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REVIEW

REVIEWS IN Aquaculture

Transforming sustainable aquaculture by applying circularity principles

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Abstract

A circular economy is considered one way to reduce environmental impacts of human activities, by more efficient use of resources and recovery, resulting in less waste and emissions compared to linear take-make-dispose systems. Muscat et al. developed five ecological principles to guide biomass use towards a circular economy. A few studies have demonstrated environmental benefits of applying these principles to land-based food systems, but to date, these principles have not been explored in aquaculture. The current study expands on these principles and provides a narrative review to (i) translate them to aquaculture, while identifying implications for the main species and production systems, and (ii) identify the main pathways to make aquaculture more circular. We show that the underlying concepts of the 'safeguard', 'entropy', and 'recycle' principles have been well researched and sometimes well implemented. In contrast, the 'avoid' and 'prioritise' principles have been explored much less; doing so would provide an opportunity to decrease environmental impacts of aquaculture at the food-system level. One example is prioritising the production of species that contribute to food and nutrition security, have low environmental impacts and thinking at wider food system scale to avoid feed-food competition in aquaculture. We identified six priorities that could make aquaculture more circular: (i) increase production and demand for the most essential species, (ii) decrease food loss and waste at farm and post-harvest stages, (iii) support nutrient recycling practices at multiple scales, (iv) adapt aquafeed formulations, (v) inform consumers about benefits of species of low trophic levels and other environmentally friendly aquatic foods, and (vi) address urgent research gaps.

KEYWORDS
aquatic foods and byproducts, ecological intensification, environmental sustainability, food and nutrition security, integrated aquaculture

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1 | INTRODUCTION

Global expansion of diverse food systems has maintained human well-being, but has also had a major influence on environmental changes.[1] A circular economy (CE) is considered one way to reduce environmental impacts of human activities,[2] by more efficient use of resources, resulting in less waste and emissions compared to linear take-make-dispose systems. Prieto-Sandoval et al.[3] defined CE as 'an economic system that represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources, close energy and materials loops, and facilitate sustainable development through its implementation at the micro, meso and macro levels'. Major aspects of CE are thus to shift to regenerative production practices and radically transform consumers into users.[4] In pursuit of more sustainable use of natural resources, CE concepts are already translated into policies in China, the European Union (EU), Canada, and other regions of the world.[5]

Muscat et al.[6] developed a CE framework to guide the use of biomass (rather than materials) towards a circular bioeconomy. This framework expands the study of de Boer and van Ittersum[7] by focusing more on environmental justifications and implications of a CE and less on social and economic consequences, because planetary boundaries are the ultimate limits for society and economies to develop and thrive. Muscat et al. recommended the following five ecological principles: (i) safeguard and regenerate ecosystems, (ii) avoid non-essential products and wasting those that are essential, (iii) prioritise biomass streams for basic human needs (e.g., food before feed or energy), (iv) use and recycle byproducts of agroecosystems (i.e., ecosystems supporting food production systems), and (v) use renewable energy while minimising overall energy use. These principles have been explored for agriculture and livestock (e.g., refs 8, 9) but not for aquaculture. Aquaculture is a critical food source in many regions and across the world,[10] and is projected to expand rapidly over the coming decade.[11] Aquaculture production interacts with terrestrial food systems (through ecosystem connectivity and feed interdependence),[12,13] while aquatic food products can supplement or replace terrestrial food products in households. To better understand the future role of aquaculture in circular food systems, the current study expands on Muscat et al.'s framework.

Although some CE concepts have been explored for aquaculture, these studies have focused on relatively few topics. The most studied CE concepts for modern aquaculture include waste management,[14] recycling of nutrients and byproducts,[15–18] novel ingredients in aquafeeds derived from the CE,[19,20] and production systems that reuse excess nutrients at the farm scale (e.g., aquaponics, integrated multi-trophic aquaculture [IMTA]) or at a large scale in combination with agriculture (e.g., reusing sludge from ponds/tanks as fertiliser).[21] These applications do not encompass all aspects of Muscat et al.'s framework. *Reviews in Aquaculture* recently dedicated a special issue on circularity[22] and provided regional or species specific case studies (e.g., refs 18, 23, 24). However, no publication has provided a state-of-the-art view of the current implementation of CE concepts in global aquaculture and/or of the main mechanisms that accelerate the transition to more circular aquaculture and food systems. Similarly, no review has included implications of applying CE to aquaculture products and systems at the production and consumption stages.

As aquaculture is highly diverse, the five CE principles of Muscat et al. could have multiple implications for a variety of aquaculture species and systems (Appendix S1, section S1). To test this, we review and discuss core concepts of Muscat et al. principles including the use and efficiency of food-grade ingredients in aquafeed, the ability to recycle resources that are inedible to humans, generation of byproducts and reuse options, environmental impacts, and energy efficiency. We provide a narrative review to (i) translate the five circularity principles to the field of aquaculture and identify implications of circularity for the main species and production systems, and (ii) identify the main pathways that would render aquaculture more circular. CE principles are applied from the perspective of achieving greater environmental sustainability. Although also discussed in this study, social and economic aspects are less developed.

This review is organised into five sections, one per principle, that summarise the main concepts developed in the five circularity principles. The five sections are followed by a discussion of the most novel concepts for the aquaculture sector, recommendations to render aquaculture more circular, and key research gaps.

2 | FIRST PRINCIPLE: SAFEGUARDING AND REGENERATING THE HEALTH OF AQUATIC ECOSYSTEMS

The 'safeguard' principle focuses on the need to safeguard and regenerate the health of agroecosystems (and therefore aquatic ecosystems). Safeguarding the health of ecosystems implies keeping aquaculture within an ecosystem's carrying capacity. This requires regenerative systems and practices that do not alter ecosystem functioning or structure beyond irreversible or unacceptable levels or, even better, can improve the provision of ecosystem services.[25]

2.1 | Production systems and their environmental impacts

Aquaculture, like other farming activities, interacts with ecosystems involved in the production and use of inputs (i.e., resource ecosystems) and those influenced by the release of outputs (i.e., receiving ecosystems) (Figure 1). These interactions operate cumulatively and synergistically at multiple spatial scales (i.e., farm, land, sea, and global)[26] and can have both negative and positive (section 2.3) impacts on ecosystems. Major stressors from aquaculture are well described in the literature (e.g., refs 27–31) and differ between productions systems, especially between fed and unfed systems but between extensive, semi-intensive and intensive systems (Figure 1 and Appendix S1, section S2).

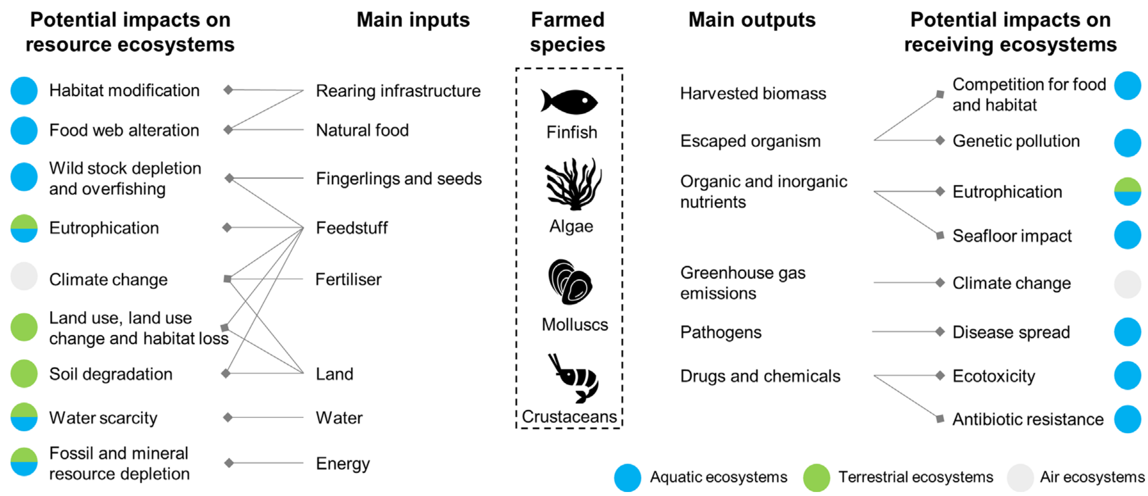

FIGURE 1 Main inputs and outputs of aquaculture systems and their potential environmental impacts on resource and receiving ecosystems based on refs 27–31.

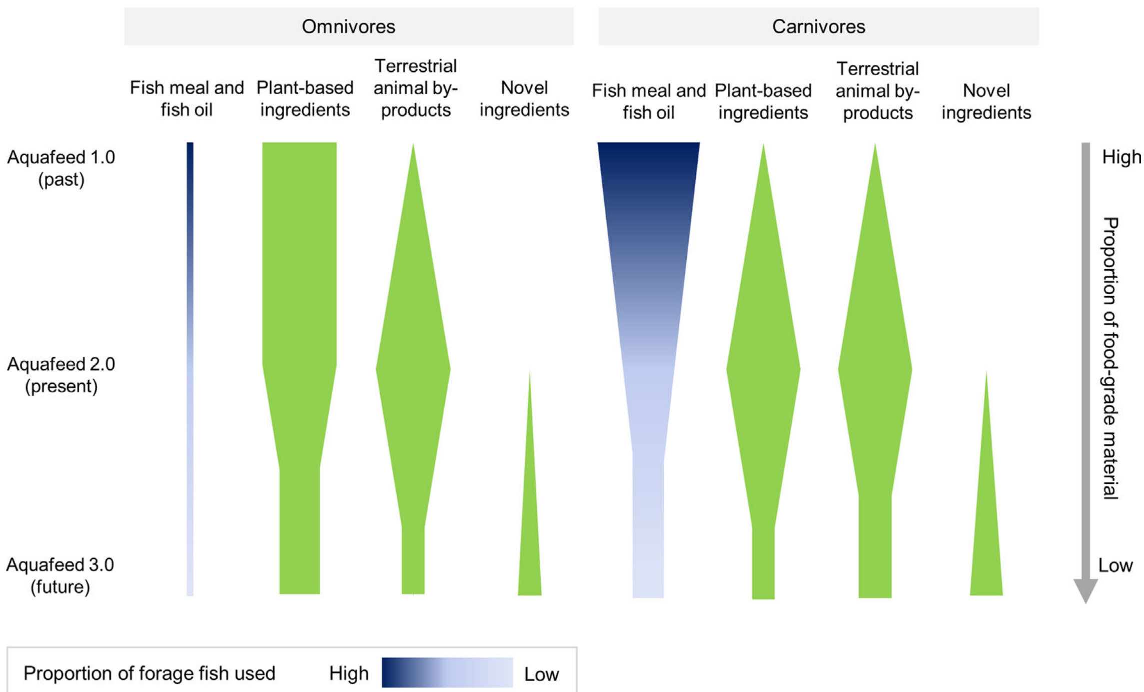

FIGURE 2 Diagram of the main types of ingredients used in the compound feed of omnivorous and carnivorous species in aquaculture over time. The width represents the approximate relative percentage of an ingredient type in the feed. For future aquafeed (aquafeed 3.0), the width is based on refs 7, 8, 19, 20, 38, 39 but remain largely speculative. According to these refs and circularity principles, aquafeed 3.0 would contain mainly non-food-competing feedstuff from the circular economy (section 4.2). In aquafeed 3.0, fish meal and fish oil would mainly be sourced from fishery and aquaculture byproducts (and no more from forage fish) that cannot be used for human food. The proportion of animal-based ingredients, fish meal and fish oil in carnivores' future diets is expected to be larger in the feed of carnivorous species than in the feed of omnivorous species because carnivores use more efficiently these animal-products. The proportion of plant-based ingredients in the feed of omnivores is expected to decrease to reduce feed-food competition and pressure on arable lands, but this proportion will remain larger than that in the feed of carnivores. The proportion of novel ingredients in the feed of both carnivores and omnivores is expected to increase due to progress in recycling technologies and valorisation of food system leftovers but a larger proportion of novel ingredients might be included in the feed of carnivores due to their relative high costs. Novel ingredients include, but are not restricted to, insects, single cell protein, and macro-algae (see a longer list in Appendix S1, section S5).

The diversity of production systems and stressors make it challenging to determine the overall environmental pressure of the aquaculture sector. First, the use of high-quality compound feeds is becoming more prevalent in the production of the vast majority of finfish and crustaceans, except for ca. 8Mt of carp species per year.[32] Even herbivorous and omnivorous species such as carps, catfish and tilapia that could feed partly from the natural food web or agricultural leftovers in semi-intensive farming systems, are increasingly being fed higher-quality compound feeds.[28] This greater reliance on compound feed can increase local stressors on aquatic ecosystems (e.g., emission of organic and inorganic nutrients in the water) and distant stressors on land and aquatic ecosystems involved in producing feedstuffs (e.g., land conversion, use of pesticides and fertiliser on land, depletion of wild stocks). Extensive aquaculture can benefit circularity by recycling nutrients, but the global trend is towards more intensified production systems and the large areas needed for extensive production easily result in land-use change.[33,34] The second trend is the ongoing switch in sourcing protein from aquatic to crop-based ingredients for the diets of carnivorous finfish (Figure 2). This switch implies that an increasing part of the environmental impacts caused by aquaculture occur on terrestrial ecosystems[35] (e.g., soil degradation, deforestation) and freshwater resources (e.g., eutrophication, water depletion).[36] The third trend is that the aquaculture sector depends more on freshwater than on marine ecosystems as freshwater aquaculture currently provides the majority (73%) of the total human-edible production from global aquaculture.[37] Overall, these three trends show that safeguarding and regenerating the quality of freshwater and terrestrial ecosystems is a priority for the sector to thrive, especially given the increasing competing for these resources for food and non-food uses. A better balance with aquaculture systems that minimise their consumption of water (e.g., recirculating aquaculture systems, RAS, or closed biofloc systems) and/or rely almost exclusively on marine waters (e.g., seaweed, mussels) could reduce the overall pressure of aquaculture on freshwater ecosystems. Furthermore, a switch to aquafeed 3.0 (Figure 2) mainly containing non-food-competing feedstuff from the CE (section 4.2) could decrease the indirect land use of the aquaculture sector.

2.2 | Carrying capacity, assimilative capacity, and resilience

The concept of carrying capacity as used by Muscat et al. refers to the 'ecological carrying capacity' and not other types of carrying capacity (e.g., physical, production, or social capacity[40,41]) defined in aquaculture.[42] Despite the variety of stressors mentioned (Figure 1), studies of ecological carrying capacity have generally focused on a few stressors specific to each form of aquaculture. In bivalve aquaculture, safeguarding ecological carrying capacity generally requires preventing phytoplankton depletion in the resource ecosystem and impacts on sediments.[43] In fed aquaculture, safeguarding ecological carrying capacity usually focuses on maintaining the load of particulate and dissolved nutrients within the assimilative capacity of the receiving ecosystem.[44] Current research is expanding the concept of ecological carrying capacity to include effects of other important stressors, such as diseases and pathogens.[45] Carrying capacity has already been used to support aquaculture management. At the farm scale, it can be used to set the maximum stocking density of a farm before installation, to support monitoring programmes, or for certification purposes.[42] At the waterbody or catchment scale, it can be used to determine the maximum number of licences to issue in a specific zone. However, the concept of carrying capacity as currently used in the aquaculture literature rarely extends to the health of distant global resource ecosystems or to the long-term ability to provide ecosystem services.

2.3 | Regenerative practices and systems

Regenerative aquaculture can be defined as a farming approach that uses aquatic ecosystem (instead of soil in agriculture) conservation as the entry point to regenerate and contribute to provisioning, regulating, and supporting ecosystem services.[46] Like for soil, ensuring a healthy aquatic ecosystem implies regulating carbon and nutrient contents, maintaining physical quality (e.g., currents, abiotic parameters), and conserving biodiversity. It also implies using ecologically sound practices to decrease environmental stressors such as minimising feed use, banning the use of toxic substances, preventing escapees, and avoiding introducing alien species (Appendix S1, section S2). A healthy aquatic ecosystem also implies promoting agroecological practices that can minimise external inputs or impacts on the environment,[47] such as using mixed species systems such as IMTA, and other integrated systems (section 5.2). Mixed species systems can have many positive effects on receiving ecosystems[48] depending on species associations and other factors (e.g., location, season, farming technology). The key benefit, and often the main reason to adopt such a system, is lower net nutrient emissions.[49] Other benefits can include maintaining water quality,[50] recycling water,[51] decreased risk of fish escaping,[52] less need for chemical treatments,[53] and habitat preservation.[54] A first core aspect of regenerative aquaculture would therefore be the farming of complementary species[48] that have ecological synergies to increase and improve environmental benefits.

Another core aspect of regenerative aquaculture is to develop aquaculture in the context of ecosystem functions and services, as commonly recommended in previous aquaculture sustainability frameworks.[26,55] The objective is to maintain ecosystem services provided by the natural ecosystem and to provide new services via aquaculture activities (see a list in ref 56). This includes the role of fish ponds in retaining water, recycling organic nutrients, and providing fertilisers for adjacent crops.[57–59] For extensive pond systems, some of these services (e.g., providing fertilisers and habitats for biodiversity) depend strongly on pond management practices and thus aquaculture activities.[60–62] Ecosystem services of marine aquaculture systems are also well documented, especially those provided by extractive marine species[63,64] such as nutrient removal by bivalves or seaweed.[65,66] Based on these ecological benefits, extractive aquaculture has been recommended as a way to restore natural ecosystems (i.e., restorative aquaculture[67]) and could generate net positive environmental results. The shift from protecting to restoring and regenerating ecosystems may require new aquaculture business models that are better suited for creating additional monetary or non-monetary value from the ecosystem services provided and consumed by aquaculture systems.

3 | SECOND PRINCIPLE: AVOIDING PRODUCING NON-ESSENTIAL PRODUCTS AND WASTING THOSE THAT ARE ESSENTIAL

The 'avoid' principle focuses on avoiding unnecessary extraction of natural resources and environmental impacts upstream and downstream in the value chain by producing only essential products and not wasting them (e.g., food loss and waste). This principle explores the relative value of different products, the characteristics that make them more or less essential, and identifies geographic and social contexts in which these products are considered essential. Aquaculture mainly produces food, but also serves other purposes (e.g., production of pharmaceuticals, cosmetics, ornamental fish, and biofuel; conservation aquaculture[68]) that represents 18%–23% of global volumes (global volumes and percentages of aquatic animals, algae and ornamental fish used as human food based on refs[30,32]). Food is essential, but not all aquaculture food products may be equally essential.

3.1 | Nutritional and health benefits of fresh aquaculture products

From a nutrition perspective, aquaculture products can be considered essential given that many provide energy and especially essential macro- and micronutrients in relatively large amounts relative to the recommended human intake. In aquaculture products, these nutrients include high-quality protein that contains essential amino acids, essential omega-3 fatty acids, and bioavailable micronutrients.[69] However, the nutritional composition and nutrient bioavailability of aquaculture products for humans can vary greatly, partly due to the wide variety of species produced, ranging from plants to molluscs, crustaceans, and finfish (details per taxa group is provided in Appendix S1, section S3). For fed aquaculture diet composition can also strongly influence the nutrient profile of aquatic products (Appendix S1, section S3).

The relative importance of aquatic foods varies depending on the nutritional needs of the target population but also based on the accessibility and availability of the aquatic foods.[70] Consuming aquatic foods can have multiple health benefits for specific age classes (Appendix S1, section S3), and evidence suggests the nutrients they provide are even more important in the first 1000 days of life.[71] Thus, the accessibility and availability of aquaculture products is crucial, especially for children, pregnant women, and women of childbearing age in the Global South, where consumption of omega-3 fatty acids does not meet health recommendations and micronutrient deficiencies are persistent.[72–74] For aquaculture to have a clear and positive impact on human health, it is crucial to produce the species that are most likely to contribute to food security.

3.2 | Contribution to food security

Aquaculture's contribution to food security should be analysed species by species, as previous attempts to understand the role of the entire sector resulted in contrasting and incomplete narratives (Appendix S1, section S3). Henriksson et al.[31] classified the 69 most produced species (excluding aquatic plants) into four groups as a function of mean prices and production volumes, which influence the affordability and accessibility of aquaculture products, respectively. The most affordable and accessible species (i.e., 'accessible commodities') include carp, catfish, tilapia, milkfish (*Chanos chanos*), snakehead (*Channidae* spp.), and bivalves. These species are usually sold in local or regional markets at relatively low prices due to their tolerance to disease and abiotic factors, and their ability to use primary producers, agricultural byproducts, or food waste as feed.[31] Two other groups proposed by Henriksson et al., namely 'accessible niche' species (low prices, low volumes) and 'luxury commodity' species (high prices, large volumes), have a moderate contribution to global food security, but can have an important contribution to protein and fatty acids supply locally. For example, species like Atlantic salmon (*Salmo salar*) and Rainbow trout (*Oncorhynchus mykiss*), are classified luxury commodities and are currently among the most consumed aquaculture species in EU countries[75] and in the USA.[76] In this classification, the least essential species include cash- and export-oriented species (i.e., 'luxury niche' species), such as abalone (e.g., *Haliotis discus hanni*), Pacific tuna (*Thunnus thynnus*), giant river prawn (*Macrobrachium rosenbergii*), and Coho salmon (*Oncorhynchus kisutch*). The combination of high prices, in part due to the intensive use of resources (e.g., high-quality feed, energy, therapeutants), costly production systems (e.g., offshore, RAS), low volumes, and international trade often via airfreight, reduce their accessibility to low-income consumers. Although accessible commodities represent a high percentage of total production, the trend is towards more luxury products.[32] The income generated by these luxury products could be considered an indirect contribution to food security (Appendix S1, section S3); however, even if future studies were to determine the impacts of income earned from aquaculture,[74] those who benefit from these profits would not be the nutritionally vulnerable.[77] Hence, prioritising the production of accessible commodities over that of luxury species is beneficial from the perspective of resource use and human utility.

3.3 | Loss and waste in aquaculture value chains

Achieving nutrition security requires reducing loss and waste in the value chain of essential aquaculture products. Although the main drivers of food loss and waste in aquaculture value chains are well documented, limited data are available on the precise amounts of food loss and waste in global aquaculture. Many sources refer to a 2011 FAO report[78] that provides aggregated values for fisheries and aquaculture products. According to the report, aquatic food-supply chains in all geographic regions experience food loss and waste from primary production to final consumption; however, the percentage of loss varies (ca. 29%–50% among regions), as do the main stages at which loss and waste occur[78] (Appendix S1, section S3). According to the FAO,[78] North America and Oceania had the highest loss (ca. 50% of total production), half of which occurred at the consumption stage.[79] These loss and waste estimates for aquatic foods are higher than those for terrestrial meat (20%–27%), dairy products (10%–25%), oilseeds and pulses (18%–29%), and cereals (20%–35%), likely due to the highly perishable nature of aquatic foods. Hence, reducing loss and waste in aquaculture value chains is a priority, especially for the species that contribute the most to food security, but context-specific mechanisms will have to be used to do so, as some causes of loss are region-specific (Appendix S1, section S3 and section 7.3).

4 | THIRD PRINCIPLE: PRIORITISING BIOMASS STREAMS FOR BASIC HUMAN NEEDS

The third principle focuses on prioritising the use of biomass and natural and limited resources for basic human needs. One important aspect of this principle is to avoid feed-food competition,[80] such as by using arable land to produce human food (and not feed) and feeding farmed animals byproducts from these food systems[81–84] and/or products that humans cannot or do not want to eat (i.e., 'non-food-competing feedstuff').[8]

4.1 | Efficiency of using land, fresh water, and feed at the product level

At the food-system level, optimising the use of land, fresh water, or biomass requires allocating these resources to the most efficient food-production systems and species (i.e., those that provide the most essential nutrients, health benefits, and other services per unit of resource). Although resource-use efficiency varies widely among aquaculture systems and species, environmental footprint studies (e.g., life cycle assessment [LCA]) indicate that some aquaculture production systems are better positioned than terrestrial animal production systems. On average, fish species have lower land use and similar water use to most terrestrial animal species, but most plant-source foods are more resource-efficient than animal source foods (ASF).[85] In fed aquaculture systems, most land use is associated with feed production (and hence often located out of the farm).[27] For this reason, extractive species, such as seaweeds, filter feeding finfish, and bivalves, generally outperform other aquaculture species in land and water use, and chicken (the most resource efficient terrestrial ASF).[27] Using food system byproducts as feed (e.g., rice bran) or fertiliser (e.g., manure), as performed in semi-intensive systems, can further decrease the amount of land needed for aquaculture.

Although it has clear limitations,[86] comparing the feed-use efficiency of aquaculture animals to those of terrestrial animals based on the feed-conversion ratio (FCR) indicates a better feed-use efficiency in fish than in pigs and cattle, and similar to that of chickens.[87] The relatively low FCRs of fish is due to using less energy because of their poikilothermic metabolism, buoyancy in the water and relatively lighter skeleton. Furthermore, aquaculture has an unexplored potential to be more resource efficient if efforts are invested in improving (e.g., through genetics, feeding, disease reduction) and promoting more efficient aquaculture species.[31] In terms of environmental footprint, aquaculture products show high variability, but with many species having advantages over other ASF and large potential for additional resource efficiency gain. Product environmental footprints, however, do not consider potential direct[88] or indirect feed-food competition[89] and thus do not fully capture the land, freshwater or feed-use efficiency of these aquaculture systems.

4.2 | Feed-food competition

Direct feed-food competition occurs when food-grade or human edible ingredients are used in feed. The extent to which global aquaculture currently uses food suitable for human consumption is unknown, but certain aquaculture systems and species are more likely to cause feed-food competition than others. Unfed species and unfed systems do not cause direct feed-food competition, as their feed is based on resources naturally available in the environment that (currently) are usually not consumed by humans. Thus, most extractive species and extensive systems are likely to have a positive net contribution to the human food supply. On the other hand, the extent to which fed species and systems may contribute to direct feed-food competition depends mainly on (i) the percentage of human-edible ingredients in the diet, (ii) the ability of these species to digest and retain nutrients from diverse non-food-competing feedstuffs, and (iii) the human-edible yields of the animal products.[90]

Soya bean, fishmeal, fish oil, and maize products are the most commonly used ingredients in aquafeed in terms of volumes.[13,91] Fishmeal and fish oil are increasingly made from byproducts (27% and 48%, respectively[10]) that are less likely to be food-grade, but some estimates indicate that more than 90% of the forage fish used to make fish meal could potentially be consumed by humans[92] (Appendix S1, section S5). Similarly, most of the protein in soya bean (and potentially in soya bean meal) can theoretically be used in human food.[93] Thus, a high percentage of raw ingredients used in aquafeed could theoretically be re-directed to human food, but maintaining food-grade standards (e.g., hygiene, aspect) can involve additional costs, market acceptance should be prepared, and adequate regulations should support the transition from feed to food markets. Determining whether a foodstuff is human-edible is difficult as the definition can be based on physiological criteria (e.g., digestibility), the market, cultural norms, or legal considerations, and can change due to advances in food technology.[94,95]

Beyond the human edibility of a foodstuff, some analyses also include the indirect feed-food competition (e.g., use of arable land to grow fodder maize instead of food maize) to determine which feedstuff are food-competing. For example, Sandström et al.[96] estimate that 49% of the ca. 67 Mt of feedstuffs used in fed aquaculture globally (farm made + commercial feeds) causes direct or indirect feed-food competition, especially processed wild fish, maize, and wheat. The 49% of food-competing feedstuff in aquafeed is lower than that estimated for poultry (68%) and higher than that for pigs (38%) and cattle (3%). This relatively high percentage supports the need to identify non-food-competing feedstuffs. Ingredients that are considered non-food-competing in aquafeeds include byproducts from crops (e.g., wheat bran), terrestrial or aquatic animals (e.g., fishmeal, blood meal, feather meal, meat and bone meal), and industries (e.g., biodiesel, brewing), as well as food waste.[97] Some novel ingredients used in aquaculture feedstuff (e.g., insects larvae, single cell organisms, and macro-algae) can also be considered non-food competing depending on their production process and possible uses (Appendix S1, section S5). Reducing indirect feed-food competition in aquaculture will imply reducing its dependence on arable and highly productive lands. For example, by reducing its dependence to soya bean meal, because its demand contributes to soy bean production and therefore can be considered as an indirect competitor to human food.[90,98] Changing land use from crops used in compound aquafeeds to food crops will increase the global amount of food produced; however, the consequences of this change on biodiversity, productivity, and ecosystem services are unknown. Likewise, reducing feed food competition caused by aquaculture would imply reducing the dependence on reduction fisheries, and making a more efficient use of forage fish stocks for food purposes. Overall, more research is needed to quantify indirect feed-food competition in aquaculture and the potential benefits of reducing it. Further research is also needed to clarify the potential trade-offs linked with re-allocating any resources for another use.

Feed-food competition in aquaculture can also be minimised by balancing the different types of animals produced, and by increasing human edible yields. In circular food systems, the main advantage of omnivorous species is their ability to transform plant-based byproducts into valuable nutrients (Figure 3). In contrast, carnivorous species are fed diets with high protein and fat contents and a low carbohydrate content, indicating that their role in a circular food system involves mainly upcycling animal byproducts. Although produced in smaller volumes, detritivorous species such as sea cucumber, sea urchins, and other ecosystem scavengers[39] presenting an interesting nutritional value[99] should be considered, as they can feed upon low-quality organic matter such as fish faeces.[100] The human-edible portion of aquatic animals depends greatly on the type of animal and is influenced by the processing industry and consumers' cultures (Box 1). For some aquatic animals, no byproducts remain after processing and consumption. For example, small fish (e.g., tilapia, anchovies, sardines), crustaceans, molluscs, and echinoderms (e.g., sea cucumbers) are often eaten whole, and in the process provide more micronutrients in the diet than eating only the fillets or meats.[10] However, processing the main products, mainly the fillet or meat, often produces several byproducts (e.g., heads, skeletons, trimmings, viscera, blood, skin, shells, tails) that are consumed directly as food or processed into food products in certain regions (Box 1 and

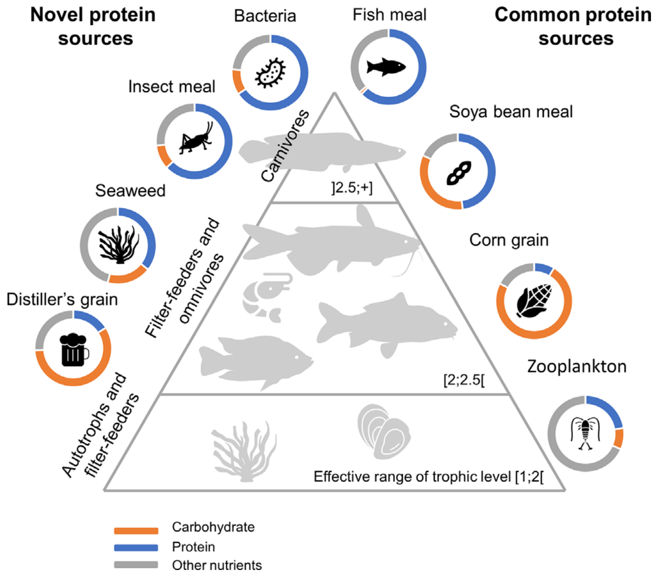

FIGURE 3 Novel and conventional protein sources used in aquafeed and examples of species that can use them best depending on their effective trophic level (based on ref 106) and the carbohydrate (orange) and crude protein contents (blue) of the ingredients. According to circularity principles, human food has the highest priority for all novel and conventional human-edible feedstuffs.

Figure 3).[101,102] Primary products obtained from processing represent 35%–70% of fish, 20%–60% of crustaceans, and 10%–24% of bivalves,[103] depending on species, market size, and technology.[10,101,104,105] Human-edible yields of aquaculture products can be increased by producing small animals that can be eaten whole or by consuming more of processing byproducts.

Until recently, the net contribution of aquaculture systems to the global food supply has been considered mainly through their 'fish-in-fish-out' ratio, which estimates the dependence of aquaculture systems on marine ingredients and their ability to produce net gains in fish (but not necessarily in human-edible protein or other nutrients). Many aquaculture species generate net gains in fish, but carnivorous species tend to consume as much or more fish than they produce.[107] Overall, global fed aquaculture currently produces three to four times as much fish as it consumes[107] (see ref 30 for more on the 'fish-in-fish-out' ratio). Few studies have analysed food-grade materials other than fish or estimated the overall net food supply of aquaculture systems. Doing so requires a method that can consider the percentage of human-edible ingredients in an animal's diet, its nutrient conversion efficiency, and its human-edible yield, such as the human-edible protein conversion ratio.[93] It was recently applied by van Riel et al.[90] to Atlantic salmon, Nile tilapia, common carp (*Cyprinus carpio*), and white-leg shrimp reared in intensive systems. In their study, the four species were considered net consumers of human-edible protein. These authors also showed the importance of defining food-competing resources when assessing human edible protein conversion ratio for fish species.

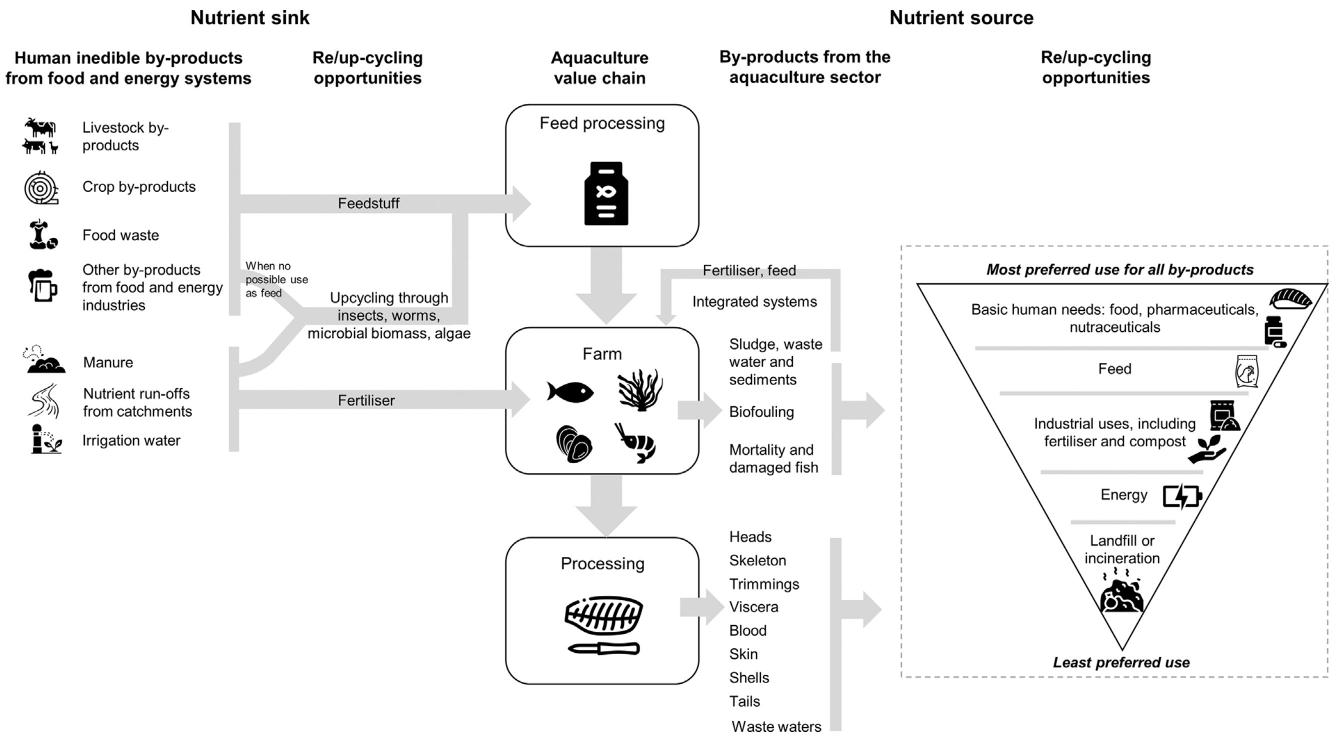

FIGURE 4 Recycling opportunities in the aquaculture value chain for food-system byproducts and in other sectors for aquaculture byproducts (based on refs 15, 101, 102, 108). A hierarchy of biomass recovery should be followed when recycling food-system byproducts in the aquaculture value chain (left side of the figure) and when recycling aquaculture byproducts (right side of the figure) to avoid food-grade ingredients ending up as feedstuff or fertiliser for aquaculture systems.

BOX 1 Use of aquaculture byproducts for food and non-food purposes

Many opportunities exist to process and use aquaculture processing byproducts for human food and non-food purposes.[15,101,102,108] In Japan and Taiwan, salmon belly flaps are a popular food consumed barbequed or fried.[102,109] Norwegians consume cod cheeks and tongues, while popular soups made from fish leftovers (e.g., heads, skeletons, gonads) are commonly consumed in France (e.g., bouillabaisse) and the Czech Republic (e.g., halászlé, vánocní rybí polévka).[23] Processing technologies enable converting aquaculture byproducts into low-cost food products such as fish surimi, sausages, pâté, cakes, snacks, soups, and sauces.[10] This can increase the human-edible portion of the fish, as long as these products have a high nutritional content, and have no detrimental effects on human health. Ultimately, functional and bioactive compounds can be isolated from aquaculture byproducts and used in nutraceuticals. However, major barriers exist, including a lack of markets, a small and inconsistent amount of available products, and the high cost of extraction technologies.[102] Examples of non-food uses of aquaculture processing byproducts include processing fish skin to produce leather and craft handbags[102] or as bandages to treat patients with full-thickness burns[110]; transforming chitin and chitosan in crustacean shells into antimicrobial substances, cosmetics, and agrochemicals[111]; transforming bivalve shells into calcium carbonate or calcium oxides for industrial applications or jewellery[112]; and using collagen and gelatine from fish heads, skeletons, or skin for pharmaceutical purposes.[113] The amounts and quality of material required, the costs of the technology involved, processing yields, economic values, and markets for the final products vary greatly, making some of these options more realistic than others. According to Olsen et al.,[101] food and feed ingredients are the most realistic upcycling of aquaculture processing byproducts.

Beyond the feasibility of upcycling, it is important to ensure that these side streams are used efficiently and follow the concept of 'cascade' use. As Muscat et al.[6] explain, biomass cascades should be based on human needs and resource efficiency rather than economics. With this aim, recovery-hierarchy pyramids can help to prioritise the best alternative to reuse these byproducts. These pyramids have been developed for aquaculture side streams (e.g., refs 102, 104) (Figure 4). The pyramid follows the Muscat et al.[6] 'prioritise' principle and emphasises retaining the food-grade value of the products and then considers further recycling to produce goods that meet other basic human needs (e.g., pharmaceuticals, clothing), animal feed, industrial uses, composting, and energy production. Incineration or landfills can be considered when biomass has no value for other purposes. It is unclear how most aquaculture byproducts are currently upcycled and thus how well this recycling follows the recovery-hierarchy pyramid.

5 | FOURTH PRINCIPLE: USING AND RECYCLING BYPRODUCTS OF AGRO- AND AQUATIC ECOSYSTEMS

The 'recycle' principle focuses on recycling nutrients and carbon from byproducts into the bio-based system in a way that is safe for humans, animals, and the environment. Agro- and aquatic ecosystems can both produce (source) and reuse (sink) byproducts and waste.

5.1 | Nutrient waste from aquaculture and opportunities to recycle it

At the farm scale, the main nutrient-rich byproducts include solid and dissolved metabolic waste, uneaten feed (in animal production systems), mortality, and biofouling. In fed aquaculture systems, unlike in terrestrial livestock systems, uneaten feed can represent most of the organic waste generated. In well-managed marine systems that feed complete pellets, ca. 1%–6% of the distributed feed remains uneaten,[114] but much higher losses have been observed on some farms,[115] depending on feeding systems and practices, feed types, and hydrodynamic conditions. Overfeeding should, and can, be avoided with better record keeping and training of the farmers; in contrast, decreasing metabolic waste is less straightforward. The amount of metabolic waste produced by certain aquaculture species has decreased greatly due to advances in animal nutrition,[116] use of exogenous enzymes and probiotics,[117] genetic selection,[118] and transgenic manipulation.[119] However, no zero-waste animal production system exists, hence the need to recycle the unavoidable losses in the production system, the receiving ecosystem, or beyond.

The ability to collect and use excess nutrients from metabolic waste and uneaten feed depends greatly on the farming system. In freshwater ponds or RAS, settled sediments, wastewater, and/or concentrated sludge can be extracted and used for several purposes, including direct fertilisation of cropland or ponds,[120] and to produce fertiliser, compost,[121] biogas, or biofuel.[122] The co-location of aquaculture and the other agricultural or industrial activity is, however, often critical to their success because of the logistics and costs involved in the transport of the wastes. Reusing waste from marine systems to fertilise land is more complex due to its salt content. Despite the many ponds in Asia, using pond sediment is not a common practice, notably because the removal of sediment is labour intensive, impractical, and revenues low to non-existent.[123] A cost-effective solution to recycle the nutrients is pond drainage, and a subsequent temporarily dry period to activate the mineralisation processes. Similarly, RAS sludge is often discarded in Europe as sewage due to regulations[21] and the relative benefits (e.g., cost, practicality) of inorganic fertilisers. Extracting solid waste from cage systems is more complex as they usually have no physical barrier to prevent particles from passing through the nets and being discharged into the surrounding water. These systems rely on the dispersal and assimilation ability of the receiving ecosystems (section 2.2). Thus, there is potential to use excess nutrients from aquaculture systems, but the complexity of collecting and processing the waste from certain systems (e.g., marine) may encourage development of systems that can recycle some excess nutrients internally (e.g., IMTA) and thus decrease their emissions to the environment.

5.2 | Recycling waste in integrated aquaculture systems

Many aquaculture production systems are circular by design, in that they are able to recycle aquaculture waste or other types of waste from the food system. This definition of circular aquaculture overlaps with the better-known concept of integrated farming systems, in which output from one subsystem (either aquatic or terrestrial) that could have been wasted is used as input for another subsystem.[124] This concept has been widely explored in aquaculture,[49] resulting in many variations of integrated/circular systems depending on the number and types of taxonomic groups, the farming technology, and the types of resources recycled (Appendix S1, section S4). A common feature of these systems is that they rely on synergies and trophic complementarity among the taxonomic groups in the system (e.g., multiple marketed species, micro-organisms, the rest of the aquatic food web) to transform and/or upcycle nutrients in the solid and dissolved waste. Theoretically, IMTA may be the circular form of aquaculture with the most potential as it can be adapted to virtually any type of rearing technology and any environment (Table 1). In practice, different barriers currently limit IMTA implementation at commercial scale, including the limited economic benefits obtained from the nutrient mitigation service, challenges related to scaling up to reach substantial mitigation level, economic issues (capital and maintenance costs), complexity of system management, risks to food safety and lack of governmental support and commitment to implementation and innovation.[125–127]

The concept of integrated aquaculture is versatile and can include interactions with terrestrial food systems (e.g., integrated agriculture/livestock-aquaculture, IAA), urban systems (e.g., integrated peri-urban aquaculture, IPA), and larger spatial scales (e.g., regional IMTA) to recycle terrestrial nutrients. In IAA and IPA systems, ponds play a key role in recycling manure from livestock, crop residues, or even human waste as fertiliser.[128] IAA was widely practiced by small households in freshwater environments, mainly in Asia,[123] but it declined due to the trend for intensified monocultures.[129] A recent review of nutrient-retention efficiency in a four-species (i.e., salmon, kelp, mussels, and polychaetes) marine IMTA system suggested that 40%–75% is a realistic estimate.[130] Fewer data are available for other types of integrated systems, and large-scale studies are required to determine whether they can be applied to commercial-size farms before drawing conclusions about their true performances.

6 | FIFTH PRINCIPLE: USING RENEWABLE ENERGY WHILE MINIMISING OVERALL ENERGY USE

The 'entropy' principle promotes using less energy (i.e., minimising cumulative energy demand and emergy use), re-evaluating reasons for

TABLE 1 Examples of integrated aquaculture systems and the main rearing technologies for fed aquaculture systems.

		Rearing technologies				
Type	System	Ponds	Cages	Raceways	Tanks	RAS
Monoculture	Biofloc	X	–	–	X	–
	Ponds	X	X	–	–	–
Polyculture	Traditional polyculture	X	X	–	–	X
	Integrated multitrophic aquaculture	X	X	X	X	X
	Aquaponics	–	–	–	X	X
	Integrated agriculture-aquaculture	X	–	–	–	X

Note: The table does not show all possible combinations (e.g., biofloc polyculture, biofloc aquaponics).
Abbreviation: RAS, recirculated aquaculture system.

using energy for basic human needs, moving towards renewable sources, and efficient use of energy and the materials required to produce this energy.

6.1 | Hotspots of energy use

The methods used to analyse value chains, such as LCA and emergy accounting (Appendix S1, section S6), demonstrate that feed production, on-farm operations, and juvenile production contribute most of the energy footprint of aquaculture systems. Many LCA studies of (fed) aquaculture systems indicate that feed production uses the most energy,[131] mainly due to the energy (e.g., electricity, oil) and other inputs (e.g., inorganic fertilisers) used to harvest, process, and transport raw ingredients and process them into complete feed. On-farm operations, such as water aeration/oxygenation,[132] recirculation (pumping),[133,134] and heating/cooling[135] are often highlighted as hotspots of energy use, particularly in RAS or intensive pond systems. Emergy accounting of aquaculture systems has also identified several of these drivers, and indicates that feed and the purchase of fingerlings often have the highest emergy inputs.[136] Post-harvest phases such as transport and distribution of aquaculture products can also be energy intensive,[137] especially when the products are airfreighted[138] or sold live. Identifying these hotspots can help better understand differences in energy efficiency among (circular and linear) production systems and species.

6.2 | Production system, species, and other key drivers of energy efficiency

In aquaculture, energy use can largely vary between the production systems.[131,139] Per unit of product, highly intensive systems such as RAS or aquaponic systems[140,141] tend to use the most energy,[131,133,134] while cage systems and extractive bivalve systems use relatively little energy.[131,142] As mentioned, these differences among production systems are mainly due to differences in the amount of energy used for on-farm operations. From an emergy perspective, i.e. when considering energy flows from nature (e.g., sun, rain, wind) and from human inputs (e.g., labour), the few studies that compare production systems with different intensities do not always demonstrate that extensive systems are more energy efficient than more intensive systems.[135,143,144] A recent review of emergy performances of aquaculture systems (David et al.[136]) concluded that monoculture usually uses more emergy from non-renewable sources than polyculture or integrated systems that use solar energy through plankton/crop production or rain to fill the ponds. However, the few emergy and LCA studies that compare the energy efficiency of monoculture and polyculture systems,[145–148] or monoculture and integrated systems,[149–152] could not demonstrate that one system outperforms the other.

The choice of species can also greatly influence the energy footprint of aquaculture production. First, the trophic level of the reared species influences the system's energy efficiency.[153] Systems that produce carnivorous species generally use more energy than those that produce extractive species,[154,155] mainly due to the contribution of feed to the energy footprint and because extractive species are usually produced only in extensive low tech systems (Appendix S1, Figure S1). The relation is less clear between intermediate trophic levels. Second, the difference between a species' water temperature requirements and the water temperature of the climate in which it is produced can also influence the amount of energy used. RAS are located mainly in the Global North, especially in Norway and Canada.[156] Consequently, several of the main species farmed in RAS (e.g., tilapia, catfish, shrimp) are warm-water species,[157] which require additional energy to maintain adequate conditions, especially in colder climates. From an energy-use perspective, this raises questions about whether warm-water species should be produced in RAS in cold countries (and vice-versa), similar to producing food where it is most environmentally efficient to do so.[158]

The energy source also strongly influences dependence on fossil fuels and the environmental footprint of aquaculture products. Although this is country specific, for land-based farms, electricity is often obtained from the central grid, while cage-based farms generally use diesel and other fossil fuels.[159] The influence of the electricity source on the environmental footprint has been shown for RAS as well as for flow-through and bivalve systems,[131,134] hence the importance of a transition to renewables or low-impact energy sources in most energy-intensive systems. This is for example possible via industrial symbiosis (use of waste heat from industry), or on-farm production of energy (e.g., wind turbines, solar panels, biomass, or biogas units). Furthermore, minimising energy use and switching to renewable sources will help aquaculture businesses to cope with the volatility of electricity and fuels costs, but may require adequate access to finance and/or funding grants to implement the required adaptations.

7 | DISCUSSION, IMPLICATIONS, AND RECOMMENDATIONS FOR MORE CIRCULARITY

One objective of this review was to examine the current implementation of CE principles in the aquaculture sector. At first glance, it might seem like 'everything old is new again'. Some of the underlying concepts of the 'safeguard', 'entropy', and 'recycle' principles are already well researched and well implemented (Appendix S1, section S7). In comparison, the 'avoid' and 'prioritise' principles are much less explored, but they provide important opportunities to decrease environmental impacts of aquaculture of the food system, increase food security, and improve human well-being.

7.1 | Towards more essential and less resource-intensive aquaculture species

The essential nature of aquaculture products has not been challenged per se, and a large body of literature has mentioned their benefits for nutrition, health,[160] and food security.[31] We chose these criteria to compare their essential nature, although criteria could include additional benefits of aquaculture products or systems, such as generating income, asset savings, a source of employment, or cultural values. This comparison showed that certain groups of animal species produced in large volumes at relatively low prices can provide the most benefits for nutrition, health, and food security. These forms of aquaculture are generally referred to as 'nutrition-sensitive', as they support the nutrition and well-being of vulnerable populations.[72,74] This review also shows that despite their favourable nutrient profiles, luxury aquaculture species are less essential for global food security because they do not target sub-populations with the greatest needs, but instead feed mainly healthier and wealthier populations in the Global North. Although not included in our criteria, the environmental performances of accessible commodities are generally higher than those of luxury species,[31] except for some salmonids (e.g., Atlantic salmon, rainbow trout) that are hyper-efficient due to technological advancements. For these reasons and from a broader resource and equity perspective, global aquaculture development should focus on accessible and resource efficient species. Some luxury commodities with low environmental footprint and large markets accessible to middle class, such as salmonids, can also contribute reducing impacts from the food system and enhance human health, especially if they replace ASF with higher GHG emissions, such as red meat.[160,161] At the same time, unnecessary resource consumption and impacts could be avoided by shifting from luxury towards low-impact and equally healthy alternative aquatic species (e.g., bivalves, carp).[27,161] These diet changes are particularly needed in the Global North, where most of the luxury niche species are produced and/or consumed and where consumers can more easily access and afford low-impact aquatic food alternatives.

7.2 | More food, lower environmental impacts, but less fed aquaculture

The consequences of reducing feed-food competition in aquaculture are not well known, as the topic is rarely studied. Feed-food competition is an emerging concept, and more research is clearly needed to better define what resources can be considered as food-competing or not. However, our literature review provides four preliminary conclusions. First, feed-food competition concerns mainly some fed aquaculture systems. Second, the high percentage (ca. 50%[96]) of food-competing feedstuffs in aquaculture must be decreased to increase the global food supply and reduce environmental impacts. Sandström et al.[96] showed that replacing some of the food-competing feedstuffs used to feed livestock and aquaculture with food-system byproducts could increase calories in the global food supply by 10%–16% and protein by 12%–19%. Reducing feed-food competition in aquaculture has potential (but unquantified) environmental benefits, as the main food-competing feedstuffs have lower environmental footprints than farmed aquatic or terrestrial animals fed these resources[85] and these benefits could increase if aquaculture animals were fed only non-food-competing feedstuffs and planktonic food web. At the farm scale, however, this could generate trade-offs in environmental performances due to higher FCRs and increased metabolic loss, for example because of lower digestibility of non-food-competing feedstuffs compared to high-quality ingredients. Third, feeding aquaculture animals only non-food-competing feedstuffs would likely require a decrease in fed aquaculture. This scenario has been explored for livestock[83,84,162] due to the limited availability, quality, and potential competition for non-food-competing feedstuffs.[13] Therefore, eliminating feed-food competition would require a decrease in fed aquaculture, perhaps most in regions that rear species of medium-to-high trophic level, such as Europe, Oceania, and the Americas.[90] Fourth, reducing feed-food competition would require maintaining the food-grade quality of aquaculture processing byproducts and consuming more of them. Total human-edible yields could double for some aquaculture species when using as many byproducts as possible for human food.[163] This shows the importance of reducing loss and waste in post-harvest stages, as well as changing consumer behaviour to increase environmental efficiency of the food system.

7.3 | Six priorities and mechanisms to make aquaculture more circular

First, policy development and technical interventions are needed to favour the production and demand for most essential species by making them more economically attractive and marketable. As mentioned, from a global resource use efficiency and equity perspective, a dietary shift from luxury to accessible commodity species is desirable. Despite increasing concerns related to environmental sustainability, profitability remains the main driver for farmers to farm luxury species and intensify production.[31] Net returns for shrimp farmers in Vietnam, for example, are correlated with level of intensification, while feeds remain one of the largest expenses.[164] Thus, better utilisation of low-cost byproducts that are not food-competing could be a win-win situation, but a transition that is most easily made for omnivorous species. Improved extensive and semi-intensive systems that often rely on agricultural byproducts (e.g., rice bran, wheat bran, and mustard oil cake) would benefit both environmentally and financially from adopting better farming practices, as excessive use of these feed resources is commonplace due to their inexpensive nature.[132] Reducing feed producers reliance on high-quality feed ingredients would also make farmers more resilient to volatility in global feed commodity markets. Higher market prices for omnivorous species would also be needed to support profitability with farmers, something that largely is driven by consumer demand and hard to change, except if product prices are affected. Price remains one of the main factors that influence decisions about purchasing aquatic food.[165] The valuation of ecosystem services provided and consumed by aquaculture systems and their accounting in the product prices (i.e., true pricing) can therefore be a way to promote more sustainable practices and products.[59] Fiscal instruments, such as taxes (or credits) on resource use (e.g., resource rent tax in Norway[166]), therapeutant release or nutrient, GHG emissions, can also help to better internalise the environmental (and ideally the social) costs of the products. Such taxes would make most environmentally friendly aquaculture products more economically attractive than those with large footprints. Lastly, governance should ensure power dynamics in the supply chain that allow a fair redistribution of wealth and welfare among farmers and other actors of the value chain.[167,168] Overall, the challenges of putting CE into reality may require creating new circular business models that are better suited for creating additional monetary and non-monetary value and incorporate a long-term perspective[169] and adequate policies to facilitate the necessary changes in aquaculture businesses[127,170] and value chains.

Second, it is crucial to reduce loss and waste at the farm and post-harvest stages, particularly for the most essential aquaculture species. Simple interventions are available to reduce loss and waste from farm to fork.[23] At the farm scale, many essential aquaculture species have below-average productivity,[31] partly due to high mortality resulting from disease outbreaks,[171] oxygen depletion,[172] or inadequate management practices. These losses should be avoided through simple biosecurity measures, such as aerating the water, improving feed management, and appropriate slaughtering methods.[23,31] In the Global North, where farm loss is often due to harmful algal blooms, diseases, and climate-related losses,[30] this requires focusing on site selection, cage design, and disease prevention (e.g., vaccines, nutraceuticals). For the post-harvest processing and distribution stages, improving quality-control measures such as good manufacturing practices, risk analysis, and critical control points are particularly important to maintain food-grade standards, make better use of animal byproducts,[101,102] and thus increase human-edible yields. Reducing mortality and increasing human-edible yields would increase the net food provision and environmental performances of aquaculture species. In the Global South, the main barriers to implementing these simple interventions include limited know-how among farmers and other supply-chain stakeholders, financial barriers, and perceived economic risks.[31] Short-term solutions to reduce food loss and waste in value chains of essential species include developing extension services and training, and providing financial support. In the longer term, significantly reducing the loss and waste of aquatic food in the Global South requires appropriate policies, regulatory frameworks, capacity building, services (e.g., electricity, potable water), and infrastructure (e.g., cold storage), as well as physical access to markets.[32]

Third, policies must be developed to support nutrient recycling at multiple scales while minimising energy use. The literature indicates that besides profit, legislation is one of the main barriers to developing or converting monoculture to IMTA or other integrated systems in regions where it does not already occur.[127] As highlighted by Regueiro et al.,[21] regulations should address fundamental aspects of licensing, access to land and water, environmental impact assessment, mixed-species farming, reinjection of side streams into feed production, and food-safety risks in multi-species systems. Support could be provided to producers who ‘de-specialise’ or already practice mixed-species farming. In aquatic-terrestrial systems, it is important to reuse nutrient-rich byproducts (e.g., sludge, manure) at a spatial scale larger than the farm (e.g., region, catchment, waterbody), such as by standardising requirements for fertilisers produced from organic matter[21] and developing processing technologies that render these organic fertilisers safer and less expensive. Using RAS sludge or pond sediments more effectively could reduce the production and use of inorganic fertilisers, which could reduce eutrophication and decrease impacts of the food system. Developing regional IMTA could help to close N and P land-sea loops, similar to establishing seaweed or bivalve farms in coastal environments to absorb nutrient runoff from agricultural land.[173] Developing regional-scale production systems will require cross-sectoral and zone-scale governance and spatial planning. These developments are similar to regional integrated crop-livestock systems that promote combining crop and terrestrial livestock production.[174]

Fourth, modifying aquafeed formulations can help reduce feed-food competition in aquaculture. Developing policies that decrease the use of food-competing and/or human-edible ingredients in aquafeed could accelerate the transition to a future aquafeed (i.e., 3.0). Certification organisations could support this transition by including criteria in their standards related to the use of virgin vs. recycled ingredients in feed. This would provide clear incentives for feed manufacturers to develop solutions to increase use of non-food-competing feedstuffs. The latter could integrate human edibility of the ingredients in new multi-objective formulation algorithms. Transparency and communication about the sensory, nutritional, and safety characteristics of aquaculture products from animals fed aquafeed 3.0 will be essential to ensure consumer trust and acceptance.[39]

Fifth, consumers need to be better educated about the benefits of eating species of low trophic level (e.g., carp, bivalves, seaweed), which can more efficiently use byproducts from the food system and aquaculture processing. To accelerate the transition to these aquaculture products, consumer behaviour and beliefs must change, and a variety of methods can influence their attitudes and confidence. Developing and requiring environmental sustainability labels on ASF products, like the nutritional labels in many countries, could better inform consumers about the advantages of bivalves or carp. Advertising campaigns and public-service programmes could promote consumption of aquatic foods of low trophic level that are less known and help build their markets.[71] An increasing consumption of aquaculture processing byproducts will be challenged by the society, especially in in areas where aquaculture is more recent.[175] Other world regions like Asian countries already import processing byproducts from the Global North for human consumption.[108] Effective strategies could include the development of inexpensive value-added fish products and innovative easy to eat dishes (e.g., carp medallions from the skeleton, blood sausage from trimmings).[23] Because global demand for aquatic food is predicted to nearly double by mid-century, consumer choices can improve production practices greatly and drive the supply towards more sustainable farmed aquatic foods.

Sixth, researchers could address urgent research gaps to help transition to more circular aquaculture. The main aspects include (i) better understanding the resilience of the ecosystems affected by aquaculture and the implications for the delivery of ecosystem services; (ii) collecting updated and location-specific data on aquaculture food loss and waste from farm to fork; (iii) in-depth analysis of direct and indirect contributions of aquaculture systems and species to food security; (iv) measuring the efficiency of aquaculture species in converting non-food-competing feedstuffs into valuable nutrients and evaluating potential impacts on animal health, welfare, productivity, and nutrient emissions; and (v) including a variety of aquaculture systems in analysis of food-system sustainability. Overall, next steps involve research that can be used as proof of concept to demonstrate the opportunities and challenges for the environment, the economy, the value chain, and society in adopting circularity in aquaculture.

AUTHOR CONTRIBUTIONS

Killian Chary: Conceptualization; writing – original draft; methodology; writing – review and editing; project administration; visualization. **Anne-Jo van Riel:** Conceptualization; writing – original draft; writing – review and editing; visualization; methodology; project administration. **Abigail Muscat:** Writing – review and editing; writing – original draft. **Aurélie Wilfart:** Writing – original draft; writing – review and editing. **Souhil Harchaoui:** Writing – original draft; writing – review and editing. **Marc Verdegem:** Writing – review and editing. **Ramón Filgueira:** Writing – review and editing; writing – original draft. **Max Troell:** Writing – review and editing. **Patrik J.G. Henriksson:** Writing – review and editing. **Imke J.M. de Boer:** Writing – review and editing; methodology. **Geert F. Wiegertjes:** Methodology; writing – review and editing.

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The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ETHICS STATEMENT

This study contains no research with human participants or animals.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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