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Aquaculture as a circular bio-economy model with Galicia as a study case: How to transform waste into revalorized by-products

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ABSTRACT

Background: World-wide aquaculture represents a very important sector capable of supplying huge amounts of animal protein. However its relevance has proportionally augmented its waste generation. In Europe, the geographical constitution of Galicia has prompted the instauration of many aquaculture-based systems along its coasts. Indeed aquaculture means a very relevant industry in Galicia, together with animal farming, agriculture and biotechnology.

Scope and approach: Over the last decade Europe legislation encourages the proper management of wastes (mostly reutilization and reducing strategies) and the sustainable use of natural resources. The application of circular bio-economy (reuse of wastes) represents a feasible model to protect human and animal health and the environment. To achieve a more efficient production system that complies with European regulations, aquaculture wastes and sub-products need to be re-utilised to increase their throughput. This approach will positively impact on their economical yield while reducing their generation and thus protecting health and environment.

Key findings and conclusions: Different applications have been considered for re-using aquaculture wastes and sub-products. One of the most efficient approaches is the establishment of models that allow the metabolic waste reduction, as the integrated multi-trophic aquaculture. For derived aquaculture sub-products, the most efficient process is recovering important biomolecules such as proteins (collagen, gelatine), polysaccharides (chitosan), lipids (omega 3) or pigments (astaxanthin or beta-carotene). Biomolecules can further be applied for human and animal consumption, food industry, cosmetics or pharmaceuticals. Due to the importance of this productive system in Galicia it is critical its update to include aquaculture into circular bio-economy.

1. Introduction

1.1. Circular bio-economy

In the last few decades, environmental issues, such as the increase of pollution levels, loss of biodiversity, or overuse of natural resources have been directly related to climate change and have been demonstrated through scientific data and reports (Almond, R.E.A., Grooten M. and Petersen, 2020). Climate change is a global challenge that raises uncertainty and specially affects sectors related with the exploitation of natural resources, such as agricultural and forestry, and thus it may eventually cause market disruptions (Kardung et al., 2021). These reports and, specially, their future previsions have provoked an international concern which has prompted the establishment of agreements and commitments between nations in order to reduce the ecological footprint caused by human actions (Almond, R.E.A., Grooten M. and Petersen, 2020; Cadman, Radunsky, Simonelli, & Maraseni, 2018). One potential approach for the reduction of green house emissions and the mitigation climate change is the development of the concept bio-economy. Bio-economy is focused on production systems based on the use of biological resources (biomass), such as food waste or algae. Generally, bio-based products possess a minor carbon dioxide footprint than their fossil-based analogues. Although some bio-based products may also have impact negative impact on water and land ecosystems, their proper management may provide the chance to develop new value chains that can improve the resilience of natural

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ecosystems (Kardung et al., 2021).

This global concern is becoming to shift the current models of production. Companies are commencing to get certificates that ensure the reliability of their production systems and the quality of the final product. Among these certificates, those based on good practices, sustainability and ecological processes are widely demanded (Osmundsen et al., 2020). This tendency has been addressed by customers who claim about the traceability of the items they consume.

Nowadays, in order to accomplish industrial requirements while satisfying environmental protection actions, many different approaches of sustainable production have been designed. Currently, one of the most applied models is 'circular economy' which has been defined as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes (…), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers" (Kirchherr, Reike, & Hekkert, 2017). This concept has been recently updated by the incorporation of the term 'bio-economy' which itself does not embed circularity and efficiency (D'Adamo, Falcone, & Morone, 2020). The European Commission defined it as follows: "bio-economy covers all (…) primary production, economic and industrial sectors that use, produce or process biological resources (agriculture, forestry, fisheries, and aquaculture) to produce food, feed, bio-based products, energy, and services". Circular economy and bio-economy converge in several points, especially, in the use of biological resources, and particularly when this biomass is a by-product that represents an input for another industrial sector. Hence, these two strategies tend to overlap since they are both based on the use of biological resources and show a strong synergy (D'Adamo et al., 2020; Kardung et al., 2021). In fact, in the very last years, the European Commission and several industrial associations apply the term 'circular bio-economy' and support their integration (Kardung et al., 2021).

Aquaculture has exponentially grown in the last decades becoming fundamental to supply the global demand of animal protein; however this current production model may become unsustainable. This industry requires vast volumes of water whose biological and chemical composition gets altered after their use. Additionally, it generates huge amounts of wastes as result of the biological activity of the cultured organism and during the selection of the produced material. Therefore, their release implies a direct impact on the environment that may be reduced by their further utilisation (Dauda, Ajadi, Tola-Fabunmi, & Akinwole, 2019). In order to minimize the environmental impact of this industry different solutions can be established such as the implementation of the use of green sources for energy supply and the application of circular bio-economy strategies. In this model, wastes represent sustainable sources of biomolecules with potential applications in cosmetics, pharmacology, agriculture (as fertilizer purposes or biodiesel), or even for creating an integrated multi-trophic aquaculture system. All these approaches would revalorize aquaculture wastes and by-products while reducing the environmental impact of this industry and offering additional economic benefits. The implement of a circular bio-economy model will provide more sustainable production systems and lead to obtain certification and labelling programme for responsible aquaculture, such as GLOBAL G.A.P., among many others (Osmundsen et al., 2020).

Table 1
Annual growth of aquaculture production in different regions (expressed as thousands of tonnes and as global percentages, in parenthesis). Data calculated from the FAO report of 2020, the statistical institute of Galicia and APROMAR (APROMAR, 2020; FAO, 2020; Instituto Galego de Estadística, 2021).

	Thousands of tonnes (%)					
Regions/ countries	1995	2000	2005	2010	2015	2018
Europe	1581 (6.5%)	2053 (6.3%)	2137 (4.8%)	2527 (4.4%)	2949 (4.0%)	3083 (1.6%)
Norway	278 (1.1%)	491 (1.5%)	662 (1.5%)	1020 (1.8%)	1381 (1.9%)	1355 (1.6%)
Spain[a]	224 (0.9%)	309 (1.0%)	219 (0.5%)	252 (0.4%)	290 (0.4%)	348 (0.4%)
Galicia	n.a.	n.a.	221[b] (0.5%)	223 (0.4%)	275 (0.4%)	290 (0.4%)
Asia	21677 (89%)	28421 (88%)	39186 (88%)	51229 (89%)	64592 (89%)	72812 (89%)
China	15856 (65%)	21522 (66%)	28121 (63%)	35513 (61%)	43748 (60%)	47559 (58%)
India	1659 (6.8%)	1942 (6.0%)	2967 (6.7)	3786 (6.6%)	5260 (7.2%)	7066 (8.6%)
Indonesia	6411 (2.6%)	788 (2.4%)	1197 (2.7%)	2305 (4.0%)	4342 (6.0)	5427 (6.6%)
Viet Nam	381 (1.6%)	498 (1.5%)	1437 (3.2%)	2683 (4.6%)	3462 (4.8%)	4134 (5.0%)
Bangladesh	317 (1.3%)	657 (2.0%)	882 (2.0%)	1308 (2.3%)	2060 (2.8%)	2405 (2.9%)
Africa	110 (0.4%)	400 (1.2%)	646 (1.5%)	1286 (2.2%)	1777 (2.4%)	2196 (2.7%)
Egypt	718 (0.3%)	340 (1.0%)	540 (1.2%)	920 (1.6%)	1178 (1.6%)	1561 (1.9%)
America	920 (3.8%)	1423 (4.4%)	2177 (4.9%)	2515 (4.3%)	3275 (4.5%)	3799 (4.6%)
Chile	157 (0.6%)	392 (1.2%)	724 (1.6%)	701 (1.2%)	1046 (1.4%)	1266 (1.5%)
Total	24382	32418	44298	57744	72771	82095

N.a.: not available data.
[a] Including Galicia data.
[b] Data from 2007.

1.2. Importance of aquaculture productivity for supplying global protein demand: galicia as study case

Worldwide population faces great issues related with the exponential increment of inhabitants over world. Food and Agriculture Organization of United Nations (FAO) has estimated that by 2050 the global population will account for 10 billion people. Current production systems and nutritional models result inefficient, unsustainable and will not support such a huge global food demand (FAO, 2018). Recently, a study has estimated the human consumption of edible protein in terms of livestock meat (367 Mt) and fish meat (172 Mt) for 2050. Nowadays, edible fish accounts for more than 30% of the global protein consumed, from which half comes from aquaculture and marineculture (Costello et al., 2020). In 2016, fish farmed production reached 54.1 Mt for finfish, 17.1 Mt for molluscs, 7.9 Mt for crustaceans and 0.9 Mt for other aquatic animals. In fact, aquaculture grows faster than other major food production sectors, probably because cultured species exhibit low feed conversion ratio (1.1–1.6 kg of feed per kg of edible fish) than livestock species (reaching maximum ratios of 4.4 for pork or 9 for beef) (FAO, 2018; Jones, Karpol, Friedman, Maru, & Tracy, 2020). Nevertheless, as fish are mostly carnivores, aquaculture diets contain high amounts of animal protein to yield optimal products (Hua et al., 2019). This requirement reduces its sustainability, therefore, in order to become the source of future food products it has to reduce food waste and stimulate a change towards sustainable and healthy diets for humans (Garcia-Oliveira, Fraga-Corral, Pereira, Prieto, & Simal-Gandara, 2020). This change is necessary to minimize the impact of this productive system that has experienced a worldwide increment, expected to be maintained or even increased (FAO, 2017; Instituto Galego de Estadística, 2021). In fact, the general trend of the representative countries/areas involved in aquaculture is to increase their annual production. Galicia, a regional part of Spain, provides more than 20% of the aquaculture products generated in Europe and represents more than the 80% (even nearly reaching 95% some years, like 2015) of the Spanish productivity (Table 1). Galicia is located in the northwest area of the Iberian Peninsula, flanked to the north by the Bay of Biscay and to the west by the Atlantic Ocean, being the second region in Spain with more kilometres of coastline (1,498)

Table 2

Production rate and economic impact of marine aquaculture in Galicia in 2019–2020. Xunta de Galicia provides data of several relevant species in terms of marine aquaculture production (expressed as tons and percentage, in parenthesis, when data was available), the annual economic balance (thousands of €) and the average market price (€/kg) (Instituto Galego de Estadística, 2021).

Groups	Species	Aquaculture production				Market price
		Production Ton *(%)*		*Benefits in thousands of €*		*€/kg*
		2019	2020	2019	2020	2019–2020
Seaweed	Green algae	0.7	1.2	4.4	7.0	0.5
	Brown algae	0.7	0.1	1.4	1.1	10
	Red algae	0.1	0.3	1.1	2.0	1.31
Bivalves	Pullet carpet shell	304 *(0.11%)*	125 *(0.05%)*	4360	2223	11.77
	Grooved carpet shell	187 (0.07%)	159 (*0.06%*)	5124	4033	27.64
	Japanese littleneck clam	1415 *(0.53%)*	1334 (*0.55%*)	12002	12683	9.26
	Cockle	623 *(0.23%)*	476 *(0.19%)*	2825	2786	4.32
	Mussel	255518 *(95%)*	232761 *(96%)*	111876	100926	0.46
	Flat oyster	394 *(0.15%)*	268 *(0.11%)*	2091	1439	5.44
	Pacific oyster	523 *(0.19%)*	455 *(0.19%)*	1189	987	2.28
	Queen scallop	18 *(0.01%)*	n.a.	7	n.a.	5.40
	Total	258964 *(97%)*	235577 *(88%)*	71906	52262	–
Fishes	Senegalese sole	410 *(0.15%)*	308 *(0.13%)*	4571	3325	10.97
	Blackspot sea bream	133 *(0.05%)*	n.a.	563	n.a.	10.75
	Turbot	8588 *(3.2%)*	7504 *(3.1%)*	66690	48903	7.45
	Salmon	12 *(0.005%)*	7 *(0.003%)*	83	33	6.36
	Total	9142 *(3.4%)*	7820 *(3.2%)*	71906	52262	–

n.a.: not available data.

(Garza-Gil, Surís-Regueiro, & Varela-Lafuente, 2017). The Galician coastline is characterized by a system of drowned river valleys classified as inland waters (rías) feed by a dense network of rivers that benefit from nutrient-rich waters and provide a sheltered area, ideal for aquaculture purposes (Outeiro, Rodríguez-Mendoza, Bañón, & Alonso-Fernández, 2020; Pita, Fernández-Márquez, Antelo, Macho, & Villasante, 2019). The Galician economy is steeped in a long-standing tradition in the exploitation of aquatic resources and developed thriving aquaculture and fishing sectors (Surís-Regueiro & Santiago, 2014). The principal difference between these activities is the ecosystem exploitation intensity, since the human intervenes in aquaculture to increase the unit of production per species, while only natural resources are harvested in the extractive activity (Stead, 2019).

Three groups of fishing activities can be found along the Galician coastline: aquaculture, shellfish harvesting, and fishing. Shellfish harvesting "on foot" is an artisanal and traditional activity that permits to commercialize important amounts of several species of bivalve molluscs (clams and cockles cultured in intertidal sandbanks) and even the goose barnacle, a crustacean of the order Pedunculata (collected from rocky coasts) (Garza-Gil et al., 2017; Surís-Regueiro & Santiago, 2014). Regarding marine aquaculture, we can distinguish rafts (mussels and oysters production), aquaculture parks (for farming clams at intertidal, shallow areas in rías) and fish farms (Surís-Regueiro & Santiago, 2014).

Bivalves are by far the main species produced in Galicia, led by the Mediterranean mussel (*Mytilus galloprovincialis*) representing a 97% of the total production in 2019 that worth 125 million €. Other relevant bivalve species cultured in Galicia are two oyster species the European flat oyster (*Ostrea edulis*) and Pacific oyster (*Crassostrea gigas*); three classes of clams the Japanese littleneck clam (*Ruditapes philippinarum*) which is the most abundant, pullet carpet shell (*Venerupis pullastra*), grooved carpet shell (*Ruditapes decussatus*); edible cockle (*Cerastoderma edule*), and queen scallop (*Aequipecten opercularis*). Galician mollusc aquaculture also counts since 2014 with the production of Japanese abalone (*Haliotis discus hannai*), a marine gastropod with high-added value that can reach high market prices (68 €/Kg on average in 2018) (APROMAR, 2020; Xunta de Galicia, 2018) (Table 2).

The fish farm (and nursery) segment consists of enterprises whose facilities engage mainly in the breeding and fattening of turbot and sole (Surís-Regueiro & Santiago, 2014). Flatfish, such as turbot and sole, are a group of great commercial value, highly accepted by the consumers for their firm, white, mild tasting flesh that generally contains low fat percentage (2–4%) (Dong et al., 2018). Galicia was a pioneer region in the aquaculture production of turbot (*Scophthalmus maximus*) in the early 80s to currently become the first European producer and, in fact, the unique autonomous community that provided turbot in 2019 tothe Spanish production (APROMAR, 2020) (Table 2). Turbot are typically ongrown in land-based tanks with an open-circuit sea water pumping system (Person-Le Ruyet, 2010). The rearing cycle begins in a hatchery, where the breeding larvae are fed live feed: rotifera *Brachionus plicatilis* (often enriched with polyunsaturated fatty acids (PUFAs) from microalgae such as *Isochrysis galbana*) followed by *Artemia* (Rodriguez Villanueva, 2011). The fry are then weaned onto a dry pelleted commercial diet and when they reach approximately 100 g of weight are transferred to large outdoor tanks until they are ongrown to market size (1.8 kg). The entire rearing period is 18–24 months (Person-Le Ruyet, 2010; Rodriguez Villanueva, 2011).

Galicia is also the first Spanish producer of Senegalese sole (*Solea senegalesnsis*), a flatfish whose potential for aquaculture was identified decades ago, but the intensive production has actually taken off in recent years (Morais et al., 2016). Galicia contributed to sole production with more than the half of the total of Spain (774 tons) (APROMAR, 2020; Instituto Galego de Estadística, 2021) (Table 2). The rearing system is land-based, similarly to that described for turbot, in fact many rearing facilities initially designed for turbot aquaculture were then adapted for sole. Recirculation aquaculture systems (RAS) are now used in most of the sole farms for a better control of environmental conditions, given the high sensitivity of the species to environmental changes (Morais et al., 2016).

Finally, Galicia was the only European producer of blackspot sea bream *Pagellus bogaraveo* (APROMAR, 2020), a promising species for the diversification of the seafood market in southern Europe (Castro, Rincón, Álvarez, Rey, & Ginés, 2018) (Table 2). The fattening is carried out offshore in sea (Salutregui Darriba, 2017), similarly to the gilthead sea bream *Sparus aurata*, widely cultured in the Mediterranean area (Castro et al., 2018).

The features of Galician marine waters, such as temperature, upwelling and tides also determine the development of the characteristic vegetation of marine macroalgae, or seaweeds, mainly composed by fucoids, kelps and carragenophytes (Piñeiro-Corbeira, Barreiro, & Cremades, 2016). Seaweeds production in Spain is mainly based on harvesting from the environment although there are few initiatives for intensive culture (APROMAR, 2020). In Galicia, seaweeds are traditionally used to obtain agar, jelly or as an agricultural fertilizer. Most of the Spanish production of carragenophytes harvested in Galicia by authorized entities are *Mastocarpus stellatus*, *Chondrus crispus* and *Gigartina pistillata* (Tasende & Peteiro, 2015). There is also an important amount of seaweeds washed ashore (seaweed deposited in the beaches by sea water), which are not covered by a specific legislation and are freely harvested for agar (*Gelidium corneum*; *Gracilaria* spp.) and alginate (*Ascophyllum nodosum*; *Fucus* spp.) extraction, or as soil conditioner (brown seaweeds of the genus *Laminaria* or *Sacchoriza* or the green seaweed *Ulva*) (APROMAR, 2014; Tasende & Peteiro, 2015). *Saccharina latissima* and *Saccorhiza polischides*, commercially known as kombu, *Undaria pinnatifida* (wakame) and *Himanthalia elongata* (sea spaghetti) were among the most demanded macroalgae for human consumption in Galicia in recent years (Tasende & Peteiro, 2015), but the lists of species suitable for alimentary use is constantly increasing (APROMAR, 2014). *Saccharina latissima* and *Undaria pinnatifida* have been object of experimental culture in Galicia since the 90s following the Chinese production method, using rafts, but adapted to Galician conditions (Campbell et al., 2019; Tasende & Peteiro, 2015). According to aquaculture production data from the Galician Regional Government, about 400 kg of seaweeds were produce by aquaculture in 2018 (Xunta de Galicia, 2018) (Table 2).

The production of microalgae is also worth of mention, since it is strictly related with marine aquaculture, given that these microorganisms constitute a critical part of fish and mollusc feeding in their larval stages. As well, there is an increasing interest in microalgae production for human consumption, cosmetics and biofuel. The annual report on Spanish aquaculture provided by APROMAR recorded a production of 8 tons of microalgae in 2017, mainly of the species *Nannochloropsis gaditana*, *Tetraselmis chuii*, *Isochrysis galbana* and *Phaeodactylum tricornutum* (APROMAR, 2020).

Finally, the oldest farmed species in Galicia, the rainbow trout *Onchorynchus mykiss*, belongs to freshwater aquaculture. More than 2400 tons of rainbow trout were produced in Galicia in 2017 (second Spanish producer), in land-based farms located along rivers where the water supply to the rearing units is simply obtained by gravity (APROMAR, 2020; Muñoz-Lechuga, Sanz-Fernández, & Cabrera-Castro, 2018).

Therefore, as demonstrated along these detailed productive data, the relevance of Galician aquaculture systems extends further beyond the regional level. For this reason, Galicia will be our study case in order to analyze alternatives to improve aquaculture sustainability, based on the potential transformations of specific wastes into revalorize by-products and their multiple applications.

2. Aquaculture waste and by-products

Since 80s aquaculture has grown very fast up to reach a global production close to 80 million tonnes by 2016. Among the European countries, Spain is the one with the higher, current (0.28 Mt) and expected (0.32 Mt), production (Gutiérrez, Lozano, & Guillén, 2020). This productivity is associated with the parallel creation of wastes whose management is of international concern. In Europe this preoccupation have been reflected through the publication of different directives, regulations and communication (Directive, 2006; EC, 2005a; 2005b, 2008, 2009). Along these legal documents, terms such as waste or sub-product have been established. Waste has been determined as any substance or object that the holder has considered as a discard. Meanwhile by-product definition contemplates substances or objects secondarily obtained as part of an integral primary production process and that can be further and directly used without requiring additional processing steps as far as they comply with all legal requirements (EC, 2008).

This legal frame and concepts have also been applied to aquaculture. Therefore, based on the above mentioned definitions, aquaculture, as any other production system that requires using inputs to create products, secondarily produces non consumed inputs, in form of waste or sub-products (Dauda et al., 2019). The concern about aquaculture-based wastes and by-products has been reflected with an increasing number of scientific works related to this field (Morris, Backeljau, & Chapelle, 2019). Along the literature different quantifications, definitions and classifications of aquaculture products, wastes and by-products have been provided. In quantitative terms, the percentage of primary products, by-products and wastes generated from aquaculture depends on the selected species. Primary products obtained through processing methods yield medium-low efficiencies for fish and molluscs while for crustaceans reach higher ratios.

For fish grown in aquaculture facilities it has been estimated that 45% is directly transformed while the remaining 55% is considered subproduct. When considering a finfish, this percentage of sub-products can be mostly explained by the sum of the percentage of head and frames, which include bone skeleton and its associated flesh, that account for 20%; viscera for 12.5% (mostly formed by gut); skin and belly flaps sum 5% while trimmings and blood represent 4% (Stevens, Newton, Tlusty, & Little, 2018). Similar efficiencies have been determined for crustaceans, where the shell, including the head, represents 60% of the total body weight while the portion directly destined to consumption is about 40%. Molluscs are the most efficient organisms since flesh constitutes 70% and shell 30% of total body weight. Among these amounts of sub-products it has to be added the fraction of died animals along the growing process which has been considered to be a 4% for each production system (Iñarra et al., 2018).

Regarding waste classifications, aquaculture wastes can be divided into four groups: solid wastes as particles in suspension (mostly derived from non-consumed animal food); dissolved organic substances (mainly phosphorus and nitrogen); dissolved chemical compounds (from pharmacological treatments); and pathogens (Dauda et al., 2019). Although, more recent works classify wastes from RAS in just two classes: biological (faecal solids, uneaten food, and detached bacterial flocs) and effluents (mostly containing organic matter and nitrate) (Lee, Kim, Emmanuel, & Koh, 2019). The relative quantification of wastes is very variable upon cultured species, climatic conditions, etc. Indeed, uneaten feed has been estimated within a wide range between 8.5 and 52%, with highest rates obtained after feeding young fish in cold waters (Ballester-Moltó, Sanchez-Jerez, Cerezo-Valverde, & Aguado-Giménez, 2017). Uneaten feed waste and faeces are main responsible for the fraction of suspended solid residue. Uneaten feed is directly related to metabolic products excreted by animals both as faeces and dissolved metabolites (ammonia, nitrite, nitrate, phosphorus, etc.). Nutrient retention (nitrogen and phosphorus) and excretion rates were relatively quantified as percentage of consumed feed in different species with a range of 3.6–35% (N equivalents) and 15–70% (P equivalents) in faeces while dissolved metabolites as result of excretion accounted for 37–72% (N) and 0–62% (P). Unionised ammonia (NH_3), the most toxic form of nitrogen, gets oxidized by Nitrosomonas into nitrite (NO_2^-). In a further step, nitrite, which still represents a toxic ion for fishes, is transformed into nitrate (NO_3^-) by Nitrobacter. Nitrate, a less toxic form, can be incorporated by plants and algae boosting their growth. As below discussed, the presence of plants and algae provides large surfaces for the establishment of autotrophic bacteria capable of decreasing the concentration of toxic forms of ammonia. The presence of phosphorus in water is usually a limiting growth factor in aquaculture since high concentrations promote the exacerbated development of aquatic plants, micro-, and macro-algae (Dauda et al., 2019). This overpopulation together with high amounts of dissolved and suspended waste reduces the oxygen content in water, increases mortality rates, and decreases productivity.

Finally, it is important to underline another two type of wastes derived from aquaculture: chemical and pathological (Dauda et al., 2019). The presence of the first one, also called residues, is due to veterinary treatments that animals require to minimize the presence of diseases and mortality rates. The second one is the pathogenic load that

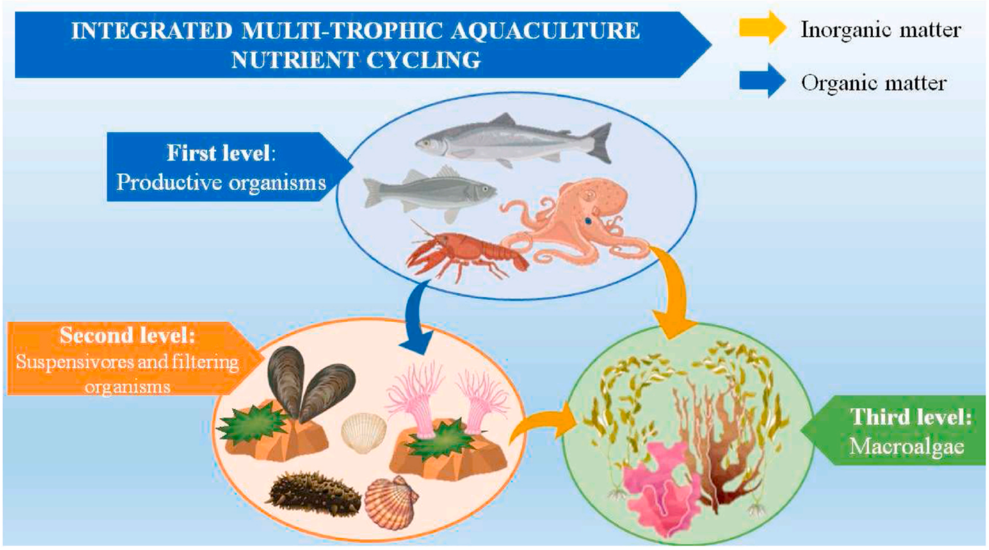

Fig. 1. Process of integrated multi-trophic aquaculture (IMTA). Organic matter from the first productive level is the substrate for feeding organisms from the second level. Inorganic matter created at first and second levels is further used for feeding organisms from third level.

may be found in waters. Microbial pathogens are responsible for numerous diseases that can strongly diminish aquaculture productivity, and efficient treatments are still not available. That is the case of the enteromyxosis, caused by the myxozoan parasites *Enteromyxum scophthalmi* that affects turbot (*Scophthalmus maximus* L.) production since it can cause up to 100% of morbidity and mortality (Ronza et al., 2019). At this purpose, it is imperative the application of best management practices, including the implementation of preventive measures, alternative therapeutic options and the treatment of water effluents (Dauda et al., 2019).

Aquaculture production has risen over the last decades and it is predicted to continue growing which means the proportional increment amount of wastes. Based on the European legal framework, wastes have to be properly managed. Their reuse may reduce their environmental impact that directly affects to human and animal health. Therefore, the approaches presented in next sections pretend to provide alternative

Table 3
Integrated Multi-trophic Aquaculture (IMTA) experiences in Galicia. IMTA models using few species provide different productivity (levels 2 and 3) that present variable applications, just taking into account their use for human or animal consumption, it is presented an estimated economical gain, and the reported environmental benefits (Guerrero & Creamades, 2012).

Location	Species	Productivity (2L and 3L)	Applications	Economical impact	Environmental impact
Esteiro (A Coruña)	1L: F (T) 2L: M (*S. latissima*)	2L:M: 7.1–10.7 kg/m	Food industry: T and M Cosmetics: M	Human consumption: *S. latissima* 19.9 €/kg[a]	Reduction of CO_2, dissolved and water nutrients involved in eutrophication
Betanzos (A Coruña)	2L: FM (Mus) 3L: M (*S. latissima*)	3L: M 5%/day, 6 kg/m	Food industry Cosmetics	Human consumption: *S. latissima* 19.9 €/kg[a]	Reduction of nitrogen (NH_3), CO_2 and nutrients involved in eutrophication
O Grove (Pontevedra)	1L: F (T) 2L: FM (Cl, O) and Sus (A) 3L: M (*Ulva* and *S. latissima*)	2L: Cl biomass: 1450% O seeds: 0.07 g/unit A: reproduction 3L: *S. latissima* B: 37% *Ulva* B: 568%	Food industry: T, Cl, O, A, M Cosmetics: M	Human consumption: T: 7.45 €/kg[b] Cl: 9–28 €/kg[b] O seeds: 225 €/kg[c] A: 46 €/kg[a] *S. latissima* 19.9 €/kg[a] *Ulva* 80–93 €/kg[a]	Ammonia reduction from 17 μM to 2–4 μM
Cambados (Pontevedra)	1L: F (T and S) 2L: Sus (A and Pw) 3L: M (*S. latissima* and *U. rotundata*)	2L: A biomass: 50% and reproduction Pw biomass (*Nereis aibuhitensis*): 12% (100% survival)	A, M: Human consumption Pw: Fish feed and sea angler	Human consumption: A: 46 €/kg[a] *S. latissima* 19.9 €/kg[a] *Ulva* 80–93 €/kg[a] Sea anglers: Pw: 18–56€/kg[d]	Removal of CO_2, dissolved and solid nutrients

Definitions: A: anemones, B: biomas, Cl: clams, F:fish, FM: filtering molluscs, L: level, M:macroalgae, Mus: mussels, O: oysters, Pw: polychaete worms, S: sole, Sus: suspensivores, T: turbot.

[a] Prices from Portmuiños products.

[b] Range of prices from Table 2.

[c] Price from Guernsey Sea Farms.

[d] (JACUMAR, n.d.).

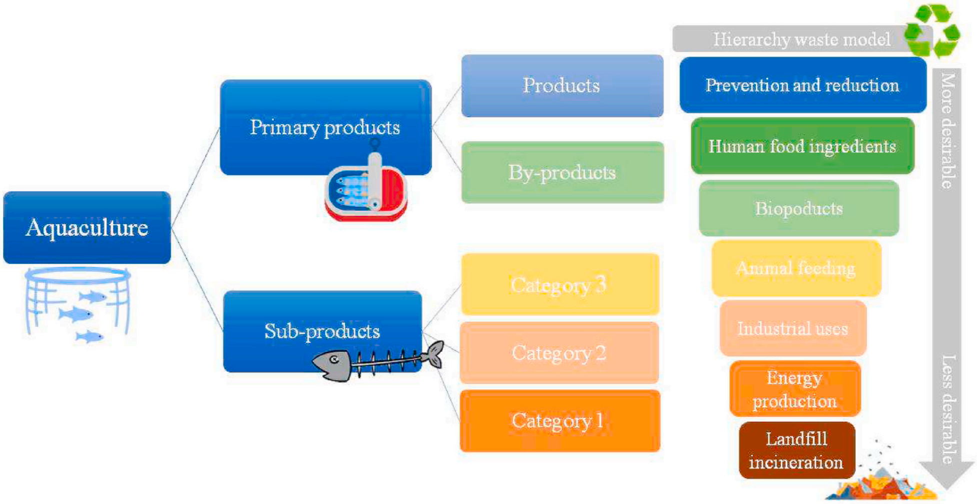

Fig. 2. Aquaculture products and by-products (re-)utilisation based-on the hierarchy waste model.

uses of wastes and their further innovative application in order to provide solutions that may revalue waste and maximise the economical throughput of aquaculture systems.

3. Integrated multi-trophic aquaculture: reutilization of aquaculture wastes

Along the last years, European Union encourages the proper management of wastes and the sustainable use of natural resources including, among others, raw materials such as biomass and biological resources and environmental media such as water (Directive, 2006; EC, 2005b; 2005a). In order to comply with the European legal frame and to continue playing a fundamental role providing animal protein in the future, aquaculture has commenced to developed sustainable production systems, profitable and environmentally friend. In order to magnify the productivity of aquaculture systems and reduce their environmental impact, derived wastes, such as metabolic products or uneaten food, have to be considered potential source of minerals, vitamins, proteins and lipids, for their further use (Lee et al., 2019; Stevens et al., 2018). Integrated multi-trophic aquaculture (IMTA) is considered a model to fulfil all these requirements. In the last years, has gained several countries attention, among them, Spain (Guerrero & Creamades, 2012). This production design implies the culture of few species from different trophic levels, so wastes produced by those from higher levels are inputs for species from lower levels, similar as occurs in natural ecosystems (Guerrero & Creamades, 2012; Jerónimo, Lillebø, Santos, Cremades, & Calado, 2020) (Fig. 1). First level usually includes fish, crustacean and cephalopods. The second one involves filtering and suspensivore invertebrates (e.g. filter molluscs, anemones, sea cucumbers, etc.), which feed on organic matter generated by first level, such as feed remains or sub-products. In the third level, marine macroalgae use inorganic compounds, like those from excretory products released by previous levels (Guerrero & Creamades, 2012; Irisarri, Fernández-Reiriz, Robinson, Cranford, & Labarta, 2013) (Fig. 1). Numerous authors defend that the presence of macroalgae is one of the most important factors in IMTA. Monoculture farms discharge great amounts of effluents with solid waste (uneaten food, faeces) and dissolved nutrients that can induce water eutrophication and affect surrounding ecosystems (Irisarri et al., 2013). Seaweeds used in the IMTA remove the excess of dissolved nutrients and CO_2, avoiding the eutrophication process (Guerrero & Creamades, 2012). IMTA systems allow the production of different valuable species with less amount of consumables and reduce the negative environmental impact (Cranford, Reid, & Robinson, 2013; Guerrero & Creamades, 2012). Therefore, production systems based on IMTA model favour the responsible use of natural resources and a sustainable productivity.

As previously indicated, Galician waters are described to be rich in nutrients that provides an appropriate environment for culturing different species with commercial value (Freitas, Salinas Morrondo, & Cremades Ugarte, 2016). Indeed, several IMTA approaches have been performed, both in closed systems and open waters, and, promoted by the National Advisory Board for Mariculture (JACUMAR) whose results have proved the efficacy of this aquaculture model (Table 3). The experiments performed in O Grove (Pontevedra) and Betanzos (A Coruña) will be explored in this section, as example of close and open circuits, respectively (Freitas et al., 2016; Guerrero & Creamades, 2012; JACUMAR, n.d.). Details of similar works have been compiled in Table 3 where it is also analyzed the economical and environmental improvement after the application of IMTA models. The IMTA experience developed in O Grove used effluents from a turbot farm to culture filtering molluscs (clam and oyster), suspensivores (anemones) and seaweeds (*Saccharina latissima* and *Ulva* spp.). Results indicated the viability of the assays for filtering molluscs: oyster seeds grew up to 0.07g and clam biomass increased from 2 to 29 kg (in 10 months with mortality rates below 18.5%). In fact, clam seeds (0.010–0.012 g/individual) obtained from this experiment were lately ongrown as part of another work. They showed not just viability but great performance reaching final sizes of 3–5.83 g/individual. Biomass of seaweed was incremented 37% for *S. latissima* and 568% for *Ulva* and the reproduction of *Anemonia viridis* was achieved. This successful biomass improvement would lead to an important economical benefit taking into consideration that nowadays, there is an increasing interest in seaweeds exploitation for alimentary and pharmaceutical purposes (Campbell et al., 2019). Besides, to be taken into account the benefit originally obtained from turbot production, economic enhancement can be achieved especially when reaching efficient production of oyster seeds (225€/kg), clams (up to 28€/kg), anemones (46€/kg) and *Ulva* (up to 93€/kg) (Table 3). Besides, this culture design using turbot effluents was demonstrated to effectively reduce ammonium concentration, previously boosted by fishes (Table 3) (Guerrero & Creamades, 2012). Regarding open water systems, most of the IMTA-based studies performed in Galicia have been related with mussels culture (Freitas et al., 2016; Guerrero & Creamades, 2012; Irisarri et al., 2013). IMTA in open water is influenced by several ambient factors, such as the sea currents, temperature and turbidity of the water, food availably, among others. Few studies were conducted in the Ría of Ares/Betanzos, in order to evaluate the production rate of *S. lattisima* when associated to mussel cultures. In a first attempt, the analysis of the δ15 N isotope ratio indicated that seaweed assimilated high amounts of ammonium excreted by the filtering bivalves, these data was accompanied of an optimal growth of *S. latissima* (Guerrero & Creamades, 2012). A further study additionally quantified the protein content assimilated for seaweeds in presence of mussel cultures. Protein amount was greater in combined cultures than in monocultures. Results suggest that the ammonium assimilated by *S. latissima* gets transformed into proteins, which ultimately enhance its nutritional value. Therefore, IMTA developed in open waters also improves water quality by reducing its ammonium charge while enhancing the efficiency of the production system. In fact, it provides two valuable sources of natural ingredients, mussels and *S. latissima* (Table 3). Both can be exploited for human consumption or for more innovative applications in cosmetics or food industry, used as alternative additive (Freitas et al., 2016). Finally, another beneficial effect of the combined use of seaweeds in aquaculture involves them in the control of pathogenic organisms. In a recent study conducted on an IMTA-RAS farm, *Ulva* species have been demonstrated to provide an optimal niche for forming biofilms of beneficial bacteria. Their presence has been related with the capacity of reducing fish larvae mortality and controlling populations of pathogenic *Vibrios* spp. (Pintado et al., 2016).

4. Innovative application of aquaculture sub-products

Even when an IMTA model is applied, aquaculture still generates different types of sub-products which may be re-used in diverse ways depending on their characteristics. In order to maximise the throughput of this industry, a hierarchic model shall be applied to all sub-products (Fig. 2). The main purpose of this pyramid is to prevent waste production, therefore to set up an efficient and properly managed system. Sub-products inevitably produced should be re-utilised to reduce them to the minimal amount and avoid their release to the environment.

Primary aquaculture products are those obtained as part of the main production process while sub-products are those secondarily obtained and can be directly utilised if they comply legal requirements (EC, 2008). An example of sub-products obtained after processing primary products are fish bone, skin, belly flaps or trimmings. These sub-products are considered to have great potential since they can be re-introduced into the food chain as ingredients destined to human consumption, which will render the maximum benefit. Even though this is the most efficient model, when their re-utilisation for human consumption it is not possible they may be re-introduced at any of the next levels of the waste hierarchy (Fig. 2). This is the case of the three categories of animal-derived materials not intended for human consumption contemplated in Regulation (EC) No 1069/2009 (EC, 2009). Category 1 mainly includes: body parts of sick animals, those used for experimental purposes, and those containing an excessive level of residues (group B3), (Directive 96/23/EC), illegal or contaminated substances. Category 2 includes manure, non-mineralised guano and digestive tract content; animal by-products containing authorized residues above permitted levels; animal products with foreign bodies; imported animals not complying with veterinary legislation; died animals; foetuses, oocytes, embryos and semen not destined for breeding purposes. Finally, category 3 compiles carcases, products and sub-products of animal origin, foodstuffs or parts of animals slaughtered that fit for human or animal consumption but not intended for this aim for legal or commercial reasons. Animal-derived materials belonging to the category 1 are the ones aimed to be reduced since their re-utilisation becomes tough. They can be applied to last steps of the waste hierarchy, it means for industrial or technical uses, such as for cosmetic purposes or energy production, before they get dumped or incinerated (Fig. 2). Similarly, by-products from category 2 can be applied for industrial or technical applications, such as for agriculture aims such as compost or silage (Fig. 2). Finally, animal-derived materials from category 3 are the most relevant ones in terms of re-utilisation since, in addition to the uses allowed for the previous categories, these materials can be also employed for manufacturing animal feed (Fig. 2) (Iñarra et al., 2018).

Table 4
Market size of biomolecules. Few compounds easily recovered from aquaculture sub-products represent natural ingredients for industrial applications with important global market size.

Biomolecules	Application	Market size (year)	Reference
Proteins	Food and nutraceutical	\$52.5 billion (2020)	("Protein Ingredients Market," 2020)
Collagen	Food, nutraceutical, medical, and cosmetics	\$3.5 billion (2019)	(S. S. Kunal Ahuja, 2019)
Gelatine	Food, nutraceutical, and cosmetics	>\$1.5 billion (2019)	(S. S. Kunal Ahuja, 2019)
Chitosan	Food, food industry, cosmetics, and water treatment	\$1.5 billion (2017)	(Kiran Pulidindi, 2017)
Astaxanthin	Nutraceutical, cosmetics, aquaculture and animal feed	>\$0.6 billion (2018)	(A. R. Kunal Ahuja, 2018)
β-carotene	Food, nutraceutical, pharmaceutical, cosmetics, and animal feed	>\$0.5 billion (2019)	(A. R. Kunal Ahuja, 2020)
Ω3 PUFAs	Food, infant formula, nutraceutical, pharmaceutical and animal feed	\$2.2 billion (2020)	("Omega 3 PUFA Market," 2020)

Numerous studies have evaluated the valorisation of aquaculture sub-products by their composition in terms of biomolecules. The re-utilisation of aquaculture sub-products permits to recover ingredients with high economical value for other industries (Table 4). The potential applications of aquaculture animal-derived products to different sectors relevant in the area of Galicia are detailed in the following sub-sections.

4.1. Human food ingredients

As explained before, aquaculture sub-products obtained from processing fresh and transformed products are the most interesting source for re-utilizing them as human food. Animal-derived by-products from category 3 have been also demonstrated to be an interesting source for animal alimentary industry (Iñarra et al., 2018). Aquaculture sub-products represent a sustainable source to recover non consumed compounds such as proteins, lipids and pigments that are mostly re-utilised for producing broths, aromas, fish protein concentrates, etc. Several compounds widely used in food industry can be obtained from sub-products, for example, fish flour, chitosan (a biopolymer derived from chitin, present in the exoskeleton of crustaceans), proteins concentrated, collagen (obtained mainly from fish skins), gelatine (produced by partial hydrolysis of collagen), and astaxanthin (Arvanitoyannis & Kassaveti, 2008; Iñarra et al., 2018; Stevens et al., 2018). Chitosan and astaxanthin are both used also as nutritional supplements in humans (Iñarra et al., 2018). One of the most common ways to extract these valuable compounds is by thermal-based maceration of previously powdered fractions that are then boiled in agitation using a small volume of water. After filtrating and decanting, the supernatant is collected to apply an ultra heat treatment or dehydration process that allow their storage for long periods (Iñarra et al., 2018).

Proteins, including collagen, and lipids are main components of fishes. However, the selection of the sub-product is fundamental for reaching optimal recovery rates. For example, protein and lipid content of whole turbot (*Scophthalmus maximus*) exemplars is pretty low (17 and 1%, respectively) (Dong et al., 2018), whereas high relative amounts of protein (82%), including 20% of soluble-collagen, and lipids (13%) were found in turbot skin (Sun et al., 2019). Interestingly, it also possesses a high calcium content (2069.0 mg kg^{-1}), and low concentrations of mercury and lead (>5 μg kg^{-1}) which reveals turbot as a safe source of collagen (Sun et al., 2019). Proteins obtained from turbot submitted to enzymatic or fermentation hydrolysis were described to possess a remarkable amino acids profile and high digestibility accompanied of scarce fish odour. Besides, they were demonstrated to have antioxidant and antihypertensive activities. All these features point to their potential use as natural additives for marine products ingredient, formulations of protein concentrates for human consumption, pet food diets, and supplements for aquaculture feeds (Fang, Sun, Dong, Xue, & Mao, 2017; Vázquez et al., 2020).

Other fish species expected to be cultured in Galicia or currently manufactured in this area, provide valuable sub-products such as salmon, cod, or hake. Atlantic salmon is a finfish known to contain high amounts of lipids (up to 45% in frames) and protein (71%), including collagen (27% in skin and 51% in scales). However, in terms of protein, cod has even a higher content (97%) than salmon (Dave et al., 2019). Similarly, European hake (*Merluccius merluccius*) sub-products, specifically skins and bones, were described to contain up to 58% of collagen, the main structural protein in connective tissue. Therefore, these by-products may represent a sustainable and innovative source of high quality type I collagen for its further use in biomedical, cosmetic, or nutraceutical fields (Blanco, G. Sotelo, & I. Pérez-Martín, 2019). Indeed, protein represents a useful ingredient for many industries since it is responsible for providing textural properties. Protein can be incorporated into food products in order to improve their organoleptic features. For instance, proteins from salmon and cod, after their alkaline treatment, were demonstrated to be capable of forming gels with good water hold capacity and breaking force (Abdollahi & Undeland, 2019). Lipids from marine organisms are also highly valuable for their associated health benefits and can be used for fortify food matrices or as nutritional supplements. Apart from above cited discards, fish canning industry represents another potential source of recovery of ω3 lipids from their sub-products with rates that can reach 3 g per litter of effluent (Monteiro et al., 2018).

Regarding freshwater production, rainbow trout (*Oncorhynchus mykiss*) frames have been treated with a separation technology named electro-dialysis with filtration membrane. This technique allowed fractionating active peptides from complex hydrolysates yielding enriched fractions with peptides that showed antioxidant properties (Suwal, Ketnawa, Liceaga, & Huang, 2018). Similarly, viscera from the common carp (*Cyprinus carpio*) and other additional by-products (muscle and head) of the fresh water fish tilapia (*Oreochromis niloticus*) have been submitted to different extraction procedures and chemically characterize. Their major bioactive compounds in the oil recovered from *C. carpio* included PUFAs (34 g/100g) and monounsaturated fatty acids (MUFAs, 45 g/100g), while saturated fatty acids (SFAs) were less abundant, accounting for 19 g/100 g. Although these concentrations were lower in the viscera of *O. niloticus* (3.3 g/100g for SFAs, 1.4 g/100g for MUFAs and 2.1 g/100g for PUFAs) they showed low n-6/n-3 PUFA ratio, and low atherogenic and thrombogenic indexes. These values indicate the great suitability of these extracts to be included as food ingredient destined for human consumption as a nutritive source and as tool for preventing coronary diseases (He et al., 2021; Kuvendziev, Lisichkov, Zeković, Marinkovski, & Musliu, 2018).

Astaxanthin is the most common carotenoid obtained from aquaculture sub-products, particularly, salmon, trout, krill, shrimps, fresh water crabs and crustacean shells are the main sources for recovery. Carotenoids and other colorants are useful food ingredients which are present in many products destined to human consume since they enhance their organoleptic characteristics by providing colour but also additional properties (i.e. antioxidant). Currently, the culture of macro and microalgae has gained importance in this area since both kind of algae have been demonstrated to represent a vary source of pigments. Pigments may be recovered from sub-products remaining after their processing. Beta-carotene is a yellow pigment known to be also a precursor to vitamin A with free radical scavenger and antioxidant properties. Together with beta-carotene few other carotenoids, including astaxanthin, have been extracted from brown macroalgae, such as *Laminaria* spp. and *Undaria pinnatifida* or green macroalgae, such as *Ulva lactuca* (Lourenço-Lopes et al., 2020). The main species of microalgae that respectively produce beta-carotene and astaxanthin are *Dunaliella salina* and *Haematococcus pluvialis* (Pereira et al., 2020). Phycoerythrin is another molecule of interest, a red pigment that can be mostly extracted from red macroalgae (Rhodophyta), as for example, *Mastocarpus stellatus*, *Gelidium pusillum*, *Gracilaria vermiculophylla* and from the microalga *Porphyridium cruentum* (Gargouch et al., 2018; Mittal, Tavanandi, Mantri, & Raghavarao, 2017; Nguyen, Morançais, Fleurence, Tran, & Dumay, 2018; Sfriso, Gallo, & Baldi, 2018). R-phycoerythrin has been demonstrated to possess diverse biological activities such as hypertensive and antioxidant (Lourenço-Lopes et al., 2020). Therefore, discards from algae production may represent a source of pigments that can further be applied as natural colorants or exploited for their bioactivities.

4.2. Animal feeding

Livestock represents a very important sector in the economy of Galicia. Therefore, the further application of wastes and sub-products of aquaculture to animal feeding has a great potential in this region.

Aquaculture sub-products and animal-derived material from categories 2 and 3 have been suggested to be a potential source of nutrients for animal feeding. Besides, if an IMTA model is not applied fish waste can be also reutilised for recovering the non consumed content of minerals, proteins and fatty acids. Sub-products, mainly heads, bones, skin, and viscera, were described to possess an ash content of 22% which indicates the high mineral concentration. The amount of protein can achieve up to a 58% of the dry matter. The most abundant monounsaturated fatty acids, reaching values of 19% of the dry matter, are palmitic and oleic acids (Arvanitoyannis & Kassaveti, 2008). For instance, they represent a good source of nutrients. A drawback of this type of fish waste and sub-product is the low concentration of heavy metals such as arsenic, lead, mercury and cadmium which hinders their detection and can cause issues when bio-accumulated. In the same way, it is necessary to avoid the presence of phycotoxins when macro and microalgae sub-products are used for feeding purposes.

Different sub-products derived from aquaculture such as fish flour, ground shell, chitosan, astaxanthin, proteins concentrated and silage, that resulted from the liquefaction of the fish, can be incorporated to feed formulation for aquaculture animals, farm animals and pets (Arvanitoyannis & Kassaveti, 2008; Iñarra et al., 2018; Stevens et al., 2018). Crushed shells represent an important calcium supplementation ($CaCO_3$) which results very useful when introduced in hen feeding. The replacement of the calcium present in limestone with that from oyster shells has been proved to enhance egg production, strength weight and thickness. Chickens fed using oyster shells also showed a quicker increase of weight. Shells from other edible mussels, such as *Chamelea gallina* or those from invasive species such as *Dreissena polymorpha* have also been showed as promising sources of calcium for feeding poultry animals (Stevens et al., 2018).

Experimental works have evaluated the reliability of feeding juvenile great scallops (*Pecten maximus*) using a mixture of algae (*Rhodomonas baltica* at 50 $\mu g\ L^{-1}$ and *Chaetoseris muelleri* at 300 $\mu g\ L^{-1}$) with salmon feed and faeces (at 30 $\mu g\ L^{-1}$). Scallops were demonstrated to incorporate both salmon feed and faeces particles, revealing a higher content of C18:1n9 fatty acids than those fed only with algae (Bergvik et al., 2019). Another experimental work studied the potential of producing bioflocs from solid waste obtained from RAS in order to feed *Artemia*. Flocs generated for this assay were called E− and T-flocs, and respectively come from European eel (*Anguilla anguilla*) and Nile tilapia (*Oreochromis niloticu*) production systems. Differences in the content of protein from both flocs were proportionally reflected in the final protein content quantified in *Artemia*. The maximum percentage of protein (70.01 ± 0.92%) was achieved when *Artemia* was fed with E-flocs (Yao, Luo, Tan, Fan, & Meng, 2018).

Silage preparations have also been object of re-utilisation of squid-based wastes. Industrial squid processing waste was mixed with different amounts of formic acid ranging from 2.5 to 3.5% to incorporate into silage. Results demonstrated that silage prepared with squid and 3% of formic acid showed protein hydrolysis, an increment in secondary lipid oxidation products and no spoilage (Martin Xavier et al., 2017). Thus, these combined products may represent an effective animal feed ingredient.

Aquaculture systems can also recycle wastes from other sectors. For instance, *Chlorella* has been satisfactorily grown by adding pre-treated pig slurry. The chemical characterization of this manure after its use for culturing the microalgae showed a reduction of the chemical oxygen demand up to 55%, the nitrogen content up to 46% and the amount of phosphorus (TP) to nearly 75%. Besides, this treatment also provides high removal ratios of heavy metals, especially copper (94%), chromium (90%), lead (72%) and zinc (70%). Therefore, this synergic model prevented the release of heavy metals, phosphorus and ammonia contaminated water and achieved great rates of biomass production (Zhou et al., 2019).

For instance, the application of aquaculture by-products for designing animal feeding has several advantages, including the reduction of cost production and environmental impact of the aquaculture industries (Arvanitoyannis & Kassaveti, 2008; Iñarra et al., 2018). This synergy between aquaculture and livestock farming has especially importance in Galicia since it reinforces two main economical activities in the region.

4.3. Agriculture

Galicia territory is divided in four provinces A Coruña, Lugo, Ourense and Pontevedra, from which 77% of the municipalities are inlands where agricultural activities represents another relevant economy sector in this region.

Although the re-use of aquaculture sub-products results more efficient in higher levels of the waste hierarchy, their employment in agriculture is also a potential destination to be considered. As explained before animal-derived materials belonging to category 2 are the most adequate for their used in agriculture as compost, mixed with other substrates, usually sawdust, splinters, branches, leaves, urban waste or manure (Iñarra et al., 2018). Indeed, a work revealed that a compost formulated with seaweed, fish waste, and pine bark (2:2:6) showed high organic matter (51%) and macronutrient contents (N:P:K proportion, 2.4:1.6:1) with low concentrations of metals and low phycotoxicity. This organic compost incremented the potato production in 53% or 30% when compared against lands without fertilizer treatments or against those using mineral ones, respectively. Therefore, it was suggested to be applicable for ecological agriculture as an organic amendment or growth substrate (Illera-Vives, Seoane Labandeira, Iglesias Loureiro, & López-Mosquera, 2017).

Historically, shells from mussel (*Mytilus galloprovincialis*) have been used as a liming agent or as mulches for soil amendment in farming in Galicia. In fact, the agricultural application of shells represents the second major shell market. Shells are crushed after their thermal treatment. The main component of shell, calcium carbonate ($CaCO_3$), neutralises acidic and metal contaminated soils while improving its fertility and increasing oxygen levels. The use of this natural product allows their application in ecological agriculture and represents a replacement for mined-$CaCO_3$ (Morris et al., 2019; Nunes et al., 2019).

4.4. Industrial uses: food packaging, cosmetic and pharmaceutical

Animal-derived materials belonging to category 2 are the most adequate for industrial application. Those from the category 3 or sub-products destined for human consume may be also used for this aim, however their re-utilisation is much more efficient when employed at higher steps of the waste hierarchy.

For food packaging, cosmetic and pharmaceutical industries, marine protein-based products such as collagen or gelatine, lipids and pigments result very useful. Besides, many marine compounds such as phlorotannins or PUFAs have been investigated over the last years as biomolecules with potential applications, especially in the field of cosmetics and medicine (Fraga-Corral et al., 2021; Kusmayadi, Leong, Yen, Huang, & Chang, 2021; Messina et al., 2021). Collagen represents the base for the treatment of osteoporosis and arthritis, but it is also a cosmetic ingredient due to its anti-aging properties. Its derivate, the gelatine, can also be found in cosmetics and drugs (Iñarra et al., 2018). Moreover, food industry is boosting the development of biodegradable active packaging to reduce single-use plastics and improve shelf-life products. Chitosan and/or gelatine have been widely chosen for creating biodegradable packages, but also carrageenans are increasingly used, while algae extracts, squid or *Litopenaeus vannamei* by-products, have been included as active ingredients to improve their preservation properties (Ganesan, Shanmugam, Ilansuriyan, Anandhakumar, & Balasubramanian, 2019; Jiang, Hu, Li, & Liu, 2019; Kchaou, Jridi, Nasri, & Debeaufort, 2020; Xu, Wei, Jia, & Song, 2020; Zhang et al., 2020). As well, freshwater cultured species, such as rainbow trout (*Oncorhynchus mykiss*), are a valuable source of active peptidic hydrolysates and oils rich in PUFAs. Both kinds of compounds have been demonstrated to have antioxidant properties and even antibacterial and antifungal properties. These features convert them in potential ingredients to prevent spoilage in a huge range of products, including food and cosmetics (Suwal et al., 2018).

As previously explained, both beta-carotene and astaxanthin are very common marine carotenoids present in salmon, trout, krill, shrimps, and crustacean shells, but also in macro- (*Laminaria* spp., *Undaria pinnatifida, Gelidium pusillum* or *Ulva lactuca*) and microalgae (*Dunaliella salina*, *Haematococcus pluvialis* or *Porphyridium cruentum* (Iñarra et al., 2018; Kusmayadi et al., 2021; Lourenço-Lopes et al., 2020; Pereira et al., 2020). Pigments represent sources of colours that additionally provide bioactivities. Astaxanthin has been reported to have antioxidant properties, stimulate immune system, prevents diabetes, cardiovascular and neurodegenerative diseases. In cosmetics, it has been used in skin care and anti-aging formulations (Iñarra et al., 2018). Beta-carotene, the main provitamin A carotenoid, possesses antioxidant activity capable of counteracting the effect of free radicals. Thus, beta-carotene may prevent oxidative damage, strongly related with the development of inflammatory processes, involved in chronic illnesses with global repercussion, such as diabetes, cardiovascular disease or cancer. Indeed, several observational studies have suggested that the dietary intake of high amounts of beta-carotene may reduce the risk of "all-cause mortality" (Zhao et al., 2016). In the same way, phycoerythrin holds a wide range of promising biological activities: antitumor, antioxidant, immunosuppressive, or hypertensive (Kusmayadi et al., 2021; Lourenço-Lopes et al., 2020). Pigments from microalgae, destined to human or animal consumption, also present good digestibility properties, since the matrix is simpler than in higher plants and then facilitate their incorporation as nutritional ingredients (Kusmayadi et al., 2021).

Apart from pigments, macroalgae represents a sustainable source of biodegradable and non-toxic natural bioactive compounds (Lourenço-Lopes et al., 2020). Many compounds obtained from different algae have been described as photo-protective. Several compounds with UV protection capacity have been found in algae species present in Galicia: *Ascophyllum nodosum*, *Bifurcaria bifurcata* and *Fucus vesiculosus* were identified to contain phlorotannins (Agregán et al., 2017), *Sargassum muticum,* an invasive algae in Galicia, contains sargachromenol (Milledge, Nielsen, & Bailey, 2016), and *Gracilaria* sp. and *Gelidium corneum* possess mycosporine-like amino acids (MAAs), a group of secondary metabolites produced which are able of absorbing UV radiation in the harmful range from 309 to 362 nm (Lourenço-Lopes et al., 2020). Algae are also a well-known source of polysaccharides (alginates, agar, carrageenans or fucoidans) that possess moisturizing properties. Brown algae grown in the coast of Galicia, such as *Laminaria* sp. and *Saccharina* sp., are recognized by their capability of synthesizing high quality alginates that showed better moisturizer capacity than the hyaluronic acid (Kanlayavattanakul & Lourith, 2016; Pimentel, Alves, Rodrigues, & P. P. Oliveira, 2018). Many micro- and macroalgae molecules have moisturizing, anti-aging, lightning and/or photoprotective properties and then have been applied for sunscreen creams, peeling, slimming, hair and dental care products (Lourenço-Lopes et al., 2020).

4.5. Biodiesel and other uses

Animal-derived materials belonging to the categories 1 and 2 are the most appropriate for applying to the production of biodiesel, but also wastes generated after recovering bioactive molecules from sub-products can be further reused for creating bioenergy. This combustible alternative represents a green source of energy for two reasons: in first place for the reduction of waste production and in second place because biodiesel is biodegradable, so it produces less air toxins and lower amounts of CO_2 than other hydrocarbon-based fuel or diesel (Dinakarkumar et al., 2016).

Wastes capable of yielding oil, such as skin, fishbone or liver, are the most suitable ones for obtaining biodiesel (Iñarra et al., 2018). In order to extract oil from aquaculture wastes or sub-products different approaches can be used, like the reactive extrusion. The lipid content obtained is then subdued to different kinds of *trans*-esterification reactions to produce biodiesel (Dinakarkumar et al., 2016). Additionally, currently microalgae cultures are growing and they represent a profitable source for obtaining biodiesel (APROMAR, 2020; Iñarra et al., 2018).

Aquaculture wastes and underused sub-products can provide an alternative substrate for producing single-cell protein (SCP). SCP refers to protein extracted from pure or mixed cultures of algae, yeast, fungi or bacteria. These microscopic and single-cell organisms can be cultured using a wide variety of substrates. They mainly require a rich-carbon source, supplemented with minerals and nitrogen, therefore wastes, sub-products and effluents from aquaculture may result into very profitable substrate for SCP production. This sustainable production of SCP can return to the aquaculture company that provided wastes as a fishmeal ingredient, since this source of proteins can partially replace the content of animal protein of fishmeal (Gasco et al., 2018, pp. 1–28).

Other potential applications of aquaculture sub-products include the use of shells as constructing materials. The high content of carbonate calcium of shells has allowed their exploitation as plastering substance or to partially replace the content of cement for obtaining concrete (Razali, Aris, Razali, & Pa'ee, 2017).

5. Future trends and conclusions

Aquaculture continues to grow faster than other major food production sectors, and with most fishery stocks expected to remain unsustainably fished or overfished for at least the next decade, aquaculture must bridge the growing gap between supplies of aquatic food and demand from a growing and wealthier global population that demands high amounts of animal protein (FAO, 2018). In Galicia, due to its representative proportion of coastal area and rich nutrients waters, aquaculture has been established as a key economic sector. The global relevance of Galician aquaculture productivity is recognized world-wide and expected to continue growing. Nevertheless, this increasing production trend has a drawback: whether it keeps growing following the current model, it will promote the generation of huge amounts of wastes. Therefore, it is necessary to improve the production model in order to comply with the European legislation relative to waste management (disposal, reutilization and reducing strategies) and sustainable use of natural resources (Directive, 2006; EC, 2005a; 2005b, 2008, 2009). This legal frame encourages the application of optimized models of waste hierarchy and improving the use of natural resources to enhance the environmental protection and so human and animal health. In order to achieve a more efficient production system, different prototypes to integrate multiple trophic levels (IMTA) were implanted in Galicia. They allow minimising the generation of wastes and were demonstrated to be successful both from an economical and ecological point of view. However, even this efficient model can generate wastes and sub-products, as part of the culture process, or as part of the transformation of the primary products. In this scenario, a circular bio-economy model should be adopted to re-utilise wastes and sub-products and maximise their throughput while reducing their negative environmental impact. Previously published works have already supported, with experimental data or solid argue theoretical frames, the re-utilisation of aquaculture wastes and sub-products to increase their throughput while providing alternative and sustainable sources for the aquaculture sector or other industries (animal and human nutrition, cosmetics, pharmaceutical, etc.) (Garcia-Oliveira et al., 2020; Mittal et al., 2017; Monteiro et al., 2018; Nguyen et al., 2018; Osmundsen et al., 2020; Stevens et al., 2018; Vázquez et al., 2020). Most of these published works have addressed the sustainability issue of aquaculture production systems from different perspectives. For instance, a study that analyzed the criteria of eight common certification schemes and standards demonstrated that they mainly get focussed on the environmental domain. However, the wide qualitative analysis performed by this work did not allowed the revision of specific strategies to minimize the environmental impact of aquaculture (Osmundsen et al., 2020). Another review article evaluated the main challenges that current food production systems faces nowadays. This paper detected specific problems of production systems and offered innovative solutions. In this work aquaculture is considered as a solution for avoiding overfishing issues and the IMTA model is slightly detailed (Garcia-Oliveira et al., 2020). Other experimental works analyzed sustainable sources of functional ingredients, such as pigments, hydrolysates proteins or PUFAs, from very specific marine products, such as underused algae species, industrial fish wastes or by-products (Mittal et al., 2017; Monteiro et al., 2018; Nguyen et al., 2018; Vázquez et al., 2020). The closest study to ours evaluated the potential applications of fish by-products also following a food recovery hierarchy scheme, although their case study just contemplates a fish species, the Atlantic salmon (*Salmo salar*) (Stevens et al., 2018). The main applications of the biomolecules recovered from aquaculture rely on their re-introduction into the food chain for humans or animals follow by their incorporation into agricultural and industrial sectors (food packaging, cosmetics and pharmaceutical). Some of these sectors, such as animal farming, agriculture and biotechnology, possess a relevant importance for the Galician economy. Hence, this sustainable production model can also promote the creation of a stronger economical network based on a transversal and multi-disciplinary circular bio-economy. Nevertheless, the recent implementation of 'circular economy', 'bio-economy' or 'circular bio-economy' strategies present few drawbacks as the time and cost-consuming processes that delay the approval of new products derived from these production systems (Kardung et al., 2021). In fact, it has addressed the little effort that some industrial sectors have carried out to establish a tailored policy framework and to promote environmental, social and economic changes based on the application of circular bio-economy models (D'Adamo et al., 2020). Therefore, even though these innovative and sustainable models have been demonstrated to be efficient, they still require visibility and stronger support. Even though this manuscript analyses the potential applications for aquaculture residues produced in Galicia in order to provide specific data, they are applicable for any other world region where agriculture, animal farming and biotechnology industries support and boost the economical development of the area. Indeed, the development of circular bio-economy production systems represents an innovative approach which can increase the creation of new job positions, so necessary in rural areas but also in industrial ones to minimize their environmental impact (D'Adamo et al., 2020).

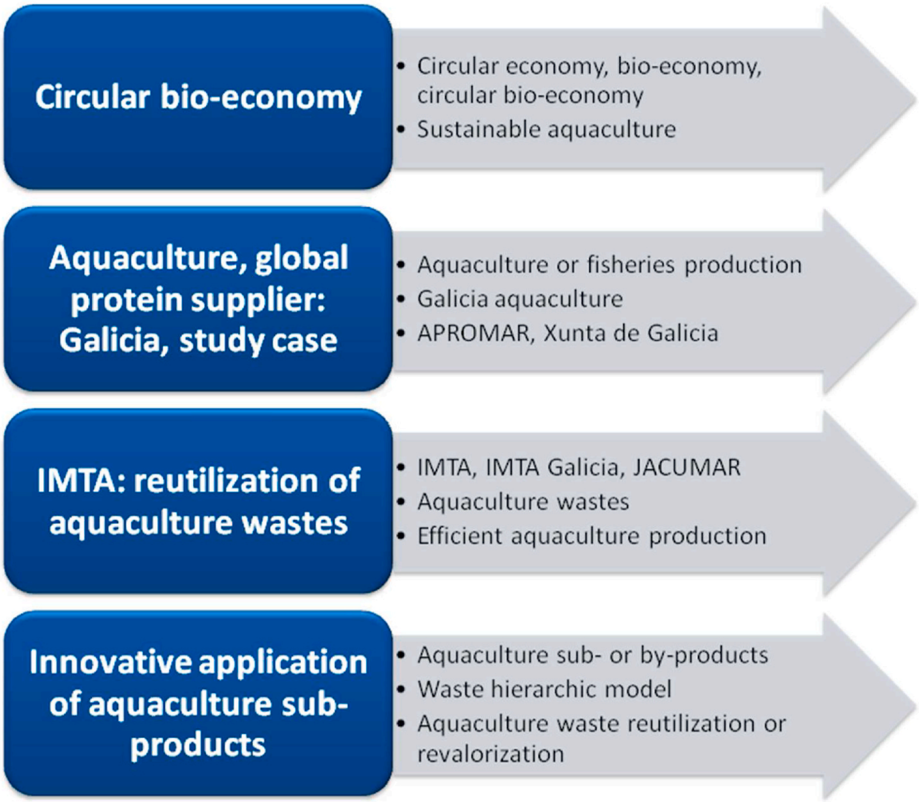

Fig. 3. Graphical representation of the main keywords utilised at all the steps of our theoretical analysis for transforming aquaculture using circular bio-economy models.

Therefore, this review provides an overview of the full spectrum of possibilities that offer the re-utilisation of aquaculture wastes and sub-products in terms of economical and environmental benefits, based on a specific study case: Galicia. The main aim was offering a solid theoretical framework based on an extensive review of the existing literature (Fig. 3) that may support and reinforce the implementation of circular bio-economy strategies in aquaculture to transform it into a much more efficient, sustainable and green production system.

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References

Abdollahi, M., & Undeland, I. (2019). Physicochemical and gel-forming properties of protein isolated from salmon, cod and herring by-products using the pH-shift method. *Lebensmittel-Wissenschaft und -Technologie, 101*, 678–684. https://doi.org/10.1016/j.lwt.2018.11.087

Agregán, R., Munekata, P. E., Domínguez, R., Carballo, J., Franco, D., & Lorenzo, J. M. (2017). Proximate composition, phenolic content and *in vitro* antioxidant activity of aqueous extracts of the seaweeds *Ascophyllum nodosum, Bifurcaria bifurcata* and *Fucus vesiculosus*. Effect of addition of the extracts on the oxidative stabili. *Food Research International, 99*, 986–994. https://doi.org/10.1016/j.foodres.2016.11.009

Almond, R. E. A., Grooten, M., & Petersen, T. (Eds.). (2020). *Living planet report 2020. Bending the curve of biodiversity loss*. Gland, Switzerland: WWF. Retrieved from https://livingplanet.panda.org/es-es/.

APROMAR. (2014). *Documento de análisis 2: Situación actual de la explotación y cultivo de macroalgas en Galicia, Andalucía y Asturias*.

APROMAR. (2020). La acuicultura en España 2020. Retrieved from. http://www.apromar.es/content/informes-anuales.

Arvanitoyannis, I. S., & Kassaveti, A. (2008). Fish industry waste: Treatments, environmental impacts, current and potential uses. *International Journal of Food Science and Technology, 43*(4), 726–745. https://doi.org/10.1111/j.1365-2621.2006.01513.x

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? *Marine Pollution Bulletin, 119*(1), 23–30. https://doi.org/10.1016/j.marpolbul.2017.03.004

Bergvik, M., Stenså s, L., Handå, A., Reitan, K. I., Strand, Ø., & Olsen, Y. (2019). Incorporation of feed and fecal waste from salmon aquaculture in great scallops (*Pecten maximus*) Co-fed by different algal concentrations. *Frontiers in Marine Science, 5*, 524. https://doi.org/10.3389/fmars.2018.00524

C. Blanco, M., Sotelo, G., & Pérez-Martín, I. (2019). New strategy to cope with common fishery policy landing obligation: Collagen extraction from skins and bones of undersized hake (*Merluccius merluccius*). R. *Polymers, 11*(9). https://doi.org/10.3390/polym11091485

Cadman, T., Radunsky, K., Simonelli, A., & Maraseni, T. (2018). From paris to Poland. *The International Journal of Social Quality, 8*(2).

Campbell, I., Macleod, A., Sahlmann, C., Neves, L., Funderud, J., Overland, M., et al. (2019). The environmental risks associated with the development of seaweed farming in Europe-prioritizing key knowledge gaps. *Frontiers in Marine Science, 6*, 107.

Castro, P. L., Rincón, L., Álvarez, B., Rey, E., Ginés, R., BlackCastro, P. L., et al. (2018). Blackspot seabream (*Pagellus bogaraveo*) fed different diets. Histologic study of the lipid muscle fiber distribution and effect on quality during shelf life. *Aquaculture, 484*, 71–81. https://doi.org/10.1016/J.AQUACULTURE.2017.10.042, 2018.

Costello, C., Cao, L., Gelcich, S., Cisneros-Mata, M.Á., Free, C. M., Froehlich, H. E., et al. (2020). The future of food from the sea. *Nature*. https://doi.org/10.1038/s41586-020-2616-y

Cranford, P. J., Reid, G. K., & Robinson, S. M. C. (2013). Open water integrated multi-trophic aquaculture: Constraints on the effectiveness of mussels as an organic extractive component. *Aquaculture Environment Interactions, 4*(2), 163–173. https://doi.org/10.3354/aei00081

D'Adamo, I., Falcone, P. M., & Morone, P. (2020). A new socio-economic indicator to measure the performance of bioeconomy sectors in Europe. *Ecological Economics, 176*, Article 106724. https://doi.org/10.1016/j.ecolecon.2020.106724

Dauda, A. B., Ajadi, A., Tola-Fabunmi, A. S., & Akinwole, A. O. (2019). Waste production in aquaculture: Sources, components and managements in different culture systems. *Aquaculture and Fisheries, 4*(3), 81–88. https://doi.org/10.1016/J.AAF.2018.10.002

Dave, D., Liu, Y., Clark, L., Dave, N., Trenholm, S., & Westcott, J. (2019). Availability of marine collagen from Newfoundland fisheries and aquaculture waste resources. *Bioresource Technology Reports, 7*, Article 100271. https://doi.org/10.1016/J.BITEB.2019.100271

Dinakarkumar, Y., Bharathiraja, D. B., Rithika, J., Dhanasree, S., Ezhilarasi, V., Lavanya, A., et al. (2016). Production of biofuels from fish wastes: An overview. *Biofuels, 1–7*. https://doi.org/10.1080/17597269.2016.1231951

Directive, E. (2006). *Directive 2006/12/EC of the European parliament and of the council of 5 april 2006 on waste, L114* p. 21). Official Journal of the European Union.

Dong, X.-P., Li, D.-Y., Huang, Y., Wu, Q., Liu, W.-T., Qin, L., et al. (2018). Nutritional value and flavor of turbot (*Scophthalmus maximus*) muscle as affected by cooking methods. *International Journal of Food Properties, 21*(1), 1972–1985. https://doi.org/10.1080/10942912.2018.1494196

EC. (2005a). *Commission communication: Taking sustainable use of resources forward: A thematic strategy on the prevention and recycling of waste.* COM(2005)666/F1.

EC. (2005b). *Commission Communication: Thematic Strategy on the sustainable use of natural resources.* COM(2005)670/F1.

EC. (2008). Directive 2008/98/EC of the European parliament and of the council of 19 november 2008 on waste and repealing certain directives. *Official Journal of European Union, 312*(3).

EC. (2009). *Regulation (EC) No 1069/2009 of the European Parliment and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation)*.

Fang, B., Sun, J., Dong, P., Xue, C., & Mao, X. (2017). Conversion of turbot skin wastes into valuable functional substances with an eco-friendly fermentation technology. *Journal of Cleaner Production, 156*, 367–377. https://doi.org/10.1016/j.jclepro.2017.04.055

FAO. (2017). *Global aquaculture production 1950-2017*.

FAO. (2018). *The State of world Fisheries and aquaculture 2018 - Meeting the sustainable development goals.* AqTHE state OF the world series of the food and agriculture organization of the united Nations.uaculture. *35*. issn 10.

FAO. (2020). The state of world fisheries and aquaculture 2020. Sustainability in action. Rome. Rome. https://doi.org/10.4060/ca9229en.

Fraga-Corral, M., Otero, P., Echave, J., Garcia-Oliveira, P., Carpena, M., Jarboui, A., et al. (2021). By-products of agri-food industry as tannin-rich sources: A review of tannins' biological activities and their potential for valorization. *Foods, 10*(1). https://doi.org/10.3390/foods10010137

Freitas, J. R. C., Salinas Morrondo, J. M., & Cremades Ugarte, J. (2016). *Saccharina latissima* (Laminariales, Ochrophyta) farming in an industrial IMTA system in Galicia (Spain). *Journal of Applied Phycology, 28*(1), 377–385. https://doi.org/10.1007/s10811-015-0526-4

Ganesan, A. R., Shanmugam, M., Ilansuriyan, P., Anandhakumar, R., & Balasubramanian, B. (2019). Composite film for edible oil packaging from carrageenan derivative and konjac glucomannan: Application and quality evaluation. *Polymer Testing, 78*, Article 105936. https://doi.org/10.1016/j.polymertesting.2019.105936

Garcia-Oliveira, P., Fraga-Corral, M., Pereira, A. G., Prieto, M. A., & Simal-Gandara, J. (2020). Solutions for the sustainability of the food production and consumption system. *Critical Reviews in Food Science and Nutrition*, 1–17.

Gargouch, N., Karkouch, I., Elleuch, J., Elkahoui, S., Michaud, P., Abdelkafi, S., et al. (2018). Enhanced B-phycoerythrin production by the red microalga *Porphyridium marinum*: A powerful agent in industrial applications. *International Journal of Biological Macromolecules, 120*, 2106–2114. https://doi.org/10.1016/J.IJBIOMAC.2018.09.037

Garza-Gil, M. D., Surís-Regueiro, J. C., & Varela-Lafuente, M. M. (2017). Using input–output methods to assess the effects of fishing and aquaculture on a regional economy: The case of Galicia, Spain. *Marine Policy, 85*, 48–53. https://doi.org/10.1016/J.MARPOL.2017.08.003

Gasco, L., Gai, F., Maricchiolo, G., Genovese, L., Ragonese, S., Bottari, T., et al. (2018). *Fishmeal alternative protein sources for aquaculture feeds*. Cham: Springer. https://doi.org/10.1007/978-3-319-77941-6_1

Guerrero, S., & Creamades, J. (2012). *Integrated multi-trophic aquaculture (IMTA): A sustainable, pioneering alternative for marine cultures in Galicia*.

Gutiérrez, E., Lozano, S., & Guillén, J. (2020). Efficiency data analysis in EU aquaculture production. *Aquaculture, 520*, Article 734962. https://doi.org/10.1016/j.aquaculture.2020.734962

He, C., Cao, J., Bao, Y., Sun, Z., Liu, Z., & Li, C. (2021). Characterization of lipid profiling in three parts (muscle, head and viscera) of tilapia (*Oreochromis niloticus*) using lipidomics with UPLC-ESI-Q-TOF-MS. *Food Chemistry, 347*, 129057. https://doi.org/10.1016/j.foodchem.2021.129057

Hua, K., Cobcroft, J. M., Cole, A., Condon, K., Jerry, D. R., Mangott, A., et al. (2019). The future of aquatic protein: Implications for protein sources in aquaculture diets. *One Earth, 1*(3), 316–329. https://doi.org/10.1016/j.oneear.2019.10.018

Illera-Vives, M., Seoane Labandeira, S., Iglesias Loureiro, L., & López-Mosquera, M. E. (2017). Agronomic assessment of a compost consisting of seaweed and fish waste as an organic fertilizer for organic potato crops. *Journal of Applied Phycology, 29*(3), 1663–1671. https://doi.org/10.1007/s10811-017-1053-2

Iñarra, B., Bald, C., Martín, D. S., Orive, M., Cebrián, M., & Zufía, J. (2018). Guía de valorización de subproductos de la acuicultura. Retrieved from. https://www.azti.es/wp-content/uploads/2018/12/AZTI_guia_VALACUI101218online.pdf.

Instituto Galego de Estadística. (2021). IGE. Produción de acuicultura mariña en Galicia. Retrieved June 14, 2021, from. https://www.ige.eu/igebdt/selector.jsp?COD=2705&paxina=001&c=0301004.

Irisarri, J., Fernández-Reiriz, M. J., Robinson, S. M. C., Cranford, P. J., & Labarta, U. (2013). Absorption efficiency of mussels *Mytilus edulis* and *Mytilus galloprovincialis* cultured under integrated multi-trophic aquaculture conditions in the Bay of fundy (Canada) and ría ares-betanzos (Spain). *Aquaculture, 388–391*(1), 182–192. https://doi.org/10.1016/j.aquaculture.2013.01.034

JACUMAR. (n.d.). Acuicultura integrada: Experiencia piloto para el desarrollo de sistemas de cultivo multitróficos (2008-2011). Planes Nacionales de Cultivos Marinos. Informe Final C. A. Galicia.

Jerónimo, D., Lillebø, A. I., Santos, A., Cremades, J., & Calado, R. (2020). Performance of polychaete assisted sand filters under contrasting nutrient loads in an integrated multi-trophic aquaculture (IMTA) system. *Scientific Reports, 10*(1), Article 20871. https://doi.org/10.1038/s41598-020-77764-x

Jiang, W., Hu, S., Li, S., & Liu, Y. (2019). Evaluation of the preservation effect of gelatin-water soluble chitosan film incorporated with maillard peptides on bluefin tuna (*Thunnus thynnus*) slices packaging. *Lebensmittel-Wissenschaft und -Technologie, 113*, Article 108294. https://doi.org/10.1016/j.lwt.2019.108294

Jones, S. W., Karpol, A., Friedman, S., Maru, B. T., & Tracy, B. P. (2020). Recent advances in single cell protein use as a feed ingredient in aquaculture. *Current Opinion in Biotechnology, 61*(1), 189–197. https://doi.org/10.1016/j.copbio.2019.12.026

Kanlayavattanakul, M., & Lourith, N. (2016). Polysaccharides. In *Immunotherapy of cancer: An innovative treatment comes of age* (pp. 37–50). https://doi.org/10.1007/978-4-431-55031-0_3

Kardung, M., Cingiz, K., Costenoble, O., Delahaye, R., Heijman, W., Lovrić, M., et al. (2021). Development of the circular bioeconomy: Drivers and indicators. *Sustainability, 13*(1). https://doi.org/10.3390/su13010413

Kchaou, H., Jridi, M., Nasri, M., & Debeaufort, F. (2020). Design of gelatin pouches for the preservation of flaxseed oil during storage. *Coatings, 10*(2). https://doi.org/10.3390/coatings10020150

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling, 127*, 221–232. https://doi.org/10.1016/J.RESCONREC.2017.09.005

Kusmayadi, A., Leong, Y. K., Yen, H.-W., Huang, C.-Y., & Chang, J.-S. (2021). Microalgae as sustainable food and feed sources for animals and humans – biotechnological and environmental aspects. *Chemosphere, 271*, Article 129800. https://doi.org/10.1016/j.chemosphere.2021.129800

Kuvendziev, S., Lisichkov, K., Zeković, Z., Marinkovski, M., & Musliu, Z. H. (2018). Supercritical fluid extraction of fish oil from common carp (*Cyprinus carpio* L.) tissues. *The Journal of Supercritical Fluids, 133*, 528–534. https://doi.org/10.1016/j.supflu.2017.11.027

Lee, J., Kim, I. S., Emmanuel, A., & Koh, S. C. (2019). Microbial valorization of solid wastes from a recirculating aquaculture system and the relevant microbial functions. *Aquacultural Engineering, 87*(August), Article 102016. https://doi.org/10.1016/j.aquaeng.2019.102016

Lourenço-Lopes, C., Fraga-Corral, M., Jimenez-Lopez, C., Pereira, A. G., Garcia-Oliveira, P., Carpena, M., et al. (2020). Metabolites from macroalgae and its applications in the cosmetic industry: A circular economy approach. *Resources, 9*(9). https://doi.org/10.3390/resources9090101

Martin Xavier, K. A., Geethalekshmi, V., Senapati, S. R., Mathew, P. T., Joseph, A. C., & Ramachandran Nair, K. G. (2017). Valorization of squid processing waste as animal feed ingredient by acid ensilaging process. *Waste and Biomass Valorization, 8*(6). https://doi.org/10.1007/s12649-016-9764-1, 2009-2015.

Messina, C. M., Arena, R., Manuguerra, S., Renda, G., Laudicella, V. A., Ficano, G., et al. (2021). Farmed gilthead sea bream (*Sparus aurata*) by-products valorization: Viscera oil ω-3 enrichment by short-path distillation and in vitro bioactivity evaluation. *Marine Drugs, 19*(3). https://doi.org/10.3390/md19030160

Milledge, J. J., Nielsen, B. V., & Bailey, D. (2016). High-value products from macroalgae: The potential uses of the invasive brown seaweed, *Sargassum muticum. Reviews in Environmental Science and Biotechnology, 15*(1), 67–88. https://doi.org/10.1007/s11157-015-9381-7

Mittal, R., Tavanandi, H. A., Mantri, V. A., & Raghavarao, K. S. M. S. (2017). Ultrasound assisted methods for enhanced extraction of phycobiliproteins from marine macro-algae, *Gelidium pusillum* (Rhodophyta). *Ultrasonics Sonochemistry, 38*, 92–103. https://doi.org/10.1016/j.ultsonch.2017.02.030

Monteiro, A., Paquincha, D., Martins, F., Queirós, R. P., Saraiva, J. A., Švarc-Gajić, J., et al. (2018). Liquid by-products from fish canning industry as sustainable sources of ω3 lipids. *Journal of Environmental Management, 219*, 9–17. https://doi.org/10.1016/J.JENVMAN.2018.04.102

Morais, S., Aragão, C., Cabrita, E., Conceição, L. E. C., Constenla, M., Costas, B., et al. (2016). New developments and biological insights into the farming of *Solea senegalensis* reinforcing its aquaculture potential. *Reviews in Aquaculture, 8*(3), 227–263. https://doi.org/10.1111/raq.12091

Morris, J. P., Backeljau, T., & Chapelle, G. (2019). Shells from aquaculture: A valuable biomaterial, not a nuisance waste product. *Reviews in Aquaculture, 11*(1), 42–57. https://doi.org/10.1111/raq.12225

Muñoz-Lechuga, R., Sanz-Fernández, V., & Cabrera-Castro, R. (2018). An overview of freshwater and marine finfish aquaculture in Spain: Emphasis on regions. *Reviews in Fisheries Science & Aquaculture, 26*(2), 195–213. https://doi.org/10.1080/23308249.2017.1381832

Nguyen, H. P. T., Morançais, M., Fleurence, J., Tran, T. N. L., & Dumay, J. (2018). Extracting and purifying pigment R-phycoerythrin from the red alga Mastocarpus stellatus. In *2018 4th international conference on green technology and sustainable development (GTSD)* (pp. 573–577). https://doi.org/10.1109/GTSD.2018.8595562

Nunes, N., Leça, J. M., Pereira, A. C., Pereira, V., Ferraz, S., Barreto, M. C., et al. (2019). Evaluation of fucoxanthin contents in seaweed biomass by vortex-assisted solid-liquid microextraction using high-performance liquid chromatography with photodiode array detection. *Algal Research, 42*(April), Article 101603. https://doi.org/10.1016/j.algal.2019.101603

Osmundsen, T. C., Amundsen, V. S., Alexander, K. A., Asche, F., Bailey, J., Finstad, B., et al. (2020). The operationalisation of sustainability: Sustainable aquaculture production as defined by certification schemes. *Global Environmental Change, 60*, Article 102025. https://doi.org/10.1016/j.gloenvcha.2019.102025

Outeiro, L., Rodríguez-Mendoza, R., Bañón, R., & Alonso-Fernández, A. (2020). Influence of aquaculture on fishing strategies: Insights from Galician small-scale fisheries. *Aquaculture, 521*, Article 735043. https://doi.org/10.1016/j.aquaculture.2020.735043

Pereira, A. G., Jimenez-Lopez, C., Fraga, M., Lourenço-Lopes, C., García-Oliveira, P., Lorenzo, J. M., et al. (2020). Extraction, properties and applications of bioactive compounds obtained from microalgae. *Current Pharmaceutical Design, 26*(16), 1929–1950. https://doi.org/10.2174/1381612826666200403172206

Person-Le Ruyet, J. (2010). Turbot culture. In *HV daniels, & WO watanabe, practical flatfish culture and stock enhancement* (pp. 123–139). Wiley Online Library.

Pimentel, F. B., Alves, R. C., Rodrigues, F., Oliveira, P. P., & B, M. (2018). Macroalgae-derived ingredients for cosmetic industry—an update. *Cosmetics, 5*, 2. Retrieved from http://www.mdpi.com/2079-9284/5/1/2.

Piñeiro-Corbeira, C., Barreiro, R., & Cremades, J. (2016). Decadal changes in the distribution of common intertidal seaweeds in Galicia (NW Iberia). *Marine Environmental Research, 113*, 106–115. https://doi.org/10.1016/j.marenvres.2015.11.012

Pintado, J., Ruiz, P., Cremades, J., Masaló, I., Jiménez, P., & Oca, J. (2016). *Co-culting Ulva ohnoi with antagonistic Phaeobacter bacteria as a strategy to protect fish-algae IMTA-RAS cultures from vibriosis*.

Pita, P., Fernández-Márquez, D., Antelo, M., Macho, G., & Villasante, S. (2019). Socioecological changes in data-poor S-fisheries: A hidden shellfisheries crisis in Galicia (NW Spain). *Marine Policy, 101*, 208–224. https://doi.org/10.1016/J.MARPOL.2018.09.018

Razali, N., Aris, R. N. F. R., Razali, N., & Pa'ee, K. F. (2017). Revalorization of aquaculture waste: The performance of calcined mussel shells as partial cement replacement. In *Proceeding of international conference on environmental research and technology*. ICERT 2017).

Rodriguez Villanueva, J. L. (2011). *Cultivo del rodaballo (Scophthalmus maximus)*.

Ronza, P., Robledo, D., Bermúdez, R., Losada, A., Pardo, B., Martinez, P., et al. (2019). Integrating genomic and morphological approaches in fish pathology research: The case of turbot (*Scophthalmus maximus*) enteromyxosis. *Frontiers in Genetics, 10*, 26. https://doi.org/10.3389/fgene.2019.00026

Salutregui Darriba, S. (2017). *Engorde de besugo (Pagellus bogaraveo) en jaulas, en la ría de Lorbé*.

Sfriso, A. A., Gallo, M., & Baldi, F. (2018). Phycoerythrin productivity and diversity from five red macroalgae. *Journal of Applied Phycology, 30*, 2523–2531. https://doi.org/10.1007/s10811-018-1440-3 LB - Sfriso2018

Stead, S. M. (2019). Using systems thinking and open innovation to strengthen aquaculture policy for the United Nations Sustainable Development Goals. *Journal of Fish Biology, 94*(6), 837–844. https://doi.org/10.1111/jfb.13970

Stevens, J. R., Newton, R. W., Tlusty, M., & Little, D. C. (2018). The rise of aquaculture by-products: Increasing food production, value, and sustainability through strategic utilisation. *Marine Policy, 90*, 115–124. https://doi.org/10.1016/j.marpol.2017.12.027. December 2017.

Sun, J., Zhang, J., Zhao, D., Xue, C., Liu, Z., & Mao, X. (2019). Characterization of turbot (*Scophthalmus maximus*) skin and the extracted acid-soluble collagen. *Journal of Ocean University of China, 18*(3), 687–692. https://doi.org/10.1007/s11802-019-3837-2

Surís-Regueiro, J. C., & Santiago, J. L. (2014). Characterization of fisheries dependence in Galicia (Spain). *Marine Policy, 47*, 99–109. https://doi.org/10.1016/J.MARPOL.2014.02.006

Suwal, S., Ketnawa, S., Liceaga, A. M., & Huang, J.-Y. (2018). Electro-membrane fractionation of antioxidant peptides from protein hydrolysates of rainbow trout (*Oncorhynchus mykiss*) byproducts. *Innovative Food Science & Emerging Technologies, 45*, 122–131. https://doi.org/10.1016/J.IFSET.2017.08.016

Tasende, M. G., & Peteiro, C. (2015). Explotación de las macroalgas marinas: Galicia como caso de estudio hacia una gestión sostenible de los recursos. *Revista Ambienta N, 111*, 116–132.

Vázquez, J. A., Rodríguez-Amado, I., Sotelo, C. G., Sanz, N., Pérez-Martín, R. I., & Valcárcel, J. (2020). Production, characterization, and bioactivity of fish protein hydrolysates from aquaculture turbot (*Scophthalmus maximus*) wastes. Biomolecules https://doi.org/10.3390/biom10020310.

Xunta de Galicia. (2018). Anuario acuicultura 2018. https://www.pescadegalicia.gal/Publicaciones/AnuarioPesca2018/indice.html. (Accessed 22 December 2019).

Xu, J., Wei, R., Jia, Z., & Song, R. (2020). Characteristics and bioactive functions of chitosan/gelatin-based film incorporated with ε-polylysine and astaxanthin extracts derived from by-products of shrimp (*Litopenaeus vannamei*). *Food Hydrocolloids, 100*, Article 105436. https://doi.org/10.1016/j.foodhyd.2019.105436

Yao, M., Luo, G., Tan, H., Fan, L., & Meng, H. (2018). Performance of feeding Artemia with bioflocs derived from two types of fish solid waste. *Aquaculture and Fisheries, 3* (6), 246–253. https://doi.org/10.1016/J.AAF.2018.07.002

Zhang, X., Liu, J., Yong, H., Qin, Y., Liu, J., & Jin, C. (2020). Development of antioxidant and antimicrobial packaging films based on chitosan and mangosteen (*Garcinia mangostana* L.) rind powder. *International Journal of Biological Macromolecules, 145*, 1129–1139. https://doi.org/10.1016/j.ijbiomac.2019.10.038

Zhao, L.-G., Zhang, Q.-L., Zheng, J.-L., Li, H.-L., Zhang, W., Tang, W.-G., et al. (2016). Dietary, circulating beta-carotene and risk of all-cause mortality: A meta-analysis from prospective studies. *Scientific Reports, 6*(1), Article 26983. https://doi.org/10.1038/srep26983

Zhou, J., Wu, Y., Pan, J., Zhang, Y., Liu, Z., Lu, H., et al. (2019). Pretreatment of pig manure liquid digestate for microalgae cultivation via innovative flocculation-biological contact oxidation approach. *The Science of the Total Environment, 694*, Article 133720. https://doi.org/10.1016/j.scitotenv.2019.133720