services and infrastructure to reduce fish lost and waste (Rudovica et al., 2021).

For example, alternative valorisation routes for scale, skin, bones, tails, and fins are needed. The conversion of these residuals into valuable materials has numerous advantages. Fish has high oil content which one has been shown to be suitable source for biofuel production, also can be converted into biodiesel *via* chemical catalysis and enzymatic approaches. Additionally, this kind of biowaste permits the methane production derived from its composition (Lee et al., 2022).

Algae circular economy has gained interest in the last years in the bioplastic production. In case of microalgae, is a renewable resource with high potential for bioplastic production, several strains have been evaluated on their functionality for production of polyhydroxyalkanoates (PHA′s). Macroalgae and seaweed are consider a low-cost source of bioderivatives such as alginate,

**TABLE 1 Anaerobic digestion of fish waste.**

| Type of waste (substrate) | Incubation time (days) | Biochemical methane potential (BMP) | References |
|---|---|---|---|
| Salmon heads | 33 | .828 ± .15 $CH_4$ $m^3$/kg VS. added | Nges et al. (2012) |
| Fish waste | 36 | F/M ratio .2 with a total maximum methane yield .165 $CH_4$ $m^3$/kg VS. added $COD_{Mn}$ | Hadiyarto et al. (2015) |
| Fish waste | 21 | 540.5 $CH_4$ ml $gVS^{-1}$ | Bucker et al. (2020) |
| Solid Anchovy slurry | 34 | 296.1 $CH_4$ ml $gVS^{-1}$ | Paone et al. (2021) |
| Fish waste | 15 | 350.5 ± 5.2 ml/$gVS_{added}$ | Hanifa Jannat et al. (2022) |
| Jellyfish Aurelia aurita | – | 121.35 ml/g and 870.12 ml/g | Kim et al. (2012) |
| Tuna, sardine, mackerel waste | 67 | .47–.59 g COD-$CH_4$/g COD added | Eiroa et al. (2012) |
| Mixed FW (1%Total Solid) | 28 | 464.5 ml $CH_4$/g VS. | Cadavid-Rodríguez et al. (2019) |
| Fish waste | – | 361 $Nm^3$ $CH_4$/Mg VS. | Greggio et al. (2018) |
| Round goby waste | – | .520–.922 $CH_4$ $m^3$/kg VS. added | Gruduls et al. (2018) |

**TABLE 2 Co-digestion of fish waste with other material.**

| Type of waste (substrate) | Ratio substrate | Biochemical methane potential (BMP) | References |
|---|---|---|---|
| FWS: JA | 1:1 | .531 $CH_4$ $m^3$/kg VS. added | Nges et al. (2012) |
| S.E.: FCIW | 94:6 | .205 $CH_4$ $m^3$/kg VS. added | Serrano et al. (2014) |
| FPW-LFB | 75:25 | 170 ml/g VS. | Choe et al. (2020) |
| FS: MSS | 30:70 | 1950 ml $CH_4$/kg of waste | (Maria M.Estevez et al., 2022) |
| FW: WH | | .408 $CH_4$ $m^3$/kg VS. added | Serrano et al. (2014) |
| FW: BWS | 20:8 | .408 $CH_4$ $m^3$/kg VS. added | Nalinga and Legonda, (2016) |
| CM:CI: FS. | 45:22:33 | .533 $CH_4$ mL/kg VS. added | Kafle et al. (2013) |
| FWS:CM2 | 80:20 | 1966 $CH_4$ $m^3$/kg VS. added | Kébé et al. (2021) |
| FW/SWG | 3:2 | 8.4 L $CH_4$ $m^3$/kg of waste | Solli et al. (2014) |
| FW/SWG | 2:3 | 4.2 L $CH_4$ $m^3$/kg of waste | Solli et al. (2014) |
| SWG | 100% | 2.9 L $CH_4$ $m^3$/kg of waste | Solli et al. (2014) |

FW, fish waste; FWS, fish waste silage; FPW- fish processed waste; FS–Fish Sludge; CM, Cod meat; MSS, Municipal Sewage Sludge CI, cod intestine; WH, water hyacinth; LFB, Liquid fraction Bamboo; CD, cow dung; SE, strawberry extraduate; MSS, municipal Sewage sludge; JA, Jerusalem artichoke; FCIW, fish canning industry waste; CM2, cow manure; BWS, –bread waste silage; SWG, seaweed grass.

carrageenan, fucoidan and ulvan which ones after their extraction and purification could be competitive and commercially expensive products (Dang et al., 2022).

Food loses and waste not only means a reductions on the quantity of the marine products from catch and harvest, it means also the decrease of its quality and nutritional values, additional on the impact on the economic sector. To avoid and prevent issues related to food and safety and fish loss, is priority to recognize and validate how to implement all stages of the fisheries and aquaculture value chains. Training on food safety and requirements should be provided to all the actors in the value chain of fishering and aquaculture and ensure the safe aquatic products on the market and fish loss reduction globally (FAO, 2022a).

Contributing to the significant progress made in the reuse of marine biomass, research, and innovation on technology for scale-up must be establish a nexus and collaboration between industry and government to promote sustainability and a circular economy in order to enhance the aquaculture productivity and efficiency on supply chains.

## 3 Advanced production of biofuels from fish-aquaculture waste, and algae bloom

Nowadays, 80% of the energy supply is produced by fossil fuels (Renewables, 2021). Energy demands are increasing worldwide due to industrialisation, population growth and modernisation, leading to the over-exploitation of limited available natural fossil fuel reserves (Kumar et al., 2020a). The high utilization of fossil fuels represents a massive issue due to gas emissions, which are the main cause of global warming. To mitigate this issue is fundamental to replace fossil fuels with third-generation biofuels, which use feedstocks that do not compete with food, reduce pressure on the land due to the low amount available, and need to be abundant to satisfy the current oil demand (Jamil et al., 2018; Mansir et al., 2018, Singh et al., 2019). To achieve this, it is necessary to use waste sources. Despite agricultural, industrial, and household, organic waste has been used for a long time as feedstocks to generate power and small quantities of synthetic oils that are not enough to satisfy the global demand (Skaggs et al., 2018). Today, there is a large number of unexplored waste sources generated from aquaculture, marine and fish industry waste but also use of biomass growth generated by photosynthesis, like algae, that could help to match the energy demand and the use of these additional wastes (Tsukahara et al., 2001; Kumar et al., 2020b). Using waste biomass represents a sustainable strategy because it reduces the utilization of food crops, optimises waste management, and reduces the gas emissions generated by waste disposal in landfills and the combustion of fossil fuels. Hence, waste biorefineries are attracting significant interest worldwide because required energy needs are met, and a solution to the waste management problem is found in the circular economy context (Tuck et al., 2012; Ahrens et al., 2017; Yuvaraj et al., 2019). The industrial processes focused on valorising terrestrial biomass are well established, but marine sources still represent an untapped resource.

The fish industry is one of the world's largest industries, where tons of fish are used daily. Every year a billion tons of fish are utilised for edible purposes, but it also generates a large amount of waste fish derived from a high mortality rate in the marine environment of the aquaculture industry and non-edible parts (e.g., head, viscera, dorsal fins, tail, skin, and liver) derived from the fish processing. This non-edible waste is considered worthless garbage and discarded without recovering valuable products by dumping on land or hauling it into the ocean (Milano et al., 2016).

The marine and aquaculture industry also produces a large amount of algae waste. Lipid-rich sources offer an attractive choice for a biofuel feedstock due to its high $CO_2$-fixing capabilities (Milano et al., 2016). Algae absorb about 183 gigatons of $CO_2$ while growing about 100 gigatons of algal-cell biomass (Dumay et al., 2004; Schenk et al., 2008).

Generally, 70% of the Earth's surface is occupied by oceans and seas that are intensively used by the fishery and aquaculture industries. The amount of waste generated is massive, mainly composed of seaweed, dead fish and fish waste derived from the manufacturing industry. This waste is rich in compounds that can be converted into biofuel using biological and chemical processes. Different conversion technologies are used to produce biofuels, such as biochemical–anaerobic digestion (biogas) and fermentation (bioethanol) and chemical conversion–extraction and transesterification (biodiesel) (Figure 2).

In this section will evaluate the advantages and disadvantages of the technologies to convert fish and algae waste into gaseous fuel (biomethane and bio-hydrogen) used to decarbonise the domestic and industrial sector and liquid (biodiesel, green diesel) used to decarbonise the heavy transportation sector.

### 3.1 Biogas and biomethane

Anaerobic digestion is a well-established technology that converts organic waste into clean bioenergy. Biogas and digested substrate (digestate) are the products of anaerobic digestion. The biogas usually contains 55%–65% $CH_4$, 35%–45% $CO_2$, 0%–3% $N_2$, 0%–1% $H_2$, and 0%–1% $H_2S$ (Milono et al., 1981).

The anaerobic digestion of organic waste is a complex process composed of a series of bio-metabolism steps, which include hydrolysis, acidogenesis, acetogenesis, and methanogenesis, respectively (Figure 3).

The mechanisms reported above are the main ones responsible for the kinetic of reactions, and they are highly dependent on environmental and/or ambient conditions such as temperature, pH, C/N ratio, C/P ratio, particle size, inhibitors, and type of substrate (Mata-Alvarez et al., 2000). The first step of the process is hydrolysis, where enzymes decompose the complex polymeric structures of cellulose, starch and proteins into monomers or oligomers such as glucose, fatty acids, and amino acids. This process is quite fast, but it can be limited by the presence of lignin-rich substrates. Ariunbaatar et al. (2014) report that this step process can be accelerated by introducing specific enzymes.

The second step (acidogenesis) transforms the products of the hydrolytic process into volatile fatty acids (VFAs), alcohols and ketones. This process is fast (30 min, and this causes an accumulation of VFA accumulation in the digester, resulting in digester toxicity if not properly controlled by operational conditions, substrate composition, and microbial population in the anaerobic digestion system (Lukitawesa-Patinvoh et al., 2020). The pH is the operating parameter that affects most the VFA formation, and it was reported that the optimal pH range is 5.5–6.5 (Mao et al., 2015).

**TABLE 3 Dark fermentation of the biomass, food waste and algae.**

| Substrate type | Microbial inoculum source | Reactor type | Temp. (°C) | pH | Maximum $H_2$yield (ml $H_2$/g $VS_{adde}$) | $H_2$ in biogas (%) | References |
|---|---|---|---|---|---|---|---|
| Food waste | Heatshock treated anaerobic sludge | Leaching bed reactor | 37 | 5.5–7 | 310 | 10–55 | Han and Shin, (2004) |
| Food waste | Acid-treated anaerobic digestion sludge | Batch | 37 | 4.6 | 169 | 23 | Shin et al. (2004) |
| Food waste and sewage sludge | Anaerobic digester sludge | Batch | 35 | 5.0–6.0 | 122.9 | – | Alavi-Borazjani et al. (2019) |
| OFMSW | Anaerobic digestate | Semi-continuous CSTR | 55 | 6.4 | 360 | 58 | Valdez-Vazquez et al. (2005) |
| OFMSW | Non-anaerobic inocula (soil, pig excreta) | Packed bed reactor | 38 | 5.6 | 99 | 47 | Alzate-Gaviria et al. (2007) |
| Cheese whey | Adapted anaerobic sludge | Batch | 55 | 7 (initia) | 111 | – | Kargi et al. (2012) |
| Pig slurry | Mesophilic methanogenic sludge | CSTR | 70 | 6.7 (feed) | 3.65 | – | Kotsopoulos et al. (2009) |
| Untreated de-oiled algae cake | Anaerobic digester sludge | Batch | 29 | 6 (initia) | 66 | – | Venkata Subhash and Venkata Mohan, (2014) |

The third step (acetogenesis) transforms most products of acidogenesis and some of the long-chain fatty acids from the hydrolysis stage into acetate, $CO_2$, and $H_2$ into ($CH_3COO$-), hydrogen ($H_2$), and carbon dioxide ($CO_2$) and the kinetic of reaction is reported to be in a range of 1.5–4 days (Ramos-Suárez et al., 2015). This step is sensible to the presence of $H_2$ and $O_{2,}$ and the operating pH has to be in a range between 6–6.2 (Geraldi, 2003; Burton et al., 2014; Stronach et al., 2012).

The fourth step (methanogenesis) plays an essential role in generating methane gas by methanogens. There are two primary mechanisms for methane generation, including acetoclastic (CH3 COOH→CH4+CO2) and hydrogenotrophic methanogenesis (CO2+4H2→$CH_4$+2H2O). Typically, methanogens are extremely sensitive to pH conditions, the presence of oxygen, and other factors such as free ammonia (FAN), $H_2S$, and Volatile Fatty Acids (VFAs) (Geraldi, 2003; Mao et al., 2015; Ramos-Suárez et al., 2015; Van et al., 2020).

Most of the literature on anaerobic digestion uses municipal waste and agricultural waste as substrates. However,Xu et al. (2018) reported that the digestion of food waste has more advantages, such as mitigation of climate change, economic benefits and diversion opportunities. For example, Bartocci et al. (2020) reported that by replacing 9,900 tonnes of corn silage with 6,600 tonnes of food waste, it is possible to reduce $CO_2$ emission by up to 42% of the electricity produced from the biogas plant could be achieved. The benefit of the anaerobic digestion of food waste against agricultural waste creates a strong interest in using fish and algae waste as substrates has been growing since 2018 due to the incredible potential of these sources for the production of biogas through anaerobic digestion.

Fish waste is a complex substrate because the composition of solid and liquid fish processing waste depends on the composition of the fish species used, which in turn depends on the sex, feeding habits, season and health of fish.

These wastes contain high levels of protein (up to 60%), fat (up to 20%) and minerals (calcium and hydroxyapatite from bones and scales), and the high content of fat seems to favour the yielding of the biomethane. An optimised model for anaerobic digestion reported that the production of biomethane can vary from .2 to .9 $CH_4$ $m^3$/kg VS. added by using different forms of fish waste (Kaspars et al., 2018) (Table 1)

Despite the methane production shown in Table 1, using fish waste as substrate can cause operational problems. Indeed, fish waste releases high levels of ammonia when digested, which inhibits the digestion of substrates (Achinas et al., 2017). High ammonia concentrations can result in the accumulation of VFAs (acetic acid as the main type in the batch tests). To mitigate the negative effect of ammonia formation co-digestion process is a possible technological solution. One of the best ways to co-digest fish waste is with agricultural waste or algae, as reported in Table 2. Nazurally (2018) reported that a general accumulation of VFAs was observed for co-digestion of algae and fish, and this phenomenon was due to the high content of fatty acid. The co-digestion is not the only way to control free ammonia formation and the accumulation of VFAs, but they can also be controlled by the reactor, type and organic loading rate and pH (Shi et al., 2017).

Table 2 reports that the digestion of pure algae produces much less methane when macroalgae are processed alone. The co-digestion of algae and fish waste seems an optimal solution for

**TABLE 4 Hydrogen production from light driven fermentation methods.**

| Technology | Basic principle | Microorganism | $H_2$ prod | Efficiency | References |
|---|---|---|---|---|---|
| Photo fermentation | In the presence of light, photosynthetic bacteria convert complex organic microalgal biomass into simpler organic | Photoheterotrophic bacteria (Rhodopseudomona, Rhodobacter) | 160.40 ml/g | 15.93% efficiency in energy conversion | Lu et al. (2021) |
| Direct biophotolysis | In the presence of a direct light source, pigmentcontaining microorganisms are used in a sequence of processes to generate hydrogen from water molecules | Cyanobacteria | > 10% | > 80% | Mona et al. (2020) |
| Dark fermentation | In the absence of light, complex organic microalgal biomass is converted into simpler organic or inorganic components | Fermentative bacteria (*Escherichia coli*, Clostridia, *Enterobacter* | 89.80 ml/gVS | 42.80% | Song et al. (2020) |
| Indirect biophotolysis | In PS I and PS II compartments, sulphur-deficient microorganisms are used in one or more step reactions to generate hydrogen from complex carbohydrates or pyruvate | Cyanobacteria | 10%–15% | 16.30% | El-Dalatony et al. (2020) |

an environmentally and economically sustainable process. The use of pure macroalgae waste in the bioreactor is not economically sustainable due to several technical issues, such as the seasonal growth associated with different types of macroalgae, the variability of the feedstock and operational costs (Ward et al., 2014; Milledge et al., 2019). In addition, the use of marine waste macroalgae produce several problems, such as difficulty in processing material such as polyphenols, cellulosic fibres and lignin-type components. This results in the reduced biodegradability of the biomass by bacterial processes and thus a limiting digestibility and gas production (Briand and Morand, 1997). Microalgae waste could be more valuable if microalgae species were grown as part of a wastewater treatment process, but this review will not discuss it.

## 3.2 Biohydrogen

Biohydrogen generated from a renewable and sustainable source is a clean energy carrier since the combustion process leads to water formation, which creates an attractive energy source compared to other renewable sources. Nowadays, 96% of hydrogen (grey) is produced through carbon-intensive processes, where steam reforming of natural gas accounts for 48% of total production capacity, while petroleum fractionation and coal gasification make up 30% and 18% of production capacity, respectively (Franchi et al., 2020). The remaining 4% of hydrogen is considered green because it is produced by renewable sources and water electrolysis. Considering the actual percentage of green hydrogen, the decarbonisation of hydrogen production (grey hydrogen) is a potential paradigm that can be only solved by implementing carbon capture and storage (CCS) integration (blue hydrogen) or considering the use of clean energy sources (green hydrogen). Using clean energy sources is expected to reduce annual carbon dioxide emissions by nearly 440 million tonnes in 2050 (Nicita et al., 2020).

The conversion of waste biomass represents an inexpensive alternative for bio-hydrogen generation because the technologies used do not require high energy consumption compared to water electrolysis. The electricity cost accounts for 80% of the total cost of hydrogen production by electrolysis (Kapdan and Kargi, 2006).

The methods for biohydrogen production can essentially be categorised into two main classes: The thermochemical conversion (pyrolysis and gasification) route relies on high-temperature operations to degrade biomass wastes to produce biohydrogen, where the types and conditions of feedstocks used can heavily influence the outcome of the products.

The biochemical conversion (dark fermentation and photobiological) fermentation route emphasises more on the physical conditions of the medium (living organisms) and the types of catalysts used. In both processes, the hydrogen must be separated by several technologies, such as absorption, adsorption, membrane separation, and cryogenics separation, irrespective of upstream processing routes (Ren and Toniolo, 2018; Jiménez-Llanos et al., 2020).

Studies on several types of biomass waste reported that hydrogen production *via* the thermochemical pathway seems techno-economic more viable than the biochemical pathways. The thermochemical pathway is proven at a commercial scale, the cost of the catalysts is lower, and the technical challenges are limited compared to the biochemical pathway (e.g., biomass pre-treatment, bioreactor design and restriction to hydrogen), and they are able to achieve overall efficiency in a range between 50%–70% depending on the operating conditions (Dascomb et al., 2013; Kannah et al., 2021).

The gasification process is the most efficient method of hydrogen production from waste products due to the high biomass conversion in the gas phase. Pyrolysis is an ideal method of hydrogen production only at high operating temperatures (over 600°C) and or at low temperatures if the pyrolysis plant is coupled with a steam reforming system able to

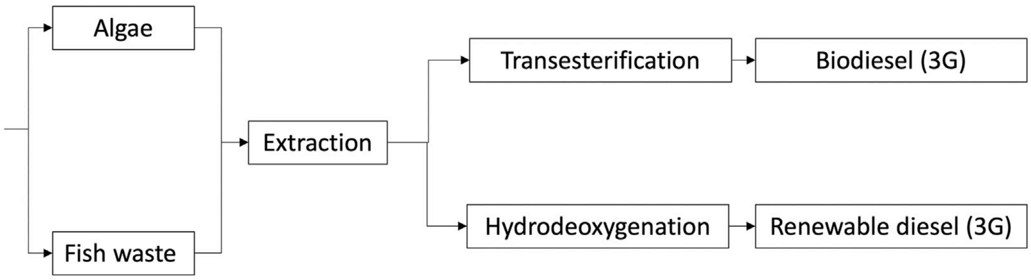



FIGURE 4
Production methods of biodiesel and renewable diesel.

hydrocrack the bio-oil produced. The thermochemical pathways required biomass waste with a moisture content not higher than 20%. The biomass with moisture content higher than 20%, such as fish or algae, must be dried. The procedure requires an additional power source or an optimised heat exchange system to reduce the moisture contained in the waste before being fed into the system. Thus, using waste with higher moisture will reduce the efficiency of the process and increase the production of hydrogen costs. On the other side, fish waste and algae are inexpensive biomass waste that produces a third-generation of biofuel at low cost. Recent studies on fish waste and algae are easy to process and obtain bio-oil or syngas as precursors in synthetic fuel production. Rowland et al. (2009) successfully demonstrated that fish waste with high moisture content could easily gasify fish waste with dried pellet wood to control the moisture level upstream of the gasifier reactor. The study also demonstrates that adding fish to the pellet wood reduces the High Heating Value (HHV) of the syngas produced, which is still high enough to make this process feasible in rural areas or for local use. Reza et al. (2022) successfully demonstrated that fish waste could easy be gasified into syngas at high temperatures without reducing the moisture content of the biomass. They reported the high syngas production and, thus, hydrogen was achieved operating at a temperature over 600°C. The high temperature favoured the cracking reaction of bio-oils contained in the fish and produced during the pyrolysis process, consequently increasing the fraction of gas produced up to 43% at 600°C. The percentage can be increased by increasing the temperature and ramp rate moving from conventional pyrolysis to a fast pyrolysis process. However, they also reported that using fish waste as feedstock produces a high amount of ash that must be removed during operations, which can affect the operating costs and, consequentially, the biofuel costs. Cao et al. (2020) reported that steam gasification is one of the most efficient processes to produce syngas and hydrogen using biomass with higher moisture content. The process is suitable for large-scale industrial production with a high gasification rate and low ash production. The utilization of a catalyst in this process reduces the operating temperature and favours the gasification process. The introduction of steam increases hydrogen production. However, the process has challenges that must be faced up, such as decreasing the tar contents, optimising the composition of the catalyst to minimise the deactivation, and reducing the energy and material costs. Duman et al. (2014) reported that the feasibility of steam gasification was affirmed by using micro and macroalgae as feedstock. The studies conducted showed that the hydrogen production capacity of macroalgae was much higher than that of microalgae. The maximum hydrogen production depends on the inorganic content of raw materials in macroalgae (18%), which favours gasification and could reach 1,036 ml/g of hydrogen production against 413 ml/g from microalgae.

The studies on biomass gasification reported successful studies on fish and algae waste. The studies report that gasification is a promising technology for hydrogen production and operating parameters such as steam/biomass, pressure temperature and water contents) that drastically affects hydrogen production, as reported in different studies (Han et al., 2013; Iovane et al., 2013; Zhang et al., 2015a).

Thermochemical processes of biomass are a mature and efficient process for converting both dry and wet biomass, but this requires high temperatures and biomass pre-treatment to feed wet biomass. Hence, the scientific community is focusing on developing a biochemical process that has the advantages of using low operating temperatures and microbial to convert wet biomass such as algae and fish waste into biohydrogen. They are still under investigation and have been proven mainly at the lab scale.

Nowadays, thermochemical conversion is the only one mature technology able to produce large amount of biohydrogen. However, this technology can compete with conventional fossil fuel (price below $2.00/kg) only if the cost of the waste biomass has a gate fee that could range anywhere from $50-$75/tonnes and the size of the gasification plant is 150 MW. Above this value the biohydrogen cost can vary between \$2.80/kg (Binder et al., 2018; Shahabuddin et al., 2020). Fish and algae waste are low-cost feedstock which could thermochemically converted into low-cost hydrogen.

Biohydrogen production by biological conversion is a promising technology due to the low operating temperature and by-product formation. However, state of the art, this technology has been proven only in a laboratory-scale, and its efficiency strongly depends on the type of technology used. The highest efficiency achieved with the biological conversions is 80% using Direct Bio-Photosynthesis and 42.80% using dark fermentation.

The predicted cost to produce Biohydrogen by biological conversion are calculated by the assumption, and the hydrogen cost can change from \$2.13/kg for direct photosynthesis to \$7.53/kg for dark fermentation (Forrunque-Ahmed et al., 2021). Although the predicted hydrogen cost productions are comparable to the thermochemical conversion this technology is still not mature to compete for thine biohydrogen production due to technical challenges to face up.

Indeed, the most developed biochemical processes are dark fermentation (DF) (light independent) and photolysis (light dependent). They are still in the demonstration phase due to the low hydrogen production. It will be essential to reduce the reactor cost and investigate different geometry to improve the performance and reduce the production cost. The feedstock cost is also considered an important parameter in lowering the cost of hydrogen. Among all these processes, photo and dark fermentation are essential to biological hydrogen production technologies. Of the two methods mentioned above, DF is the most studied and promising technology for biohydrogen production owing to its higher production rates and treatment capacity for organic wastes. DF can convert several types of substrates, including waste products rich in carbohydrates and fatty acids. At present, the DF process is not mature, and the development at the industrial scale is limited due to the lower hydrogen yield compared to its theoretical maximum yield of 4 mol of $H_2$ per mole of hexose, as well as the estimated costs associated with the $H_2$ production. The production cost in a scaled-up system can be minimised by pre-treatment of substrates, enrichment of inoculum and low-cost feedstock. Dark fermentation has been suggested as more practical than the other processes as it does not require external energy to drive the process or a large surface area to capture the necessary light. It can take advantage of existing reactor technologies to utilise organic wastes as feedstock (Han and Shin, 2004; Perera et al., 2010) (Table 3).

Dark fermentation is a complex system where environmental factors and bioreactor operation conditions such as temperature, pH and $H_2$ partial pressure control metabolic pathways of hydrogen-producing microorganisms. Furthermore, we need to consider other parameters, such as substrate types and their pre-treatment methods, bioreactor configurations, inoculum sources and enrichments that influence biohydrogen production. The complexity of the system requires that different challenges have to be overcome, such as energy balance and COD conversion and improved solid-state fermentation, which has demonstrated higher hydrogen production (Ghimire et al., 2015a, 2015b). This technology is promising to produce biohydrogen, but it still requires a lot of investigations to be economically viable on a large scale. Many researchers have documented that the $H_2$ production from wastewater, organic waste or biomass by biochemical path has the potential to reduce $H_2$ production costs (Das and Veziroğlu, 2001; Chang et al., 2011).

Differently from dark fermentation, photo-fermentation and biophotolisys are two light-driven processes in which carbon sources are converted to biohydrogen using photosynthetic bacteria. A key addition to the whole process is light energy, natural or artificial. The photo-fermentation uses photosynthetic bacteria, mainly called purple non-sulphur bacteria (PNS bacteria). Rare, green bacteria and purple bacteria are used too. The light energy is used to oxidise the carbon source and produce electrons. PNS bacteria (and the other bacteria that can be used) synthesise nitrogenase or hydrogenase enzymes. The methods take place in anaerobic conditions, and nitrogenase under anaerobic conditions use electrons and ATP (Adenosine triphosphate) and produces hydrogen and ADP (Adenosine diphosphate), as described by the Eq. 1 (Rahman et al., 2016).

$$2H + 2e^{-} + ATP \rightarrow H_2 + 4ADP + Pi \quad (1)$$

Operating conditions (i.e., pH, temperature and light intensity) depend on the specific bacteria used and the converted feedstock.

Biophotolysis uses microorganisms such as cyanobacteria or microalgae to produce biohydrogen from water. A key factor for this method is sunlight, which is essential for the system to make biohydrogen. Water is not the only reactant that can be used in these processes. Glucose as well as other organic matter, can be used in biophotolytic processes. This method of hydrogen production has been applied in different ways through the years, mostly at the laboratory scale. Biophotolytic processes can be categorised into two main categories: direct biophotolysis and indirect biophotolysis. The general chemical reaction that describes these two processes is given by reaction Eq. 2 (Anto et al., 2020).

$$2H_2O + Light\ energy \rightarrow 2H_2 + O_2 \quad (2)$$

In direct biophotolysis, the photosystem absorbs the light energy and transports electrons to ferredoxin, reducing the water molecule. The reduced ferredoxin can transport electrons to hydrogenase (biohydrogen-producing enzyme). After that, hydrogenase catalyses the conversion of a proton to biohydrogen, according to the reaction Eq. 3, (Mona et al., 2020).

$$2H^{-} + 2FD^{-} \rightarrow H_2 + O_2 \quad (3)$$

The oxygen produced acts as an inhibitor for the hydrogenase enzyme and is a major problem in direct biophotolytic systems.

Indirect biophotolysis is a process that takes place in two stages. In the first stage, the photosynthetic system produces a large amount of biomass to increase the amount of carbohydrates. In the second stage, biomass-rich carbohydrate is utilised as carbon sources. This carbon source plays a similar role to water in direct biophotolysis. This second stage has some similarities with anaerobic fermentation processes. The advantage of indirect photolysis compared to direct photolysis is that oxygen generation is separated from the stage of hydrogen evolution, so oxygen is not inhibiting the $H_2$ evolution (Rahman et al., 2016; Mona et al., 2020). Table 4 summarises the various biological hydrogen production processes with general technical information involved therein broad classification of microorganisms used with their relative advantages.

Photo fermentation was coupled with dark fermentation to convert residue from anaerobic digestion from fish waste into biohydrogen (Melitos et al., 2021). Ghimire et al. (2015c) reported that connecting the DF-Photo Fermentation reduces the control of operating parameters such as pH and the process impacts on the energy yield reaching 55 MJ/kg volatile solid food waste, adding a synergistic effect to the overall energy recovery during the conversion of food waste.

Biophotolysis is the main use to process hydrogen from water. The process has also been applied to wastewater and improved water quality in the aquaculture system. Malara et al. (2017) use photolysis to inactivate *vibrio* species (pathogens) in aquaculture.

## 3.3 Biodiesel and renewable diesel

One of the biggest challenges today is to produce a large amount of sustainable biofuel to decarbonise the heavy transportation sector and achieve the zero-emission target by 2050. Biodiesel and renewable diesel seem to be the more suitable fuel for their physical chemistry properties to replace fossil fuels. However, their economic and environmental sustainability is highly affected mainly by the feedstock type and the oil extraction method, which are responsible for the overall biodiesel and the catalyst used and for production methods and the catalyst. The utilization of edible oils (vegetable oil) is too costly and negatively impacts the environment and society (Sumathi et al., 2008). Utilising non-edible oil plants does not provide enough oil to satisfy the energy demand, and the extraction of the oil from the plant seed is complex (Hamza et al., 2020). Studies have shown that waste feedstock rich in oil, such as fat animal waste (e.g., fish waste) and algae, are potential renewable low-cost fuel sources of interest (Aniokete et al., 2022; Douvartzides et al., 2019; Madeen et al., 2021). Fish waste and algae waste from aquaculture are low-cost feedstock and have demonstrated that they can be easily converted into biofuel with minimal economic and environmental impact (Abomohra et al., 2018; Papargyriou et al., 2019).

Fish and algae waste are two sources rich in oils. The amount of oil contained depends on the type of fish and algae. Depending on the extraction methods, it is possible to extract up to 25 wt% of oils in fish waste, and 10 wt% and 60 wt% of oil from macroalgae and microalgae oils (Zhaohui et al., 2020; Gosch et al., 2012). The oil is extracted using several methods, such as wet rendering, enzymatic hydrolysis, autolysis, dry rendering, solvent extraction, and supercritical fluid extraction (Dumay et al., 2004; Falch et al., 2006; Rai et al., 2010; Ghaly et al., 2013; Jayasinghe et al., 2013; Oliveira et al., 2013; Suseno et al., 2015). While the algae oil is extracted using the Soxhlet apparatus and hexane solvent (Aravind et al., 2020). The studies reported showed that supercritical and microwave-assisted technologies are the most appropriate technologies to extract oil from waste. These technologies demonstrated a high oil recovery efficiency, lower cost, and high environmental sustainability (Zulqarnain et al., 2021). The purified oil can then be converted accordingly to the type of fuel desired. The extracted waste can produce third-generation biodiesel (Fatty Acid Methyl Ester) and renewable diesel (long-chain hydrocarbons). There are two main mature routes for the production of biodiesel and renewable diesel from marine, aquaculture, fish industry and algae, which are transesterification and hydrodeoxygenation (Figure 4).

The transesterification reaction of fish oil or algae oil with low molecular weight alcohols in the presence of a catalyst oil produces Biodiesel (FAME), a biodegradable fuel (Wu and Leung, 2011; Sharmila et al., 2021). The utilization of waste oil makes the production of biodiesel more economically and environmentally sustainable biodiesel (Rajendran et al., 2022). However, the process requires a high energy demand for biodiesel purification and recycling of large volumes of alcohol when it is carried out using homogeneous catalysis (Falch et al., 2006; Tanwar et al., 2013). The recent study focused on using a more sustainable method, replacing the homogenous catalyst with a heterogeneous catalyst based on alkaline Earth oxide (Marinković et al., 2016). Papargyriou et al. (2019) and Mahdavi et al. (2015). The heterogeneous catalysis showed comparable performance compared to the homogenous catalysis, but it has the advantage of reducing energy consumption and operating cost, producing high-purity biodiesel by reusing the catalyst for many cycles (Lee et al., 2014; Knothe and Razon, 2017). Enzymatic catalysts have also been investigated as possible heterogeneous catalysts for the conversion of fish waste oil with success. The utilization of enzymes allows the production of very pure biodiesel, which could further reduce the cost of biodiesel production. However, the enzymatic reactions show a slow reaction rate, and the high cost of the catalysts doesn't make it a commercial pathway for biodiesel production (Angulo et al., 2020).

Biodiesel production is proven at a commercial scale, and the size of the plant does not affect the price of its sustainability. This means that the plant can also be scaled up accordingly with the amount of feedstocks available locally. The main problem associated with the use of biodiesel is its low oxidation stability, poor cold flow properties and low energy content. This required that biodiesel has to be blended with fossil fuel to improve its properties and can be distributed using existing infrastructure (Knothe and Razon, 2017).

Differently from biodiesel, Renewable diesel is a mixture of long-chain hydrocarbons) with a composition like diesel derived from fossil fuels. This makes green diesel highly stable due to the absence of double bonds in its structure, and more valuable than biodiesel because it has a higher cetane number and a higher heating value than FAME biodiesel and has similar fuel properties to petroleum-diesel. This means that green diesel can replace diesel-derived fossil fuel and can be delivered using existing infrastructure (Miller and Kumar, 2014).

Hydrodeoxygenation (HDO) is a catalytic chemical process that uses hydrogen to decarboxylase the methyl ester for a stable long-chain hydrocarbon with the same characteristics as diesel derived from fossil fuel. HDO of bio-oil generally occurs under high pressure (7 MPa–20 MPa) and high temperature (200°C–400°C) conditions to increase the amount of effective hydrogen in bio-oil and reduce the oxygen content, thereby ameliorating the physical and chemical properties of bio-oil. Oxygen is removed in the form of $CO_2$ or $H_2O$, meanwhile, the unsaturated bonds become saturated (Qu et al., 2021).

The hydrodeoxygenation process has the advantages of guaranteeing large conversion, better selectivity, high stability product. However, the process requires highly harsh conditions, a complex equipment system, blockages of the reactor due to the production of high molecular weight wax and deactivation of the catalyst (Qu et al., 2021). The catalysts are the main components of this process because they guide the performance of the process. Transition metals such as Ni, Mo, Co., Zn, Ce, Nb, Fe, and Cu, among which Ni and Mo are generally used as the main active metals (Wang et al., 2015; Hong and Wang, 2017; Yang et al., 2018). The Mo-based catalysts displayed high arene selectivity, while the Ni-based catalysts mainly saturated the aromatic ring in liquid-phase reaction conditions (high hydrogen pressure) (Zhang et al., 2020).

Renewable diesel is produced by the hydro-deoxygenation of vegetable oils, and it is a mature and certified technology at a large scale. However, some gaps still need to be filled, such as selecting the suitable and best catalyst, inexpensive feedstock and studying the mechanism of the reaction. Several studies have been conducted to prove that waste material reduces the production cost, particularly when fat animal waste is used (Toldrá-Reig et al., 2020). However, the hydrodeoxygenation process of algae waste seems not to be economically sustainable due to the highest impact on the water scarcity footprint and the unit production cost (Madeen et al., 2021).

Despite the several challenges and problems related to this technology, the Techno-economic Analysis and Life-Cycle Analysis of Renewable Diesel Fuels Produced with Waste Feedstocks carried out from Longwen et al. (2022) highlight as the use of waste feedstock is still crucial for the production costs and for the Greenhouse gas emissions. However, the main challenge for this technology is the process scalability elated to the viability of large-scale production because distributed waste resources are a well-known feature for any conversion strategy using a waste resource.

# 4 Production of bioderivatives from fish-aquaculture waste and algae bloom

## 4.1 Proteins and peptides

### 4.1.1 Fish hydrolysates for the generation of biologically active peptides

Fish protein hydrolysates (FPH) can be obtained from fish processing waste (skin, muscle, head, viscera, and bones), representing a good source of protein, peptides, and amino acids. FPH contain bioactive peptides with a wide range of biological activities, such as antioxidant, antimicrobial, anti-hypertensive, antitumoral, anti-inflammatory, anticoagulant, and antidiabetic. Furthermore, it has been reported that the nutritional properties of FPH are superior to other protein hydrolysates because fish proteins are abundant in essential amino acids like lysine and valine (López-Pedrouso et al., 2020; Korkmaz and Tokur, 2022). The production of bioactive peptides includes several steps involving chemical or enzymatic hydrolysis, and the purification of the hydrolysate proteins. Fish hydrolysates could be used as commercial sources of bioactivity; however, it has been reported that biological activities are superior in purified peptides. The purification of protein hydrolysates has been investigated by several techniques such as ultrafiltration (UF), ion exchange chromatography, reverse phase high-performance liquid chromatography (RP-HPLC) and gel filtration (GF) (Ishak and Sarbon, 2018).

However, purification at industrial levels could be economically feasible only for high added value products, such as peptides for pharmacology proposes, due to the high production cost.

The common treatments to recover the bioactive compounds from fish wastes are chemical and enzymatic hydrolysis (Table 5) (Idowu et al., 2021). In chemical hydrolysis, acid or alkali conditions are used at high temperatures; the process is low-cost and fast. However, the hydrolyzed products have high variations in the amino acid profile. In enzymatic hydrolysis, lower temperatures and pH values are used. Even though this process is long and expensive, enzymatic hydrolysis produces

**TABLE 5 Extraction conditions of polysaccharides and proteins from aquaculture and marine waste.**

| Source | High-value product | Extraction Methods | Extraction conditions | Yield | References |
|---|---|---|---|---|---|
| Fish waste | Collagen | Enzymatic hydrolysis (protease) | 180 min, 50°C, and pH 8 | DH (25%) | Araujo et al. (2021) |
| Scales | Collagen | Chemical hydrolysis | Acetic acid .5 M stirring 24 h | 13.6% | Chinh et al. (2019) |
| Spine | Collagen | Enzymatic hydrolysis | 60 min, 200 rpm, 60°C, pH 8 | | Morimura et al. (2002) |
| Loach skin (*Misgurnus anguillicaudatus*) | Acid Soluble collagen | Enzymatic (pepsin aided) and chemical (acetic acid) | .5 mol/L acetic acid 24 h 4°C | 22.42% | Wang et al. (2018) |
| Channel catfish (*Ictalurus punctatus*) skin | Collagen type I | Enzymatic (pepsin aided), Homogenization-aided, and chemical (acetic acid) | HCl pH 2.4 h (100 rpm) | 64.19% | (Tan and Chang, 2018) |
| Skin of Golden Carp (Probarbus Jullieni) | Collagen type I | Chemical and enzymatic | Acetic acid .5 M Containing Porcine pepsin (50 $g^{-1}$) | 4.13% | Ali et al. (2018) |
| Skin of Pacific bluefin tuna | Collagen type I | Chemical and enzymatic | Acetic acid .5 M 24, pepsin 3,130 U/mg solid 48 h | 5.4% | Tanaka et al. (2018) |
| Skin of Cod Fish | Collagen type | Eutectic Solvents (DESs) | Choline chloride–oxalic acid 4 h, 45°C | 91.69% of the total | Bai et al. (2017) |
| Whole fish, skin, and head from North West Spain fishing fleet | Fish Protein hydrolysates with bioactive peptides | Enzymatic hydrolysis | pH 8.65, 60°C alcalase (1% v/w) 200 rpm, 4 h | Protein Content (69.8%–76.6%) Yield (83.4%–97.3%) | Henriques et al. (2021) |
| Rainbow trout (skeleton, fin, head, skin, and viscera) | Fish hydrolysates | Enzymatic hydrolysis | Protamex, 1 h, 1% enzymatic ratio, pH 7 | 74.30 Degree of Hydrolysis (DH) (%) Protein Recovery 83.43% | Korkmaz and Tokur, (2022) |
| Whiting (head and viscera) | Fish hydrolysates | Enzymatic hydrolysis | Alkaline protease, 60°C, 1 h, 1% enzymatic ratio, pH 8 | 57.46 (DH %) Protein Recovery 95.22% | Korkmaz and Tokur, (2022) |
| Anchovy (head and viscera) | Fish hydrolysates | Enzymatic hydrolysis | Flavourzyme Enzymatic ratio 1% 1.42 h, pH 7 | 68.23 (DH %) Protein Recovery 82.89% | Korkmaz and Tokur, (2022) |
| *Sargassum latifolium* | Fucoidan | Acid extraction | 2% citric acid, 2 h, 30°C | 10.1% | Gomaa et al. (2018) |
| *Fucus serratus (FS), Fucus Vesiculosus (FV),* and *Ascophyllum nodosum (AN)* | Fucoidan | Acid extraction | M HCl, 80°C, 4 h, pH 5–7 | 6.0, 9.8, and 8.0 wt% | Fletcher et al. (2017) |
| *Laminaria japonica* | Fucoidan | Acid extraction | 4 h, 80°C .1 M HCl | 17 wt% | Zhang and Row, (2015b) |
| *Durvillaea potatorum* | Fucoidan, laminarin and alginate | Acid Extraction Before Alkaline extraction | .05 M HCl, 60°C 3 h | 47.53% w/w | Abraham et al. (2019) |
| *Focus vesiculosus* | Fucoidan | Microwave extraction | 10 mM Sulfuric acid, 30 min, 120°C | 11.10% | Ptak et al. (2019) |
| *Kjellmaniella crassifolia* | Fucoidan | Enzymatic extraction | Cellulolytic Enzyme cocktail, 1:4.29 enzyme ratio, and 10 h | 4.74% | Tang et al. (2022) |
| *Saccharina latissima* | Laminarin | Cross-flow filtration | Ceramic Membrane with 5 kDa, 15 kDa, and 50 kDa molecular weight cutoffs | | (Sterner and Gröndahl 2021) |
| *Focus vesiculosus* | Laminarin | Microwave extraction | 100 mM HCl, 30 min, 120°C | 8.68% | (Ptak et al 2019) |
| *Sargassum seaweed* | Alginate | Alkali extraction | $Na_2CO_3$, 6 h 80°C | 20.76% | Mohammed et al. (2020) |
| *Saccharina latissima* and *Ascophyllu nodosum* | Alginate | Acid treatment acid extraction | .2 M HCl | 11.2% | Bojorges et al. (2022) |

(Continued on following page)

**TABLE 5 (*Continued*) Extraction conditions of polysaccharides and proteins from aquaculture and marine waste.**

| Source | High-value product | Extraction Methods | Extraction conditions | Yield | References |
|---|---|---|---|---|---|
| *Ascophyllu nodosum* | Alginate | Acid treatment acid extraction | .2 M HCl | 13.8% | Bojorges et al. (2022) |
| *Sargassum latifolium* | Alginate | Acid extraction alkaline treatment | 2% citric acid, 2 h, 30°C, $Na_2CO_3$ 2% for 3 h 40°C | 44.26% | Gomaa et al. (2018) |
| Shrimp shells | Chitin and chitosan | Chemical extraction | 1.0 M HCl 3.0 M NaOH, 75 min, room temperature | | Srinivasan et al. (2018) |
| Shrimp shells | Chitosan | Chemical extraction | 1 N HCl 65°C, 2 h 3.5% NaOH | 12.93% | Al-Manhel et al. (2018) |
| Mud crab shells | Chitosan | Chemical extraction | 1.0 M HCl 3 h, room temperature 5% NaOH 6 h, 90–95°C | 17.9% | Narudin et al. (2022) |
| Shrimp waste | Chitosan | Chemical extraction | 2 N HCl, 2 h, room Temperature 2 N NaOH, 2 h, 50°C | 12.03% | Varun et al. (2017) |
| Waste shrimp shells | Chitosan | Citric acid Demineralizati on, enzymatic deproteinization | 10 wt% citric acid, 1 h, papain and bromelain 1 wt%, pH 740°C, 6 h | 19% | Pérez et al. (2022) |
| Waste shrimp shells | Chitosan | Biological demineralization | Lactic acid And Proteolytic enzyme | 32.12% | Marzieh et al. (2019) |

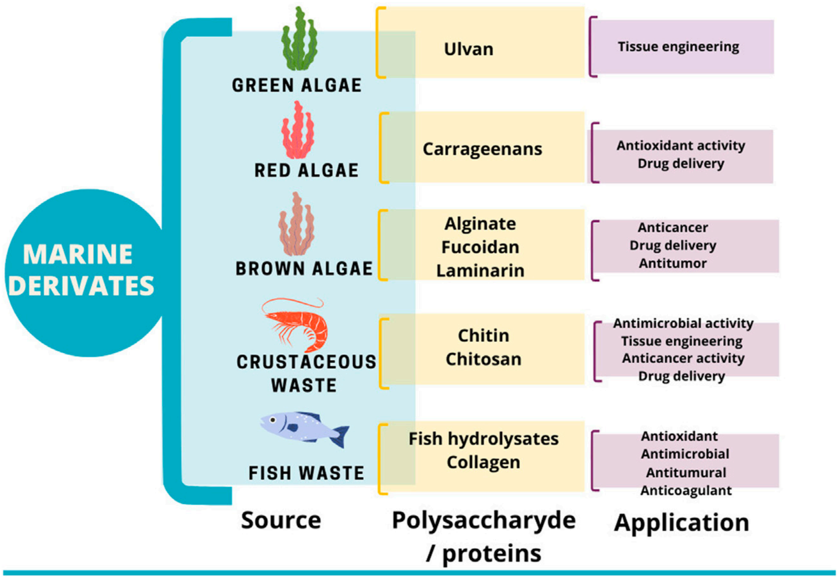



FIGURE 5
Polysaccharides and proteins extracted from aquaculture and marine wastes and their applications.

high-quality FPH. Numerous commercial enzymes have been used, such as alcalase, flavourzyme, papain, protamex, pronase (Siddik et al., 2021). Korkmaz and Tokur (2022) hydrolysed fish wastes from trout, anchovy, and whiting to produce fish proteins. They compared three commercial enzymes (alkaline protease, Protamex, and flavourzyme) and optimized the hydrolysis conditions (time, enzymatic ratio, temperature) for protein production. The highest protein content was obtained from the head and viscera of whiting (95.22%) with alkaline protease. They concluded that the degree of hydrolysis and protein recovery depends on fish species, waste composition, hydrolysis method, and enzyme. Henriques et al. (2021) characterized protein hydrolysates from the most discarded species by the North-West Spain fishing fleet (gurnard, Atlantic horse mackerel, blue whiting, red scorpionfish, pouting, and four-spot megrim). They used whole fish, skin, bones, and head and enzymatic hydrolysis using alcalase. The maximum yield of FPH and protein was achieved with the skins and bones, 97.3% of FPH yield with blue whiting, and 76.6% of protein. Also, the hydrolysates contained all the essential amino acids; glutamic and aspartic acids were the most abundant. Nevertheless, most enzymes used for hydrolysis have different specificities that are difficult to control or standardize. Subsequently, searching for proteases with higher activity and substrate specificity is essential. Further, it is important to mention that almost all the investigations have been confined to small scale because of the high cost of the enzymes (Figure 5).

### 4.1.2 Collagen

Collagen is a natural material with excellent biocompatibility and biodegradability (Bai et al., 2017). There are at least 29 types of collagens, and among these, the most common is type 1. This collagen has multiple applications in the cosmetic, food, medicine, and pharmaceutical industries (Wang et al., 2018). Collagen can be obtained from pig skin, pork, cattle bones, and other mammalian sources. Nevertheless, this material is also present in marine organisms such as fish and sponges (Subhan et al., 2021). Marine collagen has multiple advantages; for example, it can be consumed by people with religious restrictions because marine animals are not affected by infectious diseases. Also, marine collagen has lower thermal denaturalization temperature than collagen from pigs or cows (Tanaka et al., 2018). In the fishing industry, only about 25% of the total fish weight is used, with 75% of waste containing skin, bone, and scale that could produce collagen (Srikanya et al., 2017). Fish is rich in type I collagen, and the yield and properties depend on the extraction method and the raw material (Table 5). Although the yield from marine collagen is lower than from mammalian sources, different studies have been done on the improvement. For collagen extraction, two principal operations have been reported. In the first one, gelatin is obtained by a chemical pre-treatment with dilute acid or alkali. Afterward, the gelatin's enzymatic hydrolysis (using pepsin) produces the collagen peptides (Bai et al., 2017). Wang et al. (2018) used skin loach for the extraction of acid-soluble collagen (ASC) and pepsin-soluble collagen (PSC) and obtained yields of 22.42% and 27.32%, respectively. They used .5 mol/L acetic acid and pepsin (1,200 u/g) for the extraction, and the temperature of denaturalization of the obtained collagen was similar to the porcine skin collagen. Tan and Chang (2018) used catfish skins by acid, homogenization-aided, and enzymatic methods, and their recovery rate was 64.19%. However, it is difficult to separate the proteins after the alkali or acid treatment. Besides, the enzymatic process enhances the total cost of production because enzymes are expensive and cannot be reused. Therefore, new methods have been developed. Bai et al. (2017) used deep eutectic solvents for collagen extraction from cod skins. These solvents are biocompatible and environmentally friendly. Choline chloride (ChCl) was used, and under optimal conditions, the extraction efficiencies were up to 91.57%–96.01% of the total collagen peptides in only 2 h.

## 4.2 Polysaccharides

### 4.2.1 Fucoidan

Fucoidan is a polysaccharide composed of L-fucose and sulphate groups found in brown macroalgae (Luthuli et al., 2019). *Ascophyllum nodusum, Undaria pinnatifida*, and *Ecklonia cava* macroalgae have been reported as the richest sources of fucoidan (Abdel-Latif et al., 2022). The principal application of fucoidan is in the pharmaceutical industry because of its anticancer, anticoagulant, anti-inflammatory, antiproliferative, and immunomodulatory activities (Wijesinghe and Jeon, 2012). Another application of fucoidan is in aquaculture. Multiple authors have reported using fucoidan in the dietary supplementation of aquafeed. Fucoidan could be used as a growth promotor, antiviral agent, antioxidant, toxicity modulator, and to improve resistance against bacterial pathogens (Abdel-Latif et al., 2022). Regarding fucoidan production, the extraction consists of an initial purification using alcohol, an extraction step using acid, and final precipitation using ethanol (Fletcher et al., 2017). However, environmental technologies such as microwave-assisted and enzyme-assisted extraction have also been reported. For example, Ptak et al. (2019) used a microwave-assisted extraction to improve the fucoidan yield from Fucus genus. They found that fucoidan yield is maximized by extraction with 10 mM sulfuric acid, obtaining a yield of 11.10%. Tang et al. (2022) used an enzymatic-assisted extraction using a cocktail of cellulose, and they reported a yield of 4.74% for fucoidan extraction from *Kjellmaniella crassifolia*. Higher yields have been reported with acidic extractions. Zhang and Row (2015b) identified the best condition for fucoidan extraction from *Laminaria japonica*, and they obtained a yield of 17 wt% with an acidic treatment using HCl. According to season, specie, maturity and location, it has been reported that fucoidan structure is different. Fletcher et al. (2017) studied the seasonal variation of three species of brown macroalgae: *Fucus serratus* (FS), *Fucus vesiculosus* (FV), and *Ascophyllum nodosum* (AN) harvested on the coastal of Aberystwyth United Kingdom. The average content was 6 wt%–9.8 wt%, with the highest content in autumn. Abraham et al. (2019) developed and optimized a process for the extraction of multiple polysaccharides (fucoidan, alginate, and laminarin) from *Durvillaea potatorum* (giant bull kelp), using an acidic extraction before the conventional alkali extraction. They reported a higher yield (43.53% w/w) of the total polysaccharides compared with the traditional process for a single alginate product (38.97% w/w).

### 4.2.2 Alginate

Alginate is the primary cell wall component in brown seaweeds (17%–45% of the dry weight), and it is a polysaccharide formed by two monomeric units [β-D mannuronic acid (M) and α-L guluronic acid (G)] (Abraham et al., 2019; Bojorges et al., 2022). The algae variety and growing conditions affect the structure and composition. The principal sources of alginate are *Macrocystis pyrifera* from California and *Ascophyllum nodosum* from the North Atlantic (López-Pedrouso et al., 2020). Alginate is broadly used in different fields such as the cosmetic, pharmaceutical, food, and textile industries due to its gelling, film-forming, and emulsifying properties (Gomaa et al., 2018). It has also been reported that alginate has potential prebiotic activity and can decrease cholesterol levels (López-Pedrouso et al., 2020). Alginate production follows an acid and alkaline treatment by a precipitation or flocculation method, principally by adding sodium chloride and isopropanol. Also, some authors have reported a pre-treatment with formaldehyde (Table 5). For example, Mohammed et al. (2020) extract alginate from *Sargassum* seaweed using formaldehyde, acid treatment with sulfuric acid, and alkali extraction. They used a response surface methodology to optimize the extraction process; the optimum conditions were $Na_2CO_3$ 3.75% (w/v) for 6 h at 80°C, with a yield of 21.21%. Even when formaldehyde is used to improve the quality of the polysaccharides or as a preservative, it should be considered toxic, allergenic, and possibly carcinogenic. For these reasons, diverse authors have designed extraction technologies without formaldehyde. Bojorges et al. (2022) extracted alginate from *Saccharina latissima* and *Ascophyllum nodosum*. Produced alginates had a comparable composition as commercial alginates; also, after the first treatment, a high potential as a bioactive ingredient was found due to a high content of sulphated fucoidan and polyphenols. Gomaa et al. (2018) extracted alginate from *Sargassum latifolium* using citric acid for an acid extraction, followed by an alkali treatment using $Na_2CO_3$. Under the extraction conditions, the yield of alginate was 44.26%.

### 4.2.3 Chitin and chitosan

Chitin is a linear polysaccharide formed mainly of β- (1 → 4)-linked 2-acetamido-2-deoxy-β-D-glucopyranose units and partially of β-(1 → 4)-linked 2-amino-2- deoxy-β-D-glucopyranose (El Knidri et al., 2018). It is the second most abundant natural biopolymer, found in fungi, insects, algae, and crustaceans (Lionetto and Corcione, 2021). The composition of chitin is different between organisms. Three crystalline forms, α-, β-, and γ-chitin, differ in orientation, degree of orientation, number of chains, and unit size. In crustaceans and algae, the α-chitin crystalline structure is the most abundant form. This structure is the most stable and has a remarkable stability (Pellis et al., 2022). Advantages such as biodegradability, biocompatibility, and non-toxicity make chitin and its derivative chitosan widely used in medicine, pharmacy, textiles, cosmetic, and food industries (Marzieh et al., 2019).

Crustaceans are the principal source of chitin extraction. Crustacean's shells contain 20%–30% of chitin, 30%–40% of proteins, 30%–50% of calcium carbonate (Kumari et al., 2015). However, it has been reported that shrimp has a higher percentage of chitin and is a more suitable choice than crabs, in terms of high average molecular weight. Generally, the extraction process is chemical or biological and involves three major steps: demineralization, deproteinization and deacetylation. In the chemical extraction, the demineralization is done by acid treatment using HCl, $HNO_3$, and $H_2SO_4$, the deproteinization by alkaline treatment using NaOH or KOH, and the deacetylation by alkaline treatment using a strong NaOH or KOH. The principal advantages of this extraction are a short processing time and a high depolymerization degree of the final product, making them the method used on an industrial scale. However, it is considered environmentally unfriendly due to the solvents employed. Biological extraction treatments are an alternative, using lactic acid in the demineralization, proteases in the deproteinization, and chitin deacetylase for the deacetylation (El Knidri et al., 2018). Pérez et al. (2022) developed an eco-friendly process for chitosan production from waste shrimp shells. They used citric acid and enzymatic deproteinization using papain and bromelain, and their process had a 24% lower water consumption than the traditional process. In addition, an increment of 10% in chitosan yield was achieved. Marzieh et al. (2019) used a biological extraction using lactic-acid and proteolytic enzymes, followed by mild alkali treatment. The combination of these treatments exhibited a yield of 32.12% for the chitosan, making it a good strategy as a greener method for chitosan extraction.

### 4.2.4 Other polysaccharides: Carrageenan, laminarin, and ulvan

Carrageenan, a sulphated polysaccharide in the cell wall of red seaweeds (30%–75% of dry weight), is formed by alternate units of D-galactose and 3,6-anhydrogalactose. Carrageenan is principally produced from the red seaweed species *Eucheuma,* *Gigartina, Chondrus*, and *Hypnea.* At least 15 different structures have been reported. However, the most relevant are κ-, λ-, and *i*-. The structure could be modified depending on the seaweed species, growing conditions, and the extraction process (Rudke et al., 2020). Because of their properties, such as gelling and hydrocolloid, they are mainly used in the food industry. Additionally, several biological activities have been reported to exhibit, such as anti-HIV, antithrombotic, anticoagulant, anticancer, and antioxidant (Qureshi et al., 2019). Moreover, properties such as biocompatibility and high adsorption of water made it a good candidate for drug delivery systems (Khan et al., 2017). The common extraction method is under hot alkaline conditions, followed by filtration and alcohol precipitation (Qureshi et al., 2019). However, greener methods have been reported in recent years, such as microwave-assisted extraction, ultrasound-assisted extraction, photobleaching, enzyme-assisted extraction, and pressurized solved extraction (Rudke et al., 2020).

Ulvan is a sulphated polysaccharide extracted from the green algae "*Ulva lactuca*." This polysaccharide possesses attractive gelling and antioxidant properties (Guidara et al., 2019; Kidgell et al., 2019). Also, other biological activities, including immunomodulating, anticancer, and antiviral, have been reported. Consequently, ulvan is increasing its interest as a constituent in biomedical products and agriculture (Konasani et al., 2018). Similarly, to other polysaccharides, the yield and quality depend on the extraction and purification procedure and the source. Guidara et al. (2019) compared chemical extraction with enzymatic chemical extraction. They reported a high ulvan yield after the enzymatic chemical extraction 17.95%, whereas the yield was 14.22% with the chemical extraction.

Laminarin is a polysaccharide in brown macroalgae and represents up to 35% of dry weight. However, the average content of laminarin for different species of brown macroalgae is 10% (Rocher et al., 2021). It is a β-1,3-D-glucan that consists of approximately 25 glucosyl residues (Abraham et al., 2019; López-Pedrouso et al., 2020; Sterner and Gröndahl, 2021). There are variations in the structure due to the specie, season, and other environmental factors. Contrasting the other polysaccharides, laminarin does not form gels. Nevertheless, it has been reported their anti-inflammatory, anticoagulant, antitumoral and antioxidant activities (López-Pedrouso et al., 2020).

## 4.3 Biosurfactants

Surfactants are amphiphilic compounds, composed of so-called hydrophilic head and lipophilic tail that have the ability to reduce surface and interfacial tensions by accumulating at the interface and forming larger structures called micelles, in the first case, and surfactant liquid crystals, in the second (Kronberg and Lindman, 2014). They fall into four categories (neutral, anionic, cationic, and zwitterionic) depending on the nature of their hydrophilic fragment, the lipophilic fragment remaining structurally similar across all categories of surfactants. Gemini surfactants are a separate category of surfactants constituted of two hydrophilic head groups of any type and a single lipophilic tail group.

Most industrially relevant surfactants have found applications in the detergent, cosmetics, emulsification, and anti-foaming industries (Chang, 2016) and are widely derived from petroleum. In order to meet the ever-increasing demand for surfactants as petroleum reserves run out, biosurfactants have emerged as ideal alternatives. They have the characteristic overall amphiphilic structure of synthetic surfactants but vary at the hydrophilic head group, which can be one of several usual motifs encountered in natural molecules.

These are naturally synthesised by microbial sources such as bacteria (typically *Bacillus* sp. (Sakr et al., 2021), *Pseudomonas* sp. (Bhosale et al., 2019)., *Botyris cinerea* (Abidi et al., 2008), *Lactobacilli* (Gudiña et al., 2011), and *Candida utilis* (Ribeiro et al., 2019) from renewable sources and perform equally to better than synthetic surfactants in several areas (e.g., oil spill, oil recovery, wastewater treatment, and pharmaceuticals) (Ng et al., 2022). Apart from being more environmentally friendly than their current counterparts, they also present many desirable features such as being less toxic (Akbari et al., 2018), biodegradable (Vijayakumar and Saravanan, 2015), highly specific and effective at extreme temperature, salinity, and pH conditions (Pacwa-Płociniczak et al., 2011). Certainly, their main selling point is that they can be produced at a lower cost from waste (Sáenz-Marta et al., 2015; Martins and Martins, 2018; Jiménez-Peñalver et al., 2020). However, this is conditional on the isolation of the biosurfactant, as the purification process may still represent the main contribution to the overall production cost (Mukherjee et al., 2006) and identifying suitable organic waste material is crucial for the commercialization of biosurfactant. Additionally, parameters such as carbon and nitrogen sources, trace elements, temperature and pH are other variables which can strongly influence the biosurfactant yield (Patel and Desai, 1997).

Biosurfactant production by bacteria or enzymes has been investigated with all sorts of plant biomass and food industry wastes (Makkar et al., 2011; Mohanty et al., 2021). Alternatively, marine environments host a rich diversity of organisms that naturally produce biosurfactants and emulsifiers (Rahman et al., 2019), some of which are already widely used in the food industry (Liao et al., 2021). In general, biosurfactants from marine environments are derived from a wide range of organisms including, but not limited to, macroalgae, microalgae, bacteria, diatoms, and cyanobacteria (Silva et al., 2012). Algae are the most abundant resource in the ocean and represent a virtually endless source of biosurfactants called polysaccharides (Xu et al., 2017). These long polymers [tens to hundreds of kDa (Usman et al., 2017)] occur as the main structural components of marine algae or as microbial secretions, known as exopolysaccharides (EPS) (Manivasagan and Kim, 2014). Polysaccharides can be extracted with hot water (Zhang et al., 2010; Savage, 2012), although removing unwanted species with organic solvents is more efficient and less costly (Lim et al., 2014). Lately, these methods have been replaced with microwave, ultrasonic, and enzyme-assisted extraction. Microwave-assisted extraction has the advantages of short extraction time, low energy, and low cost (Sousa et al., 2010; Hahn et al., 2012; Kadam et al., 2013). Ultrasonication and enzymes are used to break down the cell walls and release the compounds of interest either by cavitation and diffusion through cell walls or by hydrolysis of some of the cell wall structures (Kadam et al., 2013). All these techniques have proved to have higher efficiency compared with conventional methods (Yuan and Macquarrie, 2015). To a lesser extent, liquid extraction methods have been improved using more environment-friendly solvents such as supercritical fluids (Herrero and Ibáñez, 2015) and ionic liquids (Kadam et al., 2013; Martins et al., 2016). Algal polysaccharides have found widespread applications in the food industry as emulsifiers and thickening and stabilizing agents, cosmetics, biomedical industry due to their anti-cancer, anti-viral, anti-inflammatory and antioxidant activities, and heavy-metal removal among others (Anestopoulos et al., 2020).

Exopolysaccharides (EPS), or extracellular polysaccharides, are complex mixtures of anionic biopolymers consisting primarily of polysaccharides as well as proteins, nucleic acids, lipids, and humic substances (Manivasagan and Kim, 2014). The huge variety of organisms (e.g., macro-/microalgae, bacteria) that produce EPS combined with the sometimes drastically different environment in which they grow has been an endless source of new biopolymers with unique properties. This comes to the price of a challenging isolation and purification of the target compounds, as exopolysaccharides are secreted along with other extracellular polymeric substances (Suresh Kumar et al., 2007; Manivasagan and Kim, 2014). Therefore, EPS may exhibit properties and functions that are actually reflected by the collective extracellular polymeric substances' characteristics of a mixture of compounds (Xiao and Zheng, 2016). In particular, sulphated polysaccharides are a category of biosurfactants exclusively found in the marine environments with additional properties that structural polysaccharides do not possess, owing to the multiple sulphate functional groups, and that slightly vary depending on the degree of sulphation of the polymers (Silva et al., 2012; Raposo et al., 2013). These are as diverse as joint lubrication and targeted drug delivery.

Another non-negligible potential feedstock for biosurfactant production is fish wastes as sources of both peptide and fatty substrates. With 30%–80% of the fish body weight being discarded during industrial processing operations (Dave and Manuel, 2014), the upcycling of these wastes also contributes to solving environmental and health problems. Zhu et al. (2020) took advantage of the richness of these wastes to synthesize lipopeptides. They first hydrolysed blended fish heads and fish livers to produce peptones that *Bacillus subtilis* transformed into lipopeptides. The lipopeptides were used in the formulation of a bio-dispersant that exhibited particularly good behaviour to treat oil spills. Similarly, Hu et al. (2021) enzymatically hydrolysed tuna fish red meat to obtain peptones that were converted into biosurfactants by *Bacillus subtillis*. They found that on a laboratory scale, the surface tension and critical micelle dilution were similar to those obtained by Zhu et al. (2020) but insist that results may vary depending on the fish source. Their process was scaled up to a 100-L pilot-scale, which is to date the most advanced process for the production of biosurfactant from fish materials. The same bacteria *Bacillus subtilis* was used to prepare lipopeptides in 30% yield from more refined materials, such as fish oil and a culture broth (Saranya et al., 2014). They were then immobilized on nanoporous activated carbon and effectively removed $Ca^{2+}$ (98%) and $Cr^{3+}$ (92%) from water solutions. By using *Ustilago maydis* FBD12 instead of *Bacillus subtillis*. Cortes-Sánchez et al. (2011) produced glycolipids from soybean and fish oils. In optimal conditions, the production of glycolipids was higher with fish oil. Moreover, the production of glycolipids from soybean oil was higher when *Candida rugosa* (lipase) was added, while this revealed detrimental when fish oil was used, suggesting that fish oil may be a better raw material. Finally, Kaskatepe et al. (2015) used *Pseudomonas aeruginosa* strains to convert fish meal into rhanmopeptides. The three strains tested (ATCC, H1, and SY1) produced biosurfactants at concentrations of 12.3 g/L, 9.3 g/L, and 10.3 g/L respectively, which decreased when the bacteria were exposed to UV light. Kadam and Savant (2019) compared the production of glycolipids from shrimp shell and fish wastes and plant biomass by *Pseudomonas stutzeri*. Curiously, fish wastes gave by far the worst yield while shrimp shell wastes were the best substrate and could produce 4 g/L–6 g/L of sucrose-based glycolipids under the optimized conditions. When fish wastes were transformed with *Corynebacterium spp*. CCT, anionic biosurfactants were produced (Martins and Martins, 2018). When compared to sugarcane bagasse, petroleum sludge, and glycerol, both fish wastes and sugarcane bagasse significantly outperformed the last two feedstocks. Despite the more industrially viable production of artificial surfactants, there seems to be a trend according to which biosurfactant production is higher when unrefined feedstocks from sources other petroleum are used. These combinations of sustainable feedstocks and natural microorganisms is economically promising as they valorise cheap wastes that would otherwise create environmental and health problems, without loss of efficiency compared with artificial surfactants.

## 5 Conclusion and future prospect

Due to the aquaculture sector is growing fast, it is necessary to implement new technologies to take advantage of the waste generated. Improving waste utilization in aquaculture is necessary to minimize its environmental impact. It has been reported that aquaculture by-products possess multiple properties that make them useful in different fields, such as energy, medicine, and food. Biofuels from aquaculture and marine waste, and macroalgae represent a promising alternative to carbon fuels because they do not compete with food crops for arable land such as the first and second generation of biofuels. Also, the cost of biofuels could be less because marine waste and macroalgae are inexpensive sources. Nowadays, most biofuels cannot compete with fossil fuels and most of them are on a laboratory scale that needs to solve challenges related to large-scale production and yields. Proteins and polysaccharides isolated from marine and aquaculture waste have shown multiple biological and physiological properties. The recovery processes for these biomolecules are now focused on enzyme-assisted processes than chemical-based processes due to their eco-friendly and green aspects. Although there are different alternatives for by-product management, as we discussed before, most of them remain in the development phase or optimization. So, future research must focus on can scale these processes to an industrial level. With this article, we hope to encourage the use of aquaculture and marine waste for the sustainable production of biofuels and bioderivates on a circular and sustainable strategy. Several applications for the by-product of aquaculture and algae are on the table. However, countries and industries must invest in infrastructure and technology for by-product utilization and monitoring the positive impact on that. With investment, by-products will contribute to the sustainable development of the society. The production of different useful products in one refinery could be a more advantageous project rather than the exclusive production of only one product reducing the cost. To secure and guarantee food safety, the integration of aquaculture and marine waste is essential as an alternative on the reuse of nutrients along the productive chains for a sustainable future in next the green world.

## Author contributions

LA-R: Write original draft, BS-R: Write original draft; GP: Write original draft; JES-H: Write original draft; HMNI: Review-editing; RP-S: Supervision, Review-editing, Funding acquisition; ADB: Write original draft, Review-editing, Funding acquisition; EMM-M: Write original draft, Review-editing, Supervision.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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