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Opportunities and limitations for the introduction of circular economy principles in EU aquaculture based on the regulatory framework

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Opportunities and limitations for the introduction of circular economy principles in EU aquaculture based on the regulatory framework

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Abstract

EU aquaculture produces only a small fraction of the internal demand of aquatic foods, but boosting this activity must be done in compliance with high standards of environmental protection and social benefits, as fostered by the policies on circular economy recently launched by the EU. Nevertheless, the assessment of the environmental sustainability of aquaculture and other food production systems is complex, due to the different tools and approached available. Moreover, the current EU regulatory framework may be restricting the options to implement

some circular solutions. This paper examines the controversies related to the assessment of environmental impacts of aquaculture processes and the different available circular solutions, with a focus on the best options to valorise aquaculture side streams and how current regulatory burdens and gaps should be solved.

1. Introduction

Human population growth exacerbates the demand for food, posing an increasing pressure over terrestrial and aquatic ecosystems, threatening biodiversity (Crist et al., 2017) and ecosystem services, and contributing to intensify climate change (Crippa et al., 2021). It is therefore paramount to prioritise the lowest-impact food production systems, while at the same time ensuring food security. Many aquaculture activities cause lower environmental impacts compared to the production of other livestock (Hillborn et al., 2018; Poore&Nemecek, 2018), and aquaculture plays a significant role in securing nutritious diets, contributing to 52% of the world supply of aquatic animal-source foods (FAO, 2020). However, aquaculture production is highly unbalanced among world regions (FAO, 2020). In the EU, aquaculture accounts only for 20% of the ca. 6.6 million t of fisheries products generated every year, and the EU must import 61 % of the fish and seafood that consumes (EUMOFA, 2019). In the context of the stagnation of EU fishing landings (EUROSTAT, 2021) enhancing internal aquaculture production seems to be the option to increase the self-sufficiency rate for aquatic products and to reduce the dependence from imports from third countries, which may not comply with the stringent requirements in food safety (European Commission, 2001) or environmental protection which EU applies (Jespersen et al., 2014).

The importance of boosting the sustainable development of EU aquaculture has been recognised by the European Commission (2002; 2009; 2013). Since environmental protection must be the bedrock of the development of EU aquaculture, the sector must be able to simultaneously intensify its productivity and its environmental performance. In this sense, circular economy (CE) strategies provide the path towards a better use of resources and less waste production. Recently, the EU launched the European Green Deal (European Commission, 2019), the roadmap for making EU's economy environmentally sustainable. As part of this agenda, a new Circular Economy Action Plan (European Commission, 2020) has been recently published which aims to involve economic actors, consumers, citizens and civil society organisations in the dynamization of the regulatory framework. This opens a new horizon for the implementation of circular economy in aquaculture production; nevertheless, assessing the environmental sustainability of aquaculture processes and their inputs is usually a complex matter, due to the diversity of analytical tools and approaches that can be used. Besides, maintaining or promoting the competitiveness, productivity and durability of the EU aquaculture sector involves dealing with a corpus of policies and regulations regarding marine and coastal management, environmental protection, waste or animal health, among others, and at different institutional levels (Alexander et al., 2015; Soininen et al., 2019), which may complicate or discourage the implementation of more sustainable aquaculture practices. One way to guarantee the sustainable aquaculture production is through the adoption of eco-labeling and certification systems (Nhu et al., 2016). Eco-labeling of the European aquaculture products can be evaluated in a positive way by the Nutri-score labeling (Purnhagen&Schebesta, 2019), promoting local products with a positive consumer perception across environmental and nutritional labels, i.e. nexus (Leivas et al., 2020). This work examines the main environmental aspects of European aquaculture under a CE approach and the different insights assessment tools may provide, together with the regulatory framework and a revision of the opportunities and constraints it determines.

2. Circular economy and aquaculture

Notwithstanding the current interest in CE, it is a controversial concept, since the expected approaches implied by "CE" can be questioned from the different points of view (Carew&Mitchell 2008). Nevertheless, there is broad consensus to define the CE based on its opposite, the linear economy: take, make, consume, and dispose; while the objective of integrating circular processes is closing loops in industrial ecosystems, minimizing waste (Stahel, 2016). CE pursues minimization of raw material inputs, valorisation of wastes or sidestreams, preservation of the resource value of a product as long as possible during its life cycle, processes redesign and reintegration of used products at their end-of-life.

CE, according to Ellen McArthur Foundation (2012), should be restorative and regenerative by design, and differentiate technical and biological cycles. Technical encompass man-made materials, whereas the biological pursue the recycling of bio-based materials for the same manufacturing processes but also for new possible applications. Regarding bio-based processes, the aquaculture sector has grown rapidly at a global level and is regarded by some as key to providing essential nutrition (Willet et al., 2019). However, its rapid growth has attracted some widespread criticism for its environmental and social impacts (Barrett et al., 2002; Whitmarsh&Wattage, 2006; Bacher, 2015; Osmundsen&Olsen, 2017; Krause et al., 2020). Much of this criticism has arisen around the provision of feed, particularly marine ingredients (proteins and oils, mostly from fisheries) and the release of nutrients from farm sites (Naylor et al., 2000; Deutsch et al., 2007; Martinez-Porchas&Martinez-Cordova, 2012). These issues coincide with poor markets for fisheries and aquaculture by-products (Stevens et al., 2018), an increasing requirement for sustainable ingredients for terrestrial and aquaculture livestock (Pelletier et al., 2011), peak phosphorus attainment (Reijnders, 2014; Daneshgar et al., 2018; Udert, 2018), and increased pressure on land and water resources (Roberts et al., 2015). Therefore, the aquaculture industry and wider food systems are ripe for application of CE principles that can solve waste management issues and the need for quality raw material inputs.

Since CE should be restorative and regenerative, it is necessary to promote the eco-design of the whole aquaculture processes from the initial phase of facility design, since once facilities are deployed environmental, economic and social implications remain immovable due to the complexity of subsequent changes. Decisions made in the design phase, i.e., feed and side-stream uses, effluent treatment..., are critical. Aquaculture future systems should be designed on the basis of ecological principles, as it is shown in recent systems like Integrated Multi-Trophic Aquaculture (IMTA), biofloc, aquaponics or aquamimicry.

In sum, new aquaculture models based in CE should explore creative designs that could offer in the long run the potential to improve profitability and sustainability through the valorisation of by-products and side-streams. This concept may include from recirculation technologies to the implementation of IMTA and biofloc schemes, or using sludge for biogas production, co-incineration or fertilisers. More effort in European institutions is required to overcome socioeconomic, logistic and legislative barriers, as well as producers' and consumers' habits, to address current problems, such as climate change or waste production, linking ecological and socioeconomic development.

3. LCA assessment in aquaculture: environmental sustainability considering circular economy

For most products, including food, a Life Cycle Assessment (LCA) approach is often taken to measure their environmental sustainability. LCA is an ISO accredited environmental impact accounting system that measures a range of global environmental impacts throughout a supply/value chain, including carbon footprint, eutrophication, acidification, water and land footprints amongst other (ISO, 2006a; 2006b). It is a preferred method of assessment in many cases because it evaluates the whole chain avoiding problem shifting that can lead to unforeseen consequences in some cases (Ayer&Tyedmers, 2009) and facilitates the identification of strengths and weaknesses other methods could not reveal (Moura et al., 2016). Despite ISO guidelines, there are methodological choices that have a considerable consequence for the result and interpretation (Ojala et al 2016); critically, the reference (functional) unit against which impacts are measured, how impacts should be divided between co-products and end-of-life/recycling scenarios. The functional unit (FU) typically used in aquaculture scenarios is the live weight of fish at the farm. This has consequences for comparing species which have different edible yields or nutritional value and therefore "functions" and in many cases the utilisation of the by-product can be very varied also (Stevens et al., 2018), which has important implications for resource efficiency. However, perhaps the most debated issue is around the allocation of impacts between co-products emanating from a single process, e.g. the edible portion and then the by-products from fisheries which may then be used for feed resources. In many cases this is done by mass so that by-products carry the same proportionate impact as the edible yield, but many authors argue that by-products should not be assessed in the same way, particularly when they cause a waste management issue and incentives are required to drive their better utilisation (Svanes et al., 2011). In such cases, co-product allocation is performed based on its economic value, so that in they carry very low environmental impacts and incentive is provided to their use from an environmental impact perspective. However, issues remain with economic allocation regarding price volatility, temporally and geographically. It has been considered that the volatile nature of prices may lead to an inconsistency of reporting that may miss real changes in environmental impacts over time (Svanes et al., 2011).

LCA application to aquaculture has some specific shortcomings in that many of the impacts associated with aquaculture are local rather than global (Newton&Little, 2018) and some of the main impacts for which aquaculture has been criticised are not considered within an LCA framework. A set of three indices for CE evaluation purpose is frequently selected: measure Global Warming Potential (GWP), non-renewable cumulative energy demand (NRED), and water scarcity index (WSI; Strazza et al., 2015); nevertheless, in many LCAs aquaculture products the acidification potential (AP) and eutrophication potential (EP) are also considered among the environmental indicators (Kusumowardani&Tjahjono, 2020). While global impacts such as GWP are important for any industry, academic and NGO criticism of environmental sustainability towards the aquaculture sector has usually been most concerned by its direct relationship with ecosystems and "ocean health" (Tlusty et al., 2019). Generally, this has fallen into two main areas: the acquisition of feed ingredients (particularly marine) and the effects of disease on wild populations, such as from sea lice (Naylor et al., 2009; Price et al., 2011; Torrissen et al., 2013). A key example is the use of fishery by-products to produce feed ingredients. "Marine ingredients", traditionally derived from small pelagic fish have been at the limit of exploitation for three decades and as particularly mariculture has grown, it has taken a larger share of the limited resource (Kok et al., 2020, Naylor et al., 2009; Shepherd et al., 2013). The impact associated with marine-ingredient use for aquafeeds have usually been measured using a basic tool called Fish-In Fish-Out (FIFO) ratios (Kok et al 2020). FIFO can be measured using different methodologies (e.g. Naylor et al., 2000; Tacon&Metian, 2009; Kok et al., 2020), but all demonstrate the relationship between the quantity of wild caught fish required to produce farmed fish. In most cases the contribution from fisheries by-products is ignored so that a diet containing marine ingredients only from by-product resources would have a FIFO of zero. The discounting of by-product resources from FIFO calculations was to drive waste reduction from fisheries and reduce the requirement for finite forage fish supplies (Kok et al., 2020) and is supported by international 3rd party certifiers such as ASC (ASC, 2017), GAA (GAA, 2016) and GlobalGAP (GlobalGAP, 2019). Consequently, feed formulators have turned to under-utilised fishery by-products as a new source of raw materials, reducing fishery waste in doing so, so that around a third of marine ingredients are now derived from by-products (Jackson & Newton, 2016).

3.1. Impact of aquafeeds provision and opportunities under the LCA perspective

Most aquaculture LCAs highlight feed as contributing to the majority of LCA impact categories (e.g. Pelletier et al., 2009, Newton& Little, 2018; Bohnes et al., 2019) except EP impacts were shared more equally between feed provision and aquaculture farm emissions. Consequently Feed Conversion Ratio (FCR), i.e., the efficiency of feed conversion is sometimes taken as a proxy for environmental impacts throughout the value chain and is a key target for reduce impact (Boyd&McNevin,2016a; 2016b). However, there are many trade-offs between different impacts related to the formulation of aquafeeds. While in CE strategies the reduction of the FCR should be a must, the formulation of feed using sustainable ingredients is also imperative.

To reach considerable reductions in FCR, farming practices can be optimized to applying new technologies such as more efficient feeders, better stock assessment and management using precision aquaculture techniques. However, although in many cases FCR has shown a decline, more energy-intensive ingredients such as gluten, soybean concentrate and rapeseed oil have replaced less energy-intensive marine ingredients, so there is a trade-off between carbon, water and land footprints against the use of highly limited marine resources (Boissy et al., 2011; Newton&Little, 2018; Malcorps et al., 2019). Other substitutes such as insects fed with food waste or seaweed has been considered (Stamer, 2015; Salomone et al., 2016; Tschirner&Kloas, 2017; Swinscoe et al., 2018). However, the reduction of all impacts considered from the LCA perspective has not been confirmed since this approach is relatively new, and in some cases the energetic demand to produce new feed materials can be extremely high (Bohnes et al., 2019). The results of environmental impacts must be exhaustive to avoid future diets displaying worse environmental profiles than existing ones. For instance, replacing the current marine ingredient-based diets with theoretically more sustainable and circular ones can lead to a second derivative, which is that the FCR increases since the new foods may be less digestible. This might lead to increased emissions through the supply chain and at the farm such as eutrophication (Mirto et al., 2010) and benthic deposition, or higher energetic demand and water consumption in recirculation systems to eliminate the ammonium nitrogen. In addition, considering the CE goal, expensive solutions should be avoided. To reach affordable protein for future aquaculture at a minimum impact, a clear system to measure farm profits and emissions for all the selected diets should be performed, also searching for new alternatives such as animal by-products, always considering possible bioaccumulation and biosecurity issues.

3.2. Fish by-products as feed ingredients under LCA perspective

In LCA, the appropriation of biotic resources is sometimes measured using the Biotic Resource Use (BRU) impact category which measures the accumulation of carbon through ecosystems and supply chains. How much the embodied impact of by-product resources contributes to the overall footprint depends on the method of co-product partitioning (Svanes et a.,l 2011), which may lead to LCA studies that either promote or oppose the use of fishery by-products for feed, depending on the methodology used (e.g. Papatryphon et al., 2004; Pelletier&Tyedmers, 2011). Svanes et al. (2011) observed that fisheries by-product directed to feed had a GWP over eight times larger using mass allocation compared to economic. There are many publications that discuss co-product allocation in detail (e.g. Pelletier&Tyedmers, 2011; Mackenzie et al., 2017) but few of them regard the problem from a CE perspective. However, the bioeconomy is different to most recycling in that there is constant transformation. By treating certain parts of CE in isolation, it is possible to come to completely opposite conclusions regarding the use of by-product resources, particularly when they are redirected from waste. For example, Kim&Kim (2010) showed that feeding municipal food waste to animals produced significantly less emissions than disposal options, while Lopes et al. (2015) suggested that producing marine ingredients from fisheries by-products was equally sustainable to “waste management” options. Similarly, a SINTEF report (2020) concluded that the use of by-product from seafood processing offered “considerable improvement potential” over non-utilisation. However, Pelletier et al. (2009) concluded that aquaculture operations using feeds with higher fisheries by-product inclusions were the main driver for considerably poorer GWP, BRU and other impacts compared to operations using few by-products. Therefore, a contradiction can arise between LCA publications within the academic literature, depending on methodology, where by-product use is both encouraged and discouraged at the same time depending on the boundaries of the study and allocation. Svanes et al. (2011) observed that mass or energy allocation (as used in SINTEF (2020) and Pelletier et al. (2009)) encourages fish processors to direct their by-products away from waste but it would discourage any buyer from purchasing them, based on their environmental footprint. A mass-based allocation treats the utilisation strategies for by-product use equally, i.e. it would have the same burden if a processor sold them for pet food, fur farming or human consumption, therefore does not encourage processors to maintain quality for higher end applications (Svanes et al., 2011) and as circularity increases, by maintaining them within the food chain, embodied impacts are accumulated. Economic allocation, by contrast would give higher burdens to human food applications based on their economic value. While this could seem counter intuitive, consistent use of economic allocation drives the upcycling of wastes, as it encourages processors to find more lucrative markets for by-products by maintaining their quality, meeting the objectives of the Food Recovery Hierarchy (US EPA, 2017). Recently Kok et al., (2020) produced an economically allocated “eFIFO” tool that allows integration with economically allocated LCA, that take into account the relative value of by-product fractions throughout the supply chain and differentiation between fishmeal and fish oil, with higher burdens going to oil as increasingly the more limited ingredient (Kok et al., 2020).

4. Product Environmental Footprint Category Rules (PEFCR) for aquaculture

Attempts are being made to harmonise approaches to measuring sustainability within the EU particularly with the development of the Product Environmental Footprint Category Rules (PEFCR). The PEFCR are the rules which should be applied to measuring the environmental footprint of EU products using LCA and have been developed in an effort to harmonise environmental foot-printing of products (Ojala et al., 2016). The EU is currently developing PEFCR for major product categories including food and feed products (European Commission, 2016). However, the guide for development of the individual PEFCRs still follows hierarchical rules based on ISO (2006a; 2006b) and is being conducted by separate expert groups. The result is inconsistency in how products may be benchmarked against each other. This is especially critical for circular economy principles which are underpinned by recycling and the use of by-products. Essentially, these principles may be seen favourably or not, depending on the methodology applied.

There is a risk, not only of inconsistency and lack of joined up thinking between the different PEFCR, but also that best practice may not be advocated due to lack of circular economy systems thinking through wider connected industries. In the PEFCR for feed for food producing animals (FEFAC, 2018) economic allocation is used, consequently low value (particularly near-waste) materials generally carry lower impacts than virgin raw materials. The PEFCR for beer also follows an economic allocation so that by-products from the brewing industry, commonly used in feed, have their impacts allocated using the same methodology. However, the PEFCR for wine, the last public version of PEFCR screening and recommendations for marine fisheries, and FCR red meat all use mass allocation so that by-products from these industries carry a larger impact than they do within the feed PEFCR. Besides creating inconsistent footprints between similar products, e.g. wine and beer, this causes inconsistency in the circular economy between the producers and users of by-products which calculate different impacts for the same resource. Using mass allocation at the point of by-product creation and economic allocation at the point of use results in some of the impact being unaccounted for and a discrepancy between benchmarking of products. There is also a danger that using two different allocation procedures creates a disincentive for by-product producers to provide their sensitive economic data if they are only required to provide volume data to assess their main product. Broadly, the PEFCR harmonisation initiative should be supported but the Circular Footprint Formula supported by PEFCR is considered complex (Ekvall et al., 2020) and there needs to be consistency between industries especially those as intrinsically linked as food. Generally, economic allocation may be regarded as supporting the transition from waste products to utilisation through gradual steps by identifying more profitable markets, which usually result in more sustainable application and is the broad goal of the circular economy, and may offer simpler solutions than currently supported by the PEFCR.

4.1. LCA and circular economy at local level: the case of effluents and sludge

Despite the encouraging efforts of the PEFCR to harmonise approaches and drive circular economy approaches, certain areas which are not covered by LCA principles are still of concern for the environmental impact of European aquaculture. LCA is the summation of several point sources of emissions for which there is usually little contextualisation to a geographic scale (Newton&Little, 2018), such as Eutrophication Potential; i.e. does a certain eutrophicating emission exceed the assimilative capacity of where it is released? Although methods such as PEFCR-supported ReCiPe include characterisation factors for eutrophication, they are often at national or regional level and currently marine eutrophication characterisation factors have not been included to date (Henryson et al., 2017; Dekker et al., 2019). Similarly, acidification or photochemical oxidation may be considered more regional issues rather than global. There is a need to harmonise methodologies for different assessments to provide a complementary measure of different impacts associated with aquaculture that promotes efficient use of resources, reduced waste and reduced impact on local and global scales. There have been a few attempts to integrate geographic contextualisation within LCA results, particularly around freshwater footprints linked to the AWARE method which is now commonly applied (Pfister et al., 2016). Other attempts to represent impacts geographically were made by Newton&Little

302 (2018) and in more detail using LCA integrated with GIS, notably by Geyer et al. (2010), Gasol et al. (2011), Dresen&Jandewerth (2012) or Mutel et al. (2012), and reviewed by Patouillard et al. (2018). However, these initiatives have not been well adopted, one of the main barriers being access to adequate data and their application to the whole supply chain. Individual impact issues tend to be applied at the production site, such as carrying and assimilative capacity (Weitzman&Filguera 2020) and few holistic value chain approaches outside of LCA have been applied. Valenti et al. (2018) produced a list of indicators that could be applied to measure environmental and socio-economic sustainability in aquaculture, yet their application to broader value chains still remains a challenge and have not been widely adopted.As it was mentioned in the first point of this section, a typical circular economy solution, is mainly related with the use of aquaculture effluent by other aquaculture species (Chatvijitkul et al., 2017), in systems such as IMTA, being a clear example of an industrial symbiosis case (a clear example of a win-win solution from a nutritional perspective) which can increase overall biomass production, mitigating environmental drawbacks at the same time. However, the IMTA systems have had much lower adoption in Europe, without no commercial success, compared to Asia, thought to be due to the possible risks related for reducing the water exchange and compromising fish health (Sanz-Lazaro & Sanchez-Jerez, 2020). Several biomitigation strategies based on IMTA systems such as the longline aquaculture of seaweeds+bivalves, seaweeds+bivalves+abalone, seaweeds+bivalves+fish, eelgrass+Manila clam+sea cucumber, etc. (Zhang et al., 2019) are well practiced in commercial scale in Asia. The IMTA model changes the traditional one-species based in high-density aquaculture methods, to new business models improving the resilience of aquaculture farmers. To promote this type of systems in Europe Sanz-Lazaro&Sanchez-Jerez (2020) propose to evolve from IMTA to Regional Integrated Multi-Trophic Aquaculture (RIMTA) this new model is based on independent allocation of cultures of low and high trophic level species and they suggested that this system can be economically supported, for instance, through nutrient quota. This new scheme can promote not only the aquaculture sustainability

but also the circular economy, but economic and logistic issues in each particular case should be assessed.In the case of aquaponics, strategies for its full development must be related to economies of scale in order to make it viable (Lobillo-Eguíbar et al., 2020). Consolidation of aquaponics as an economic activity in Europe is still behind initial expectations, and only one third of the companies truly rely on production of fish and vegetables as their source of income. Other process in which aquaculture effluents are valorised is aquaponics. Aquaponics is a case in which the proof of concept of the production system has not been fully validated yet, neither technologically nor commercially (Turnsek et al., 2020). Technology has to reach maturity and prove economic viability through the demonstration of large-scale facilities before it can be commercially implemented.

Regarding sludge Mirzoyan&Gross (2013) suggested the use of upflow anaerobic sludge blanket reactors to reduce the volume of brackish aquaculture sludge and to produce biogas at the same time. This could be an attractive option from LCA perspective but the economic impact for aquaculture plants would be limited by the specific sludge quantities and the use of digestate as fertiliser according the legislation. Yogev et al. (2020) also demonstrated the use of sludge to act as medium for phosphorous recovery and their possible use sustainable fertilizer, but again, this solution would be held back for its economic impact.

Despite the abovementioned issues, it is clear that LCA and CE should be combined to promote aquaculture sustainability. Looking at similar examples in urban agriculture, the combination of material circular indicators (MCI) with LCA indicators is shaping up to be very complex (Rufí-Salís et al., 2021). For instance, data were biased by overweighting of the water subsystem, accounting 99% of the impacts. As it was mentioned in the case of the PEFCR, this circularity indicator obscures the potential benefits of applying circular strategies, for example, in this line of urban agriculture with going to fertilizers or using recycled materials. In this case the proposal to solve it across linear indicators factors, where decreasing the values of these indicators as much as possible will correspond to a decrease both in environmental impacts and linearity of the system (i.e improving) circularity), seems to see a good approach to surpass the MCI obstacles. Also, nexus approach as it proposed in NEPTUNUS (Ruiz-Salomon et al., 2021) can be considered since circular models oriented to economic development on environmental and resources protection are clearly linked to this concept. Similar linear indicators combined to LCA, or Nexus approach along the whole aquaculture supply chains, should be applied to adapt the ideal indexes that support decision-making and prioritization in circular solutions in this field, always supported by experimental data and current policies.

5. Strategies/opportunities for eco-intensification or implementation of circular processes in EU aquaculture under current regulations

The literature reflects that studies of the supply chain in aquaculture systems pointed out different bottlenecks, such as food, technology, symbiosis, which provokes clear effects in the studied impact categories, sometimes contradictory, since reducing a specific variable (i.e. FCR), may improve a specific impact, but clearly worsen others. For this reason, the definition of specific circular economy strategies for each particular species in a specific area should be addressed, to take into account the correct impact categories at local level. Therefore, the eco-intensification scenarios should be aligned to sustainable development in economic and environmental areas but also the legislation across policy-making communities should evolve with research data to promote potential circular economy business in the aquaculture sector.

Regarding aquaculture, the lack of measures to regulate or incentivize the reinjection of side streams in productive schemes may pose a burden for the development of circular processes, with the exception of the valorisation of animal by-products, which is well developed and ruled by Regulation (EC) No 1069/2009 (European Parliament, 2009a). Although the European Green Deal and the 2020 Circular Economy Action Plan considered food, water and nutrients as key resources which should be given priority on policy development, no particular productive sectors are pointed out in those documents. Hence, circularity in EU aquaculture is circumscribed by in-force regulations dealing with different subjects: products, chemicals, waste, by-products, or water.

5.1. *Aquaculture animal by-products*

Fishmeal and fish oil (Tacon&Metian, 2008; Sarker et al., 2016; Jannathulla et al., 2019; Galkanda-Arachchige et al., 2020),continue to be essential aquafeed ingredients to maintain fish health and to promote quality attributes desired by consumers (Oliva-Teles et al., 2015; Glencross et al., 2016). Around 65 % of fishmeal and oil commodities come from wild caught whole fish. Half of European fishmeal and fish oil production is manufactured from wild caught whole fish, whereas ca. 40 % and 10 % come from wild caught and aquaculture fish by-products respectively (Jackson&Newton, 2016). It is estimated that twice the amount of fish by-products from processing plants are available but not collected for the production of marine ingredients, around 0.6 million t in Europe. Whereas in some European countries such as Norway and UK the infrastructure for the processing of aquaculture and fishery by-products is well developed (Stevens et al., 2018), in southern countries fish is mostly marketed whole to final customers, a fact that hampers collection and valorisation of by-products (Vázquez et al., 2019). Spain may be the exception to it, due to its large seafood canning industry with tradition of fish by-product utilisation (González-López, 2018).

Despite the need for alternatives to forage fish for the production of fishmeal and fish oil, the use of aquaculture by-products for this purpose was only recently permitted by EU law. Derogated Regulation (EC) No 811/2003 (European Commission, 2003) stated that only fishmeal from wild fish and their by-products could be used, since previous Regulation (EC) No 1774/2002 (European Parliament, 2002) defined fishmeal as processed animal protein derived from sea animals, except sea mammals. Later on, Regulation (EU) No 142/2011 (European Commission, 2011a) expanded the definition of fishmeal to processed animal protein derived from aquatic animals, thus permitting the use of aquaculture by-products, and established traceability and labelling measures for fishmeal and aquaculture feeds in order to avoid intra-species feeding. The reform of the EU Common Fisheries Policy (CFP), and the obligation of landing all fishing captures with the aim of gradually eliminate the wasteful practice of discarding, opens an opportunity to increase the availability of raw materials for the production of fishmeal and fish oil through the use of catches that cannot be used as food.

The outcomes scenarios should be analysed in terms of economic and environmental profit to select the best value chain for each by-product, either from fishing or from aquaculture, that can be also dependent on the country, the neighbouring industries, logistics, end-products value, etc., since aquaculture farms with “a priori” similar structures can nevertheless pursue divergent strategies toward developing innovations for by-product utilisation.

5.2. IMTA and aquaponics

In an IMTA system, two additional trophic levels can be added to high trophic-level fish or shrimp: a filter-feeder or a detritivore to feed on particulate matter and seaweeds to uptake dissolved nitrogen and phosphorous (Chopin, 2013; Correia et al., 2020). Faeces and uneaten feed are rich in organic matter and in the wild both constitute part of the natural diet of filter feeders and deposit feeders; nevertheless, Regulation (EC) No 767/2009 on the placing on the market and use of feed (European Parliament, 2009b), prohibits the use of animal waste to feed any other animal, both for food producing and non-food producing animals. This prohibition *de facto* invalidates IMTA schemes in which bivalves, sea anemones or detritivores, thus posing an insurmountable barrier.

The precautionary principle behind the ban on the use of animal waste as feed is related to the protection of animal and human health. Concern has arisen about disease transmission (Molloy et al., 2013; Alexander et al., 2016a) or the bioaccumulation of substances present in feed such as organic pollutants or metals, or drugs such as antimicrobials or antiparasitics (Rosa et al., 2020). Whereas the maximum residue limits of pharmacologically active substances are regulated in fed farmed animals (European Parliament, 2009c; European Commission, 2010), there is a legal gap regarding extractive aquaculture species such as bivalves or echinoderms. Nevertheless, other chemical hazards are regulated on these foodstuffs: pesticides (European Parliament, 2005), metals, hydrocarbons (European Commission, 2006) and persistent organic pollutants or POPs (European Commission, 2011b). Regarding seaweeds, they naturally present high concentration potential for minerals and trace elements present in the surrounding waters. Regulations on the content of certain contaminants in seaweeds and their derivatives is still recent in the EU (European Commission, 2012), and in some cases only a risk assessment is available, with a recommendation for the establishment of maximum levels (EFSA, 2019). But in practice, current limitations to the full implementation of IMTA at commercial scale in the EU are derived at the national level of regulations, which deal with fundamental aspects of authorisation and licensing, access to land and water, environmental impact assessment, or the co-cultivation of different species (Alexander et al., 2016a, 2017; Kleitou et al., 2018). It is likely that scientific and technical knowledge play an important role to demonstrate the safety of IMTA operations (Rolin et al., 2016), also helping to develop legislation on health and food safety of IMTA products (Alexander et al., 2016b) and to correct negative perceptions about IMTA from public and stakeholders (Alexander et al., 2018).

Regarding aquaponics, currently it has no clear legal status and regulations in the EU. Being a combination of fish farming and the cultivation of plants, the EU regulatory framework for this activity would be formed by the Common Fisheries Policy (CFP) and the Common Agricultural Policy (CAP), together with regulations on food safety, animal health and welfare, plant health, and the environment. Additionally, national regulations may apply to each particular aspects of this activity (Joly et al., 2015; Reinhardt et al., 2019).

5.3. Sludge and the new regulation on fertilizers

Certain types of aquaculture side streams are not efficiently valorised due to the absence of regulations that promote their use. This is the case of aquaculture sludge, i.e. particulate, organic-rich matter made from faeces and uneaten feed typically disposed of or used for low value applications, i.e. incineration. An opportunity for the upgrading of sludge arose with the Circular Economy Action Plan (European Commission, 2015), which identified the need for new valorisation routes for organic waste materials whose nutrient content made them appropriate to be used as fertilisers. Nevertheless, at that time, differences in rules and in quality and environmental standards among MS hampered the circulation of fertilisers based on recycled nutrients in the EU. As a result, only conventional non-organic fertilisers could be freely traded, according to Regulation (EC) No 2003/2003 (European Parliament, 2003). As part of the implementation of the Action Plan, this regulation was recently replaced by Regulation (EU) 2019/1009 (European Union, 2019) which harmonises the requirements for fertilisers produced from organic primary or secondary raw materials, and it could increase the interest towards organic-rich side streams such as aquaculture sludges.

6. *Conclusions*

Eco-intensification across circular economy solutions may provide the ultimate chance for EU aquaculture to develop its full potential in the supply of aquatic products and maintain competitiveness in the global market. LCA studies emerged as decision-making methodology for the environmental evaluation to evaluate circular solutions, but economics and regulations should be also aligned. Considering what is indicated in this work and the difficulties of combining LCA tools by the proposed methodologies with circular economy solutions, which to some extent could be improved through economic allocation instead of mass, the ideal would

480 be based on the development of new indicators, considering sector-specific adaptation tools to
481 minimize data mistrust and move towards homogeneity between results through a coupling of
482 LCA and reduction of linear indicators or new Nexus approach. The main idea should be not to
483 hinder eco-innovation across targeted environmental solutions based on flexible criteria.
484 Recommended future work should, therefore, include the empirical case studies quantifying the
485 environmetal and economic factors, but also the social and lesgilative issues for each specific
486 case in order to push the sustainable circular solutions in this field within the circular economy
487 framework and according to the 2030 EU agenda.

488

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490 The authors declares that they have no conflicts of interest influencing the content reported in
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492

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