



## REVIEW

# Transforming sustainable aquaculture by applying circularity principles

Killian Chary<sup>1</sup>  | Anne-Jo van Riel<sup>1,2</sup>  | Abigail Muscat<sup>3</sup>  | Aurélie Wilfart<sup>4</sup>  |  
 Souhil Harchaoui<sup>4</sup>  | Marc Verdegem<sup>1</sup>  | Ramón Filgueira<sup>5,6</sup>  |  
 Max Troell<sup>7,8</sup>  | Patrik J. G. Henriksson<sup>7,8,9</sup>  | Imke J. M. de Boer<sup>2</sup>  |  
 Geert F. Wiegertjes<sup>1</sup> 

<sup>1</sup>Aquaculture and Fisheries Group,  
 Department of Animal Sciences, Wageningen  
 University & Research, Wageningen,  
 The Netherlands

<sup>2</sup>Animal Production Systems Group,  
 Department of Animal Sciences, Wageningen  
 University & Research, Wageningen,  
 The Netherlands

<sup>3</sup>Policy Officer Joint Programming Networks,  
 Corporate Strategy and Accounts,  
 Wageningen University & Research,  
 Wageningen, The Netherlands

<sup>4</sup>UMR SAS, INRAE, Institut Agro, Rennes,  
 France

<sup>5</sup>Marine Affairs Program, Dalhousie University,  
 Halifax, Nova Scotia, Canada

<sup>6</sup>Benthic Resources, Institute of Marine  
 Research, Bergen, Norway

<sup>7</sup>Beijer Institute of Ecological Economics,  
 Royal Swedish Academy of Sciences,  
 Stockholm, Sweden

<sup>8</sup>Stockholm Resilience Centre, Stockholm  
 University, Stockholm, Sweden

<sup>9</sup>WorldFish, Jalan Batu Maung, Penang,  
 Malaysia

## Correspondence

Killian Chary, Wageningen University &  
 Research, P.O. Box 338, 6700 AH  
 Wageningen, The Netherlands.  
 Email: [killian.chary@wur.nl](mailto:killian.chary@wur.nl); [killian.chary@gmail.com](mailto:killian.chary@gmail.com)

## 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 ‘safe-guard’, ‘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

Imke J.M. de Boer and Geert F. Wiegertjes share last authorship.

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial](https://creativecommons.org/licenses/by-nc/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2023 The Authors. *Reviews in Aquaculture* published by John Wiley & Sons Australia, Ltd.

## 1 | INTRODUCTION

Global expansion of diverse food systems has maintained human well-being, but has also had a major influence on environmental changes.<sup>1</sup> A circular economy (CE) is considered one way to reduce environmental impacts of human activities,<sup>2</sup> by more efficient use of resources, resulting in less waste and emissions compared to linear take-make-dispose systems. Prieto-Sandoval et al.<sup>3</sup> 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.<sup>4</sup> 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.<sup>5</sup>

Muscat et al.<sup>6</sup> 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<sup>7</sup> 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,<sup>10</sup> and is projected to expand rapidly over the coming decade.<sup>11</sup> Aquaculture production interacts with terrestrial food systems (through ecosystem connectivity and feed interdependence),<sup>12,13</sup> 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,<sup>14</sup> recycling of nutrients and byproducts,<sup>15–18</sup> novel ingredients in aquafeeds derived from the CE,<sup>19,20</sup> 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).<sup>21</sup> These applications do not encompass all aspects of Muscat et al.'s framework. *Reviews in Aquaculture* recently dedicated a special issue on circularity<sup>22</sup> 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.

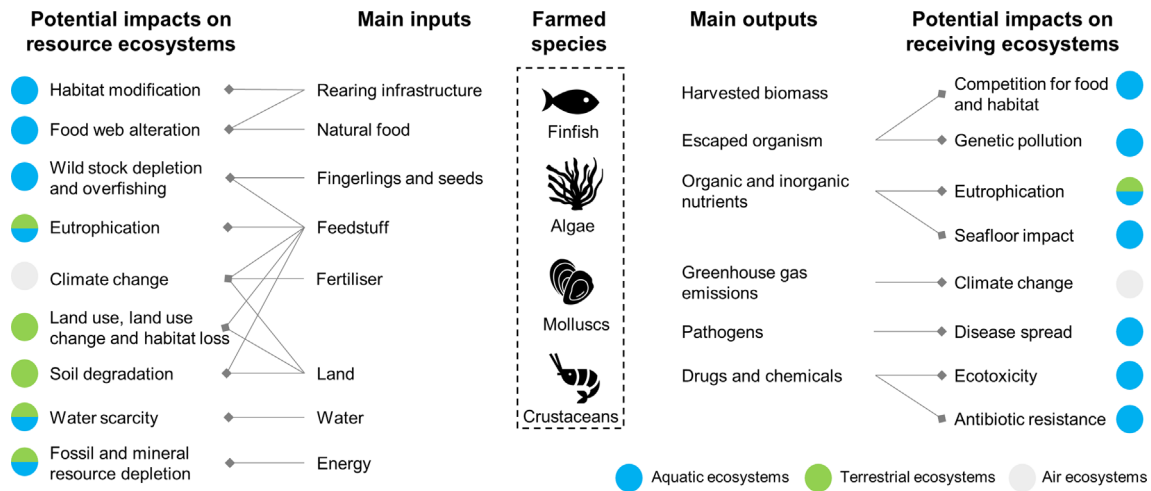
This review is organised into five sections, one per principle, that summarise the main concepts developed in the five circularity principles. The five sections are followed by a discussion of the most novel concepts for the aquaculture sector, recommendations to render aquaculture more circular, and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

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

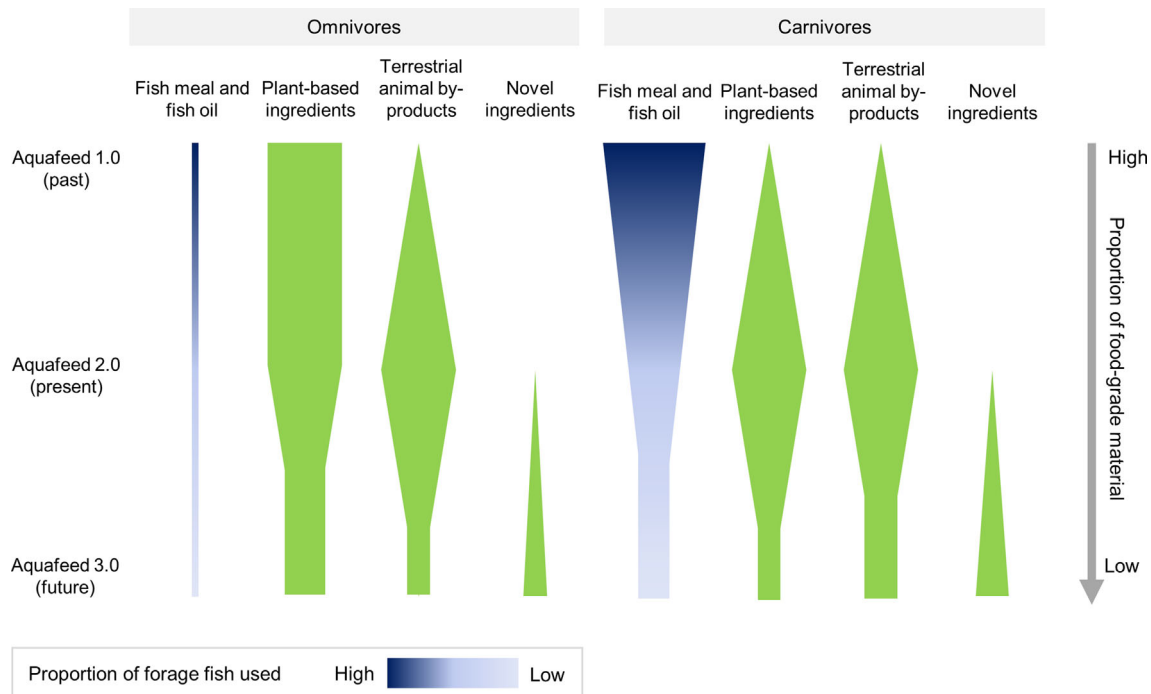
The ‘safeguard’ principle focuses on the need to safeguard and regenerate the health of agroecosystems (and therefore aquatic ecosystems). Safeguarding the health of ecosystems implies keeping aquaculture within an ecosystem's carrying capacity. This requires regenerative systems and practices that do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

### 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)<sup>26</sup> 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 production 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.<sup>32</sup> 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.<sup>28</sup> 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.<sup>33,34</sup> 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<sup>35</sup> (e.g., soil degradation, deforestation) and freshwater resources (e.g., eutrophication, water depletion).<sup>36</sup> 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.<sup>37</sup> 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<sup>40,41</sup>) defined in aquaculture.<sup>42</sup> 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.<sup>43</sup> 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.<sup>44</sup> Current research is expanding the concept of ecological carrying capacity to include effects of other important stressors, such as diseases and pathogens.<sup>45</sup> 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.<sup>42</sup> 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.<sup>46</sup> 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,<sup>47</sup> 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<sup>48</sup> 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.<sup>49</sup> Other benefits can include maintaining water quality,<sup>50</sup> recycling water,<sup>51</sup> decreased risk of fish escaping,<sup>52</sup> less need for chemical treatments,<sup>53</sup> and habitat preservation.<sup>54</sup> A first core aspect of regenerative aquaculture would therefore be the farming of complementary species<sup>48</sup> 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.<sup>26,55</sup> 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.<sup>57–59</sup> 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.<sup>60–62</sup> Ecosystem services of marine aquaculture systems are also well documented, especially those provided by extractive marine species<sup>63,64</sup> such as nutrient removal by bivalves or seaweed.<sup>65,66</sup> Based on these ecological benefits, extractive aquaculture has been recommended as a way to restore natural ecosystems (i.e., restorative aquaculture<sup>67</sup>) 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<sup>68</sup>) 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<sup>30,32</sup>). 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.<sup>69</sup> 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.<sup>70</sup> 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.<sup>71</sup> 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.<sup>72–74</sup> 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.<sup>31</sup> 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.<sup>31</sup> 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<sup>75</sup> and in the USA.<sup>76</sup> 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 hannii*), 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.<sup>32</sup> 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,<sup>74</sup> those who benefit from these profits would not be the nutritionally vulnerable.<sup>77</sup> 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<sup>78</sup> 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<sup>78</sup> (Appendix S1, section S3). According to the FAO,<sup>78</sup> North America and Oceania had the highest loss (ca. 50% of total production), half of which occurred at the consumption stage.<sup>79</sup> These loss and waste estimates for aquatic foods are higher than those for terrestrial meat (20%–27%), dairy products (10%–25%), oil-seeds 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,<sup>80</sup> such as by using arable land to produce human food (and not feed) and feeding farmed animals byproducts from these food systems<sup>81–84</sup> and/or products that humans cannot or do not want to eat (i.e., ‘non-food-competing feedstuff’).<sup>8</sup>

### 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).<sup>85</sup> In fed aquaculture systems, most land use is associated with feed production (and hence often located out of the farm).<sup>27</sup> 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).<sup>27</sup> 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,<sup>86</sup> 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.<sup>87</sup> 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.<sup>31</sup> 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<sup>88</sup> or indirect feed-food competition<sup>89</sup> and thus do not fully capture the land, freshwater or feed-use efficiency of these aquaculture systems.

### 4.2 | Feed-food competition

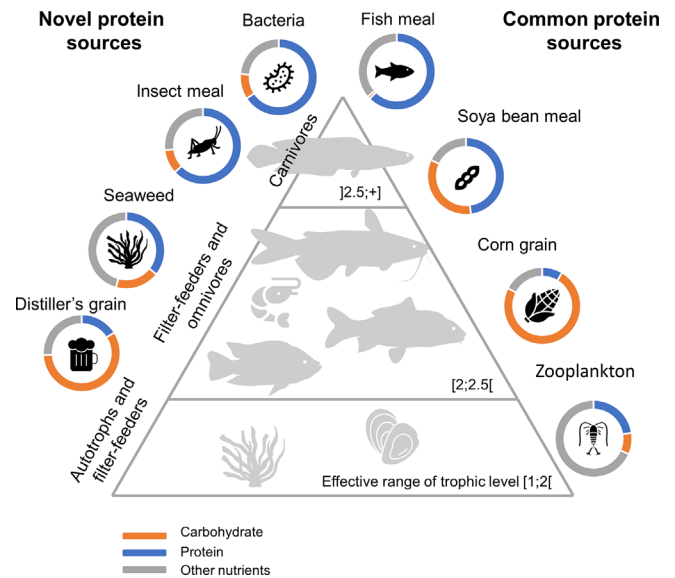
Direct feed-food competition occurs when food-grade or human edible ingredients are used in feed. The extent to which global aquaculture currently uses food suitable for human consumption is unknown, but certain aquaculture systems and species are more likely to cause feed-food competition than others. 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.<sup>90</sup>

Soya bean, fishmeal, fish oil, and maize products are the most commonly used ingredients in aquafeed in terms of volumes.<sup>13,91</sup> Fishmeal and fish oil are increasingly made from byproducts (27% and 48%, respectively<sup>10</sup>) 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<sup>92</sup> (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.<sup>93</sup> 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.<sup>94,95</sup>

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.<sup>96</sup> 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.<sup>97</sup> 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.<sup>90,98</sup> 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.

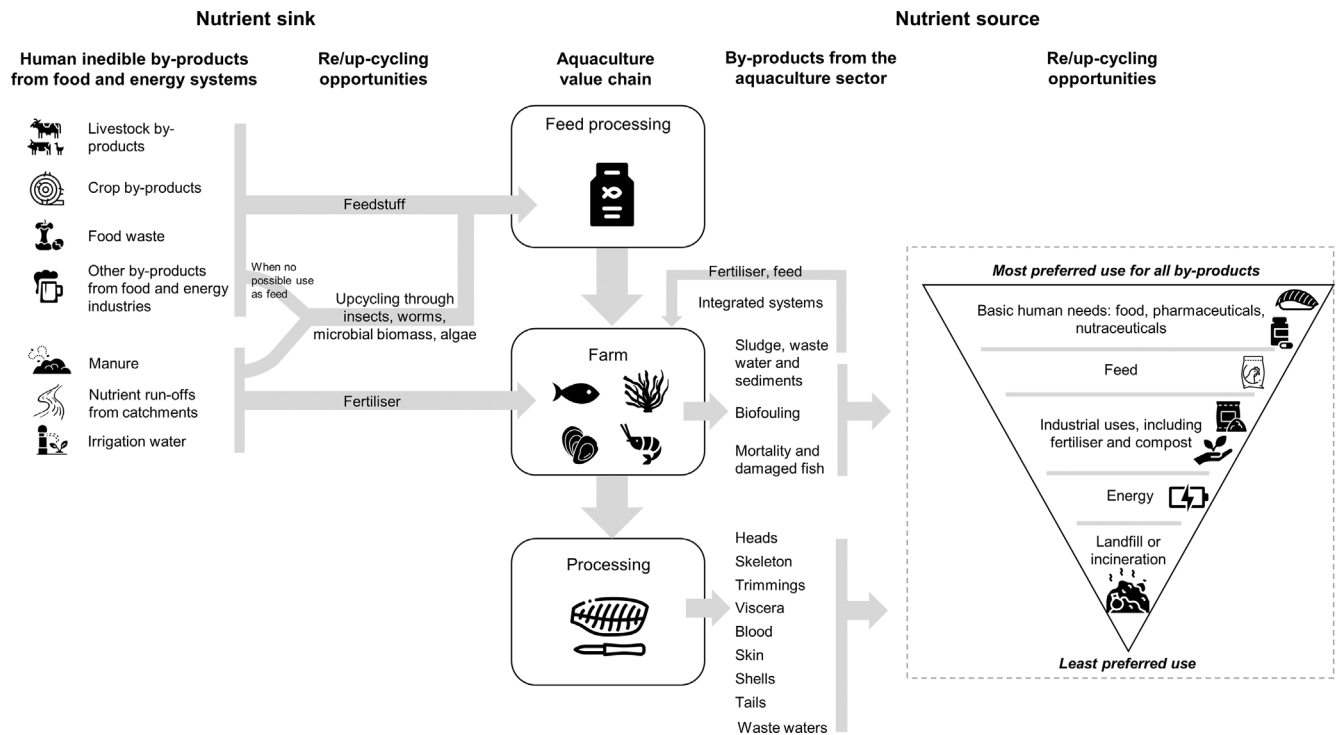
Feed-food competition in aquaculture can also be minimised by balancing the different types of animals produced, and by increasing human edible yields. In circular food systems, the main advantage of omnivorous species is their ability to transform plant-based byproducts into valuable nutrients (Figure 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<sup>39</sup> presenting an interesting nutritional value<sup>99</sup> should be considered, as they can feed upon low-quality organic matter such as fish faeces.<sup>100</sup> 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 micro-nutrients in the diet than eating only the fillets or meats.<sup>10</sup> 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).<sup>101,102</sup> Primary products obtained from processing represent 35%–70% of fish, 20%–60% of crustaceans, and 10%–24% of bivalves,<sup>103</sup> depending on species, market size, and technology.<sup>10,101,104,105</sup> 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.<sup>107</sup> Overall, global fed aquaculture currently produces three to four times as much fish as it consumes<sup>107</sup> (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.<sup>93</sup> It was recently applied by van Riel et al.<sup>90</sup> 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.<sup>15,101,102,108</sup> In Japan and Taiwan, salmon belly flaps are a popular food consumed barbecued or fried.<sup>102,109</sup> 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, vánoční rybí polévka).<sup>23</sup> Processing technologies enable converting aquaculture byproducts into low-cost food products such as fish surimi, sausages, pâté, cakes, snacks, soups, and sauces.<sup>10</sup> 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.<sup>102</sup> Examples of non-food uses of aquaculture processing byproducts include processing fish skin to produce leather and craft handbags<sup>102</sup> or as bandages to treat patients with full-thickness burns<sup>110</sup>; transforming chitin and chitosan in crustacean shells into antimicrobial substances, cosmetics, and agrochemicals<sup>111</sup>; transforming bivalve shells into calcium carbonate or calcium oxides for industrial applications or jewellery<sup>112</sup>; and using collagen and gelatine from fish heads, skeletons, or skin for pharmaceutical purposes.<sup>113</sup> 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.,<sup>101</sup> 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.<sup>6</sup> 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.<sup>6</sup> ‘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,<sup>114</sup> but much higher losses have been observed on some farms,<sup>115</sup> 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,<sup>116</sup> use of exogenous enzymes and probiotics,<sup>117</sup> genetic selection,<sup>118</sup> and transgenic manipulation.<sup>119</sup> 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,<sup>120</sup> and to produce fertiliser, compost,<sup>121</sup> biogas, or biofuel.<sup>122</sup> 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.<sup>123</sup> 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<sup>21</sup> 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.<sup>124</sup> This concept has been widely explored in aquaculture,<sup>49</sup> 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.<sup>125–127</sup>

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.<sup>128</sup> IAA was widely practiced by small households in freshwater environments, mainly in Asia,<sup>123</sup> but it declined due to the trend for intensified monocultures.<sup>129</sup> 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.<sup>130</sup> 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 energy use), re-evaluating reasons for

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

Type	System	Rearing technologies				
		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,<sup>131</sup> 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,<sup>132</sup> recirculation (pumping),<sup>133,134</sup> and heating/cooling<sup>135</sup> are often highlighted as hotspots of energy use, particularly in RAS or intensive pond systems. Emery 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.<sup>136</sup> Post-harvest phases such as transport and distribution of aquaculture products can also be energy intensive,<sup>137</sup> especially when the products are airfreighted<sup>138</sup> 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.<sup>131,139</sup> Per unit of product, highly intensive systems such as RAS or aquaponic systems<sup>140,141</sup> tend to use the most energy,<sup>131,133,134</sup> while cage systems and extractive bivalve systems use relatively little energy.<sup>131,142</sup> 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.<sup>135,143,144</sup> A recent review of emergy performances of aquaculture systems (David et al.<sup>136</sup>) 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,<sup>145–148</sup> or monoculture and integrated systems,<sup>149–152</sup> 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.<sup>153</sup> Systems that produce carnivorous species generally use more energy than those that produce extractive species,<sup>154,155</sup> 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.<sup>156</sup> Consequently, several of the main species farmed in RAS (e.g., tilapia, catfish, shrimp) are warm-water species,<sup>157</sup> 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.<sup>158</sup>

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.<sup>159</sup> The influence of the electricity source on the environmental footprint has been shown for RAS as well as for flow-through and bivalve systems,<sup>131,134</sup> 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,<sup>160</sup> and food security.<sup>31</sup> 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.<sup>72,74</sup> 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,<sup>31</sup> 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.<sup>160,161</sup> 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).<sup>27,161</sup> 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%<sup>96</sup>) of food-competing feedstuffs in aquaculture must be decreased to increase the global food supply and reduce environmental impacts. Sandström et al.<sup>96</sup> 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<sup>85</sup> 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<sup>83,84,162</sup> due to the limited availability, quality, and potential competition for non-food-competing feedstuffs.<sup>13</sup> 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.<sup>90</sup> 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.<sup>163</sup> 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.<sup>31</sup> Net returns for shrimp farmers in Vietnam, for example, are correlated with level of intensification, while feeds remain one of the largest expenses.<sup>164</sup> 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.<sup>132</sup> 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.<sup>165</sup> 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.<sup>59</sup> Fiscal instruments, such as taxes (or credits) on resource use (e.g., resource rent tax in Norway<sup>166</sup>), 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.<sup>167,168</sup> 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<sup>169</sup> and adequate policies to facilitate the necessary changes in aquaculture businesses<sup>127,170</sup> 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.<sup>23</sup> At the farm scale, many essential aquaculture species have below-average productivity,<sup>31</sup> partly due to high mortality resulting from disease outbreaks,<sup>171</sup> oxygen depletion,<sup>172</sup> 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.<sup>23,31</sup> In the Global North, where farm loss is often due to harmful algal blooms, diseases, and climate-related losses,<sup>30</sup> 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,<sup>101,102</sup> 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.<sup>31</sup> 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.<sup>32</sup>

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.<sup>127</sup> As highlighted by Regueiro et al.,<sup>21</sup> 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<sup>21</sup> 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.<sup>173</sup> 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.<sup>174</sup>

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.<sup>39</sup>

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.<sup>71</sup> An increasing consumption of aquaculture processing byproducts will be challenged by the society, especially in areas where aquaculture is more recent.<sup>175</sup> Other world regions like Asian countries already import processing byproducts from the Global North for human consumption.<sup>108</sup> 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).<sup>23</sup> 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. **Aurélié 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.

#### ACKNOWLEDGEMENTS

The authors thank Henrice Jansen for her thorough and helpful comments on an early version of this manuscript and Johan Schrama for his help in the design of Figure 2. The authors thank Michelle and Michael Corson for English copyediting and proofreading.

#### CONFLICT OF INTEREST STATEMENT

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.

#### ORCID

**Killian Chary**  <https://orcid.org/0000-0001-9549-9227>  
**Anne-Jo van Riel**  <https://orcid.org/0000-0001-7954-2440>  
**Abigail Muscat**  <https://orcid.org/0000-0002-6106-2884>  
**Aurélié Wilfart**  <https://orcid.org/0000-0002-3593-0334>  
**Souhil Harchaoui**  <https://orcid.org/0000-0002-6407-8291>  
**Marc Verdegem**  <https://orcid.org/0000-0002-2058-3894>  
**Ramón Filgueira**  <https://orcid.org/0000-0002-3332-8649>  
**Max Troell**  <https://orcid.org/0000-0002-7509-8140>  
**Patrik J. G. Henriksson**  <https://orcid.org/0000-0002-3439-623X>  
**Imke J. M. de Boer**  <https://orcid.org/0000-0002-0675-7528>  
**Geert F. Wiegertjes**  <https://orcid.org/0000-0001-9265-3436>

#### REFERENCES

1. Willett W, Rockström J, Loken B, et al. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet*. 2019;393(10170):447–492. doi:10.1016/S0140-6736(18)31788-4
2. Hamam M, Chinnici G, Di Vita G, et al. Circular economy models in agro-food systems: a review. *Sustainability*. 2021;13(6):34–53. doi:10.3390/su13063453
3. Prieto-Sandoval V, Jaca C, Ormazabal M. Towards a consensus on the circular economy. *J Clean Prod*. 2018;179:605–615. doi:10.1016/j.jclepro.2017.12.224
4. Lazarevic D, Valve H. Narrating expectations for the circular economy: towards a common and contested European transition. *Energy Res Soc Sci*. 2017;31:60–69. doi:10.1016/J.ERSS.2017.05.006
5. McDowall W, Geng Y, Huang B, et al. Circular economy policies in China and Europe. *J Ind Ecol*. 2017;21(3):651–661. doi:10.1111/JIEC.12597
6. Muscat A, de Olde EM, Ripoll-Bosch R, et al. Principles, drivers and opportunities of a circular bioeconomy. *Nat Food*. 2021;2(8):561–566. doi:10.1038/s43016-021-00340-7
7. de Boer IJM, Van Ittersum MK. *Circularity in Agricultural Production*. Wageningen University & Research; 2018.
8. van Zanten HHE, van Ittersum MK, de Boer IJM. The role of farm animals in a circular food system. *Glob Food Sec*. 2019;21:18–22. doi:10.1016/j.gfs.2019.06.003
9. van Selm B, Frehner A, de Boer IJM, et al. Circularity in animal production requires a change in the EAT-lancet diet in Europe. *Nat Food*. 2022;3(1):66–73. doi:10.1038/s43016-021-00425-3



10. FAO. *The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation*. FAO; 2022. doi:[10.4060/cc0461en](https://doi.org/10.4060/cc0461en)
11. OECD/FAO. *OECD-FAO Agricultural Outlook 2022–2031*. OECD Publishing; 2022.
12. Cottrell RS, Fleming A, Fulton EA, Nash KL, Watson RA, Blanchard JL. Considering land–sea interactions and trade-offs for food and biodiversity. *Glob Chang Biol*. 2018;24(2):580–596. doi:[10.1111/GCB.13873](https://doi.org/10.1111/GCB.13873)
13. Troell M, Naylor RL, Metian M, et al. Does aquaculture add resilience to the global food system? *Proc Natl Acad Sci USA*. 2014; 111(37):13257–13263. doi:[10.1073/pnas.1404067111](https://doi.org/10.1073/pnas.1404067111)
14. Carvalho Pereira J, Lemoine A, Neubauer P, Junne S. Perspectives for improving circular economy in brackish shrimp aquaculture. *Aquacult Res*. 2022;53(4):1169–1180. doi:[10.1111/are.15685](https://doi.org/10.1111/are.15685)
15. Campanati C, Willer D, Schubert J, Aldridge DC. Sustainable intensification of aquaculture through nutrient recycling and circular economies: more fish, less waste, blue growth. *Rev Fish Sci Aquac*. 2021; 30(2):1–50. doi:[10.1080/23308249.2021.1897520](https://doi.org/10.1080/23308249.2021.1897520)
16. de la Caba K, Guerrero P, Trung TS, et al. From seafood waste to active seafood packaging: an emerging opportunity of the circular economy. *J Clean Prod*. 2019;208:86–98. doi:[10.1016/j.jclepro.2018.09.164](https://doi.org/10.1016/j.jclepro.2018.09.164)
17. Alonso AA, Álvarez-Salgado XA, Antelo LT. Assessing the impact of bivalve aquaculture on the carbon circular economy. *J Clean Prod*. 2021;279:123873. doi:[10.1016/j.jclepro.2020.123873](https://doi.org/10.1016/j.jclepro.2020.123873)
18. Das SK, Mondal B, Sarkar UK, Das BK, Borah S. Understanding and approaches towards circular bio-economy of wastewater reuse in fisheries and aquaculture in India: an overview. *Rev Aquac*. 2022;15: 1100–1114. doi:[10.1111/RAQ.12758](https://doi.org/10.1111/RAQ.12758)
19. Eroldoğan OT, Glencross B, Novoveska L, et al. From the sea to aquafeed: a perspective overview. *Rev Aquac*. 2022;15:1028–1057. doi:[10.1111/RAQ.12740](https://doi.org/10.1111/RAQ.12740)
20. Colombo SM, Turchini GM. ‘Aquafeed 3.0’: creating a more resilient aquaculture industry with a circular bioeconomy framework. *Rev Aquac*. 2021;13(3):1156–1158. doi:[10.1111/raq.12567](https://doi.org/10.1111/raq.12567)
21. Regueiro L, Newton R, Soula M, et al. Opportunities and limitations for the introduction of circular economy principles in EU aquaculture based on the regulatory framework. *J Ind Ecol*. 2022;26(6):2033–2044. doi:[10.1111/jiec.13188](https://doi.org/10.1111/jiec.13188)
22. Roy K, Turkmen S, Turchini GM. Triggering circularity in aquaculture – an introductory virtual special issue. *Rev Aquac*. 2021. Accessed November 18, 2022. <https://onlinelibrary.wiley.com/page/journal/17535131/homepage/circularity-in-aquaculture-introduction>
23. Mraz J, Jia H, Roy K, Roy K. Biomass losses and circularity along local farm-to-fork: a review of industrial efforts with locally farmed freshwater fish in land-locked Central Europe. *Rev Aquac*. 2022;15:1083–1099. doi:[10.1111/RAQ.12760](https://doi.org/10.1111/RAQ.12760)
24. Peñarubia O, Toppe J, Ahern M, Ward A, Griffin M. How value addition by utilization of tilapia processing by-products can improve human nutrition and livelihood. *Rev Aquac*. 2022;15:32–40. doi:[10.1111/RAQ.12737](https://doi.org/10.1111/RAQ.12737)
25. IPBES. In: Brondizio ES, Settele J, Díaz S, Ngo HT, eds. *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. IPBES secretariat; 2019.
26. Soto D, Aguilar-Manjarrez J, Brugère C, et al. Applying an ecosystem-based approach to aquaculture: principles, scales and some management measures. In: Soto D, Aguilar-Manjarrez J, Hishamunda N, eds. *Building an Ecosystem Approach to Aquaculture*. FAO/Universitat de les Illes Balears Expert Workshop. 7–11 May 2007, Palma de Mallorca, Spain. Vol 14. FAO Fisheries and Aquaculture Proceedings; 2008:15–35. doi:[10.1017/S0020818300006160](https://doi.org/10.1017/S0020818300006160)
27. Gephart JA, Henriksson PJG, Parker RWR, et al. Environmental performance of blue foods. *Nature*. 2021;597(7876):360–365. doi:[10.1038/s41586-021-03889-2](https://doi.org/10.1038/s41586-021-03889-2)
28. Edwards P. Aquaculture environment interactions: past, present and likely future trends. *Aquaculture*. 2015;447:2–14. doi:[10.1016/j.aquaculture.2015.02.001](https://doi.org/10.1016/j.aquaculture.2015.02.001)
29. Diana JS. Aquaculture production and biodiversity conservation. *Bio-science*. 2009;59(1):27–38. doi:[10.1525/bio.2009.59.1.7](https://doi.org/10.1525/bio.2009.59.1.7)
30. Naylor RL, Hardy RW, Buschmann AH, et al. A 20-year retrospective review of global aquaculture. *Nature*. 2021;591(7851):551–563. doi:[10.1038/s41586-021-03308-6](https://doi.org/10.1038/s41586-021-03308-6)
31. Henriksson PJG, Troell M, Banks LK, et al. Interventions for improving the productivity and environmental performance of global aquaculture for future food security. *One Earth*. 2021;4(9):1220–1232. doi:[10.1016/j.ONEEAR.2021.08.009](https://doi.org/10.1016/j.ONEEAR.2021.08.009)
32. FAO. *The State of World Fisheries and Aquaculture 2020. Sustainability in Actions*. FAO; 2020:224. doi:[10.4060/ca9229en](https://doi.org/10.4060/ca9229en)
33. Tacon AGJ. Trends in global aquaculture and aquafeed production: 2000–2017. *Rev Fish Sci Aquac*. 2020;28(1):43–56. doi:[10.1080/23308249.2019.1649634](https://doi.org/10.1080/23308249.2019.1649634)
34. Jonell M, Henriksson PJG. Mangrove–shrimp farms in Vietnam—comparing organic and conventional systems using life cycle assessment. *Aquaculture*. 2015;447:66–75. doi:[10.1016/j.aquaculture.2014.11.001](https://doi.org/10.1016/j.aquaculture.2014.11.001)
35. Cottrell RS, Blanchard JL, Halpern BS, Metian M, Froehlich HE. Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. *Nat Food*. 2020;1(5):301–308. doi:[10.1038/s43016-020-0078-x](https://doi.org/10.1038/s43016-020-0078-x)
36. Pahlow M, van Oel PR, Mekonnen MM, Hoekstra AY. Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production. *Sci Total Environ*. 2015;536:847–857. doi:[10.1016/J.SCITOTENV.2015.07.124](https://doi.org/10.1016/J.SCITOTENV.2015.07.124)
37. Krause G, Le Vay L, Buck BH, et al. Prospects of low trophic marine aquaculture contributing to food security in a net zero-carbon world. *Front Sustain Food Syst*. 2022;6:209. doi:[10.3389/fsufs.2022.875509](https://doi.org/10.3389/fsufs.2022.875509)
38. van Zanten HHE. Upcycled non-competing feedstuff. *Nat Food*. 2022;3(9):681. doi:[10.1038/s43016-022-00590-z](https://doi.org/10.1038/s43016-022-00590-z)
39. Colombo SM, Roy K, Mraz J, et al. Towards achieving circularity and sustainability in feeds for farmed blue foods. *Rev Aquac*. 2022;15: 1115–1141. doi:[10.1111/raq.12766](https://doi.org/10.1111/raq.12766)
40. McKindsey CW, Thetmeyer H, Landry T, Silvert W. Review of recent carrying capacity models for bivalve culture and recommendations for research and management. *Aquaculture*. 2006;261(2):451–462. doi:[10.1016/j.aquaculture.2006.06.044](https://doi.org/10.1016/j.aquaculture.2006.06.044)
41. Ferreira JG, Grant J, Verner-Jeffreys DW, Taylor NGH. Carrying capacity for aquaculture, modeling frameworks for determination of. In: Christou P, Savin R, Costa-Pierce BA, Misztal I, Whitelaw CBA, eds. *Sustainable Food Production*. Springer; 2013.
42. Weitzman J, Filgueira R. The evolution and application of carrying capacity in aquaculture: towards a research agenda. *Rev Aquac*. 2019;12(3):1297–1322. doi:[10.1111/raq.12383](https://doi.org/10.1111/raq.12383)
43. Filgueira R, Comeau LA, Guyondet T, McKindsey CW, Byron CJ. Modelling carrying capacity of bivalve aquaculture: a review of definitions and methods. In: Meyers RA, ed. *Encyclopedia of Sustainability Science and Technology*. Springer; 2015:1–33. doi:[10.1007/978-1-4939-2493-6\\_945-1](https://doi.org/10.1007/978-1-4939-2493-6_945-1)
44. Tett P, Portilla E, Gillibrand PA, Inall M. Carrying and assimilative capacities: the ACEX-R-LESV model for sea-loch aquaculture. *Aquacult Res*. 2011;42:51–67. doi:[10.1111/j.1365-2109.2010.02729.x](https://doi.org/10.1111/j.1365-2109.2010.02729.x)
45. Ferreira JG, Taylor NGH, Cubillo, A, et al. An integrated model for aquaculture production, pathogen interaction, and environmental effects. *Aquaculture*. 2021;536:736438.
46. Schreefel L, Schulte RPO, de Boer IJM, Schrijver AP, van Zanten HHE. Regenerative agriculture – the soil is the base. *Glob Food Sec*. 2020;26:100404. doi:[10.1016/j.gfs.2020.100404](https://doi.org/10.1016/j.gfs.2020.100404)
47. Mizuta DD, Froehlich HE, Wilson JR. The changing role and definitions of aquaculture for environmental purposes. *Rev Aquac*. 2023; 15(1):130–141. doi:[10.1111/raq.12706](https://doi.org/10.1111/raq.12706)

48. Thomas M, Pasquet A, Aubin J, Nahon S, Lecocq T. When more is more: taking advantage of species diversity to move towards sustainable aquaculture. *Biol Rev.* 2021;96(2):767-784. doi:10.1111/BRV.12677
49. Soto D. *Integrated Mariculture: A Global Review*. FAO Fisheries and Aquaculture Technical Paper. No. 529. FAO; 2009:183.
50. Li M, Callier MD, Blancheton JP, et al. Bioremediation of fishpond effluent and production of microalgae for an oyster farm in an innovative recirculating integrated multi-trophic aquaculture system. *Aquaculture.* 2019;504:314-325. doi:10.1016/j.aquaculture.2019.02.013
51. Sandifer PA, Stephen HJ. Conceptual design of a sustainable pond-based shrimp culture system. *Aquac Eng.* 1996;15(1):41-52. doi:10.1016/0144-8609(95)00003-W
52. Wang Q, Cheng L, Liu J, Li Z, Xie S, De Silva SS. Freshwater aquaculture in Pr China: trends and prospects. *Rev Aquac.* 2015;7(4):283-302. doi:10.1111/RAQ.12086
53. Vaughan DB, Grutter AS, Hutson KS. Cleaner shrimp are a sustainable option to treat parasitic disease in farmed fish. *Sci Rep.* 2018; 8(1):13959. doi:10.1038/s41598-018-32293-6
54. Troell M. Integrated marine and brackishwater aquaculture in tropical regions: research, implementation and prospects. In: Soto D, ed. *Integrated Mariculture: A Global Review*. FAO Fisheries and Aquaculture Technical Paper. No. 529. FAO; 2009:47-131.
55. Costa-Pierce BA, ed. *Ecological Aquaculture - The Evolution of the Blue Revolution*. Blackwell Science; 2002.
56. Willot PA, Aubin J, Salles JM, Wilfart A. Ecosystem service framework and typology for an ecosystem approach to aquaculture. *Aquaculture.* 2019;512:734260. doi:10.1016/J.AQUACULTURE.2019.734260
57. Rey-Valette H, Blayac T, Salles JM. Evaluating the contribution of nature to well-being: the case of ecosystem services related to fish-farming ponds in France. *Ecol Econ.* 2022;191:107217. doi:10.1016/J.ECOLECON.2021.107217
58. Palásti P, Kiss M, Gulyás Á, Kerepeczki É. Expert knowledge and perceptions about the ecosystem services and natural values of Hungarian fishpond systems. *Water.* 2020;12(8):2144. doi:10.3390/W12082144
59. Custódio M, Villasante S, Calado R, Lillebø AI. Valuation of ecosystem services to promote sustainable aquaculture practices. *Rev Aquac.* 2020;12(1):392-405. doi:10.1111/RAQ.12324
60. Ruggiero A, Céréghino R, Figuerola J, Marty P, Angélibert S. Farm ponds make a contribution to the biodiversity of aquatic insects in a French agricultural landscape. *C R Biol.* 2008;331(4):298-308. doi:10.1016/J.CRV.2008.01.009
61. Lemmens P, Mergey J, de Bie T, Van Wichelen J, de Meester L, Declerck SAJ. How to maximally support local and regional biodiversity in applied conservation? Insights from pond management. *PLoS One.* 2013;8(8):e72538. doi:10.1371/journal.pone.0072538
62. Cuenca-Cambronero M, Blicharska M, Perrin JA, et al. Challenges and opportunities in the use of ponds and ponds as nature-based solutions. *Hydrobiologia.* 2023;850:3257-3271. doi:10.1007/s10750-023-05149-y
63. van der Schatte OA, Jones L, Le VL, Christie M, Wilson J, Malham SK. A global review of the ecosystem services provided by bivalve aquaculture. *Rev Aquac.* 2020;12(1):3-25. doi:10.1111/RAQ.12301
64. Alleway HK, Gillies CL, Bishop MJ, Gentry RR, Theuerkauf SJ, Jones R. The ecosystem services of marine aquaculture: valuing benefits to people and nature. *Bioscience.* 2019;69(1):59-68. doi:10.1093/biosci/biy137
65. Petersen JK, Saurel C, Nielsen P, Timmermann K. The use of shellfish for eutrophication control. *Aquacult Int.* 2015;24(3):857-878. doi:10.1007/S10499-015-9953-0
66. Xiao X, Agusti S, Lin F, et al. Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. *Sci Rep.* 2017;7(1):1-6. doi:10.1038/srep46613
67. Alleway H, Brummett R, Junning C, et al. *Global Principles of Restorative Aquaculture*. The Nature Conservancy; 2021.
68. Leal MC, Rocha RJM, Rosa R, Calado R. Aquaculture of marine non-food organisms: what, why and how? *Rev Aquac.* 2018;10(2):400-423. doi:10.1111/raq.12168
69. Tacon AGJ, Metian M. Fish matters: importance of aquatic foods in human nutrition and global food supply. *Rev Fish Sci.* 2013;21(1):22-38. doi:10.1080/10641262.2012.753405
70. Zamborain-Mason J, Viana D, Nicholas K, et al. A decision framework for selecting critically important nutrients from aquatic foods. *Curr Environ Health Rep.* 2023;10:172-183. doi:10.1007/s40572-023-00397-5
71. Ahern M, Shakuntala HT, Oenema S. *The Role of Aquatic Foods in Sustainable Healthy Diet*. UN Nutrition; 2021.
72. Gephart JA, Golden CD, Asche F, et al. Scenarios for global aquaculture and its role in human nutrition. *Rev Fish Sci Aquac.* 2020;29(1):122-138. doi:10.1080/23308249.2020.1782342
73. Thilsted SH, Thorne-Lyman A, Webb P, et al. Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy.* 2016;61:126-131. doi:10.1016/J.FOODPOL.2016.02.005
74. Golden CD, Seto KL, Dey MM, et al. Does aquaculture support the needs of nutritionally vulnerable nations? *Front Mar Sci.* 2017;4:159. doi:10.3389/fmars.2017.00159
75. EUMOFA. *The EU Fish Market 2021 Edition*. 2021. Accessed September 01, 2023. [https://www.eumofa.eu/documents/20178/477018/EN\\_The+EU+fish+market\\_2021.pdf/27a6d912-a758-6065-c973-c1146ac93d30?t=1636964632989](https://www.eumofa.eu/documents/20178/477018/EN_The+EU+fish+market_2021.pdf/27a6d912-a758-6065-c973-c1146ac93d30?t=1636964632989)
76. Love DC, Asche F, Conrad Z, et al. Food sources and expenditures for seafood in the United States. *Nutrients.* 2020;12(6):1-11. doi:10.3390/NU12061810
77. Bennett NJ, Blythe J, White CS, Campero C. Blue growth and blue justice: ten risks and solutions for the ocean economy. *Mar Policy.* 2021;125:104387. doi:10.1016/J.MARPOL.2020.104387
78. FAO. *Global Food Losses and Food Waste - Extent, Causes and Prevention*. FAO; 2011.
79. Love DC, Fry JP, Milli MC, Neff RA. Wasted seafood in the United States: quantifying loss from production to consumption and moving toward solutions. *Glob Environ Chang.* 2015;35:116-124. doi:10.1016/j.gloenvcha.2015.08.013
80. Breewood H, Garnett T. *What Is Feed-Food Competition? (Foodsource: Building Blocks)*. University of Oxford; 2020.
81. Rööß E, Bajželj B, Smith P, Patel M, Little D, Garnett T. Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. *Glob Environ Chang.* 2017;47:1-12. doi:10.1016/J.GLOENVCHA.2017.09.001
82. Muscat A, de Olde EM, de Boer IJM, Ripoll-Bosch R. The battle for biomass: a systematic review of food-feed-fuel competition. *Glob Food Sec.* 2020;25:100330. doi:10.1016/J.GFS.2019.100330
83. Schader C, Muller A, El-Hage Scialabba N, et al. Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. *J R Soc Interface.* 2015;12(113):20150891. doi:10.1098/RSIF.2015.0891
84. van Hal O, de Boer IJM, Muller A, et al. Upcycling food leftovers and grass resources through livestock: impact of livestock system and productivity. *J Clean Prod.* 2019;219:485-496. doi:10.1016/j.jclepro.2019.01.329
85. Poore J, Nemecek T. Reducing food's environmental impacts through producers and consumers. *Science.* 2018;360(6392):987-992. doi:10.1126/science.aag0216
86. Tlustý M, Tyedmers P, Ziegler F, et al. Commentary: comparing efficiency in aquatic and terrestrial animal production systems. *Environ Res Lett.* 2018;13(12):128001. doi:10.1088/1748-9326/aae945

87. Fry JP, Mailloux NA, Love DC, Milli MC, Cao L. Feed conversion efficiency in aquaculture: do we measure it correctly? *Environ Res Lett*. 2018;13(2):024017. doi:10.1088/1748-9326/aaa273
88. Shepon A, Eshel G, Noor E, Milo R. The opportunity cost of animal based diets exceeds all food losses. *Proc Natl Acad Sci USA*. 2018; 115(15):3804-3809. doi:10.1073/pnas.1713820115
89. van Zanten HHE, Mollenhorst H, Klootwijk CW, van Middelaar CE, de Boer IJM. Global food supply: land use efficiency of livestock systems. *Int J Life Cycle Assess*. 2016;21(5):747-758. doi:10.1007/s11367-015-0944-1
90. van Riel AJ, Nederlof MAJ, Chary K, Wiegertjes GF, de Boer IJM. Feed-food competition in global aquaculture: current trends and prospects. *Rev Aquac*. 2023;15(3):1142-1158. doi:10.1111/raq.12804
91. Tacon AGJ, Hasan MR, Metian M. *Demand and Supply of Feed Ingredients for Farmed Fish and Crustaceans: Trends and Prospects Vol 564*. FAO; 2011.
92. Cashion T, Le Manach F, Zeller D, Pauly D. Most fish destined for fishmeal production are food-grade fish. *Fish Fish*. 2017;18(5):837-844. doi:10.1111/faf.12209
93. Laisse S, Baumont R, Dusart L, et al. The net feed conversion efficiency of livestock: a new approach to assess the contribution of livestock to human feeding. *Inra Prod Anim*. 2018;31(3):269-288. doi:10.20870/PRODUCTIONS-ANIMALES.2018.31.3.2355
94. Wilkinson JM. Re-defining efficiency of feed use by livestock. *Animal*. 2011;5(7):1014-1022. doi:10.1017/S175173111100005X
95. Ertl P, Zebeli Q, Zollitsch W, Knaus W. Feeding of by-products completely replaced cereals and pulses in dairy cows and enhanced edible feed conversion ratio. *J Dairy Sci*. 2015;98(2):1225-1233. doi:10.3168/JDS.2014-8810
96. Sandström V, Chrysafi A, Lamminen M, et al. Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply. *Nat Food*. 2022;3(9):729-740. doi:10.1038/s43016-022-00589-6
97. Albrektsen S, Kortet R, Skov PV, et al. Future feed resources in sustainable salmonid production: a review. *Rev Aquac*. 2022;14:1790-1812. doi:10.1111/RAQ.12673
98. Mottet A, de Haan C, Falucci A, Tempio G, Opio C, Gerber P. Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. *Glob Food Sec*. 2017;14:1-8. doi:10.1016/j.gfs.2017.01.001
99. Bordbar S, Anwar F, Saari N. High-value components and bioactives from sea cucumbers for functional foods—a review. *Mar Drugs*. 2011;9(10):1761-1805. doi:10.3390/MD9101761
100. Zamora LN, Yuan X, Carton AG, Slater MJ. Role of deposit-feeding sea cucumbers in integrated multitrophic aquaculture: progress, problems, potential and future challenges. *Rev Aquac*. 2018;10(1): 57-74. doi:10.1111/raq.12147
101. Olsen RL, Toppe J, Karunasagar I. Challenges and realistic opportunities in the use of by-products from processing of fish and shellfish. *Trends Food Sci Technol*. 2014;36(2):144-151. doi:10.1016/j.tifs.2014.01.007
102. Stevens JR, Newton RW, Tlusty M, Little DC. The rise of aquaculture by-products: increasing food production, value, and sustainability through strategic utilisation. *Mar Policy*. 2018;90:115-124. doi:10.1016/j.marpol.2017.12.027
103. FAO. *Yield and Nutritional Value of the Commercially More Important Fish Species*. Vol 309. FAO Fisheries Technical Paper; 1989.
104. Fraga-Corral M, Ronza P, Garcia-Oliveira P, et al. Aquaculture as a circular bio-economy model with Galicia as a study case: how to transform waste into revalorized by-products. *Trends Food Sci Technol*. 2022;119:23-35. doi:10.1016/J.TIFS.2021.11.026
105. Boyd CE, McNevin AA, Davis RP. The contribution of fisheries and aquaculture to the global protein supply. *Food Secur*. 2022;14(3): 805-827. doi:10.1007/s12571-021-01246-9
106. Cottrell RS, Metian M, Froehlich HE, et al. Time to rethink trophic levels in aquaculture policy. *Rev Aquac*. 2021;13(3):1583-1593. doi:10.1111/RAQ.12535
107. Kok B, Malcorps W, Tlusty MF, et al. Fish as feed: using economic allocation to quantify the fish in:fish out ratio of major fed aquaculture species. *Aquaculture*. 2020;528:735474. doi:10.1016/J.AQUACULTURE.2020.735474
108. Newton R, Telfer T, Little D. Perspectives on the utilization of aquaculture coproduct in europe and asia: prospects for value addition and improved resource efficiency. *Crit Rev Food Sci Nutr*. 2014; 54(4):495-510. doi:10.1080/10408398.2011.588349
109. Batista I. By-catch, underutilized species and underutilized fish parts as food ingredients. In: Shahidi F, ed. *Maximising the Value of Marine By-Products*. Woodhead Publishing; 2006:171-195. doi:10.1533/9781845692087.2.171
110. Lima-Junior EM, Filho MOM, Costa BA, et al. Innovative treatment using tilapia skin as a xenograft for partial thickness burns after a gunpowder explosion. *J Surg Case Rep*. 2019;2019(6):1-4. doi:10.1093/JSCR/RJZ181
111. Vidal JL, Jin T, Lam E, Kerton F, Moores A. Blue is the new green: valorization of crustacean waste. *Curr Res Green Sustain Chem*. 2022;5:100330. doi:10.1016/J.CRGS.2022.100330
112. Summa D, Lanzoni M, Castaldelli G, Fano EA, Tamburini E. Trends and opportunities of bivalve shells' waste valorization in a prospect of circular blue bioeconomy. *Resources*. 2022;11(5):48. doi:10.3390/resources11050048
113. Usman M, Sahar A, Inam-Ur-Raheem M, Rahman U, Sameen A, Aadil RM. Gelatin extraction from fish waste and potential applications in food sector. *Int J Food Sci Technol*. 2022;57(1):154-163. doi:10.1111/IJFS.15286
114. Chary K, Brigolin D, Callier MD. Farm-scale models in fish aquaculture – an overview of methods and applications. *Rev Aquac*. 2022;14(4):2122-2157. doi:10.1111/RAQ.12695
115. Ballester-Moltó M, Sanchez-Jerez P, Cerezo-Valverde J, Aguado-Giménez F. Particulate waste outflow from fish-farming cages. How much is uneaten feed? *Mar Pollut Bull*. 2017;119(1):23-30. doi:10.1016/j.marpolbul.2017.03.004
116. Glencross BD, Booth M, Allan GL. A feed is only as good as its ingredients – A review of ingredient evaluation strategies for aquaculture feeds. *Aquacult Nutr*. 2007;13(1):17-34. doi:10.1111/j.1365-2095.2007.00450.x
117. Chauhan A, Singh R. Probiotics in aquaculture: a promising emerging alternative approach. *Symbiosis*. 2019;77(2):99-113. doi:10.1007/S13199-018-0580-1
118. Gjedrem T, Baranski M. *Selective Breeding in Aquaculture: An Introduction*. Vol 10. Springer; 2009. doi:10.1007/978-90-481-2773-3
119. Lu J, Li J, Furuya Y, et al. Efficient productivity and lowered nitrogen and phosphorus discharge load from GH-transgenic tilapia (*Oreochromis niloticus*) under visual satiation feeding. *Aquaculture*. 2009;293(3-4):241-247. doi:10.1016/J.AQUACULTURE.2009.04.021
120. Van Tung T, Tran QB, Phuong Thao NT, et al. Recycling of aquaculture wastewater and sediment for sustainable corn and water spinach production. *Chemosphere*. 2021;268:129329. doi:10.1016/J.CHEMOSPHERE.2020.129329
121. Drózd D, Malińska K, Mazurkiewicz J, et al. Fish pond sediment from aquaculture production-current practices and the potential for nutrient recovery: a review. *Int Agrophys*. 2020;34:33-41. doi:10.31545/intagr/116394
122. Mirzoyan N, Tal Y, Gross A. Anaerobic digestion of sludge from intensive recirculating aquaculture systems: review. *Aquaculture*. 2010;306(1-4):1-6. doi:10.1016/J.AQUACULTURE.2010.05.028
123. Zajdband AD, Zajdband AD, Lichtfouse E. Integrated agri-aquaculture systems. In: Lichtfouse E, ed. *Genetics, Biofuels and Local Farming Systems*. Vol 7. Springer; 2011:87-127. doi:10.1007/978-94-007-1521-9\_4



124. Edwards P. A systems approach for the promotion of integrated aquaculture. *Aquac Econ Manag.* 1998;2(1):1-12. doi:10.1080/13657309809380209
125. Hughes AD, Black KD. Going beyond the search for solutions: understanding trade-offs in European integrated multi-trophic aquaculture development. *Aquac Environ Interact.* 2016;8:191-199. doi:10.3354/AEI00174
126. Rosa J, Lemos MFL, Crespo D, et al. Integrated multitrophic aquaculture systems – potential risks for food safety. *Trends Food Sci Technol.* 2020;96:79-90. doi:10.1016/j.tifs.2019.12.008
127. Sickander O, Filgueira R. Factors affecting IMTA (integrated multi-trophic aquaculture) implementation on Atlantic Salmon (*Salmo salar*) farms. *Aquaculture.* 2022;561:738716. doi:10.1016/j.aquaculture.2022.738716
128. Edwards P. A review of recycling organic wastes into fish, with emphasis on the tropics. *Aquaculture.* 1980;21(3):261-279. doi:10.1016/0044-8486(80)90136-2
129. Little D, Edwards P. *Integrated Livestock-Fish Farming Systems.* FAO; 2003.
130. Nederlof MAJ, Verdegem MCJ, Smaal AC, Jansen HM. Nutrient retention efficiencies in integrated multi-trophic aquaculture. *Rev Aquac.* 2022;14(3):1194-1212. doi:10.1111/raq.12645
131. Bohnes FA, Hauschild MZ, Schlundt J, Laurent A. Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. *Rev Aquac.* 2019;11(4):1061-1079. doi:10.1111/raq.12280
132. Henriksson PJG, Rico A, Zhang W, et al. Comparison of Asian aquaculture products by use of statistically supported life cycle assessment. *Environ Sci Technol.* 2015;49(24):14176-14183. doi:10.1021/ACS.EST.5B04634/ASSET/IMAGES/MEDIUM/ES-2015-04634V\_0003.GIF
133. Aubin J, Papatryphon E, van der Werf HMG, Chatzifotis S. Assessment of the environmental impact of carnivorous finfish production systems using life cycle assessment. *J Clean Prod.* 2009;17(3):354-361. doi:10.1016/j.jclepro.2008.08.008
134. Ayer NW, Tyedmers PH. Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. *J Clean Prod.* 2009;17(3):362-373. doi:10.1016/J.JCLEPRO.2008.08.002
135. Wilfart A, Prudhomme J, Blancheton J-P, Aubin J. LCA and emergy accounting of aquaculture systems: towards ecological intensification. *J Environ Manage.* 2013;121:96-109. doi:10.1016/j.jenvman.2013.01.031
136. David LH, Pinho SM, Agostinho F, Kimpara JM, Keesman KJ, Garcia F. Emergy synthesis for aquaculture: a review on its constraints and potentials. *Rev Aquac.* 2020;13(2):1119-1138. doi:10.1111/raq.12519
137. Tlustý MF, Lagueux K. Isolines as a new tool to assess the energy costs of the production and distribution of multiple sources of seafood. *J Clean Prod.* 2009;17(3):408-415. doi:10.1016/J.JCLEPRO.2008.08.001
138. Liu Y, Rosten TW, Henriksen K, Hognes ES, Summerfelt S, Vinci B. Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (*Salmo salar*): land-based closed containment system in freshwater and open net pen in seawater. *Aquac Eng.* 2016;71:1-12. doi:10.1016/J.AQUAENG.2016.01.001
139. Ghamkhar R, Boxman SE, Main KL, Zhang Q, Trotz MA, Hicks A. Life cycle assessment of aquaculture systems: does burden shifting occur with an increase in production intensity? *Aquac Eng.* 2021;92:102130. doi:10.1016/J.AQUAENG.2020.102130
140. Bordignon F, Sturaro E, Trocino A, Birolo M, Xiccato G, Berton M. Comparative life cycle assessment of rainbow trout (*Oncorhynchus mykiss*) farming at two stocking densities in a low-tech aquaponic system. *Aquaculture.* 2022;556:738264. doi:10.1016/j.aquaculture.2022.738264
141. Greenfeld A, Becker N, Bornman JF, Spatari S, Angel DL. Is aquaponics good for the environment?—evaluation of environmental impact through life cycle assessment studies on aquaponics systems. *Aquac Int.* 2022;30(1):305-322. doi:10.1007/510499-021-00800-8/TABLES/5
142. Bohnes FA, Hauschild MZ, Schlundt J, Nielsen M, Laurent A. Environmental sustainability of future aquaculture production: analysis of Singaporean and Norwegian policies. *Aquaculture.* 2022;549:737717. doi:10.1016/J.AQUACULTURE.2021.737717
143. Zhang LX, Ulgiati S, Yang ZF, Chen B. Emergy evaluation and economic analysis of three wetland fish farming systems in Nansi Lake area, China. *J Environ Manage.* 2011;92(3):683-694. doi:10.1016/J.JENVMAN.2010.10.005
144. Wang G, Dong S, Tian X, Gao Q, Wang F. Sustainability evaluation of different systems for sea cucumber (*Apostichopus japonicus*) farming based on emergy theory. *J Ocean Univ China.* 2015;14(3):503-510. doi:10.1007/S11802-015-2453-Z
145. Aubin J, Baruthio A, Mungkung R, Lazard J. Environmental performance of brackish water polyculture system from a life cycle perspective: a Filipino case study. *Aquaculture.* 2015;435:217-227. doi:10.1016/j.aquaculture.2014.09.019
146. Kluts IN, Potting J, Bosma RH, Phong LT, Udo HJM. Environmental comparison of intensive and integrated agriculture–aquaculture systems for striped catfish production in the Mekong Delta, Vietnam, based on two existing case studies using life cycle assessment. *Rev Aquac.* 2012;4(4):195-208. doi:10.1111/J.1753-5131.2012.01072.X
147. Mungkung R, Aubin J, Prihadi TH, Slombrouck J, Van Der Werf HMG, Legendre M. Life cycle assessment for environmentally sustainable aquaculture management: a case study of combined aquaculture systems for carp and tilapia. *J Clean Prod.* 2013;57:249-256. doi:10.1016/J.JCLEPRO.2013.05.029
148. Medeiros MV, Aubin J, Camargo AFM. Life cycle assessment of fish and prawn production: comparison of monoculture and polyculture freshwater systems in Brazil. *J Clean Prod.* 2017;156:528-537. doi:10.1016/J.JCLEPRO.2017.04.059
149. Chary K, Aubin J, Sadoul B, Fiandrino A, Covès D, Callier MD. Integrated multi-trophic aquaculture of red drum (*Sciaenops ocellatus*) and sea cucumber (*Holothuria scabra*): assessing bioremediation and life-cycle impacts. *Aquaculture.* 2020;516:734621. doi:10.1016/j.aquaculture.2019.734621
150. Mendoza Beltran A, Chiantore M, Pecorino D, et al. Accounting for inventory data and methodological choice uncertainty in a comparative life cycle assessment: the case of integrated multi-trophic aquaculture in an offshore Mediterranean enterprise. *Int J Life Cycle Assess.* 2018;23(5):1063-1077. doi:10.1007/s11367-017-1363-2
151. Wilfart A, Favalier N, Metaxa I, et al. Integrated multi-trophic aquaculture in ponds: what environmental gain? An LCA point of view. *12th International Conference on Life Cycle Assessment of Food 2020 (LCA Food 2020), Towards Sustainable Agri-Food Systems.* 2020:206-208.
152. Cavalett O, De QJF, Ortega E. Emergy assessment of integrated production systems of grains, pig and fish in small farms in the South Brazil. *Ecol Model.* 2006;193(3-4):205-224. doi:10.1016/J.ECOLMODEL.2005.07.023
153. Henriksson PJG, Pelletier NL, Troell M, Tyedmers PH. Life cycle assessments and their applications to aquaculture production systems. In: Christou P, Savin R, Costa-Pierce BA, Misztal I, Whitelaw CBA, eds. *Sustainable Food Production.* Springer; 2013:1050-1066. doi:10.1007/978-1-4614-5797-8\_191
154. Troell M, Tyedmers P, Kautsky N, Rönnbäck P. Aquaculture and emergy use. *Encycl Energy.* 2004;1:97-108. doi:10.1016/B0-12-176480-X/00205-9
155. Hornborg S, Ziegler F. *Aquaculture and Emergy Use: A Desk-Top Study.* 2014. [https://swemarc.gu.se/digitalAssets/1536/1536133\\_publication-emergy-use-in-aquaculture.pdf](https://swemarc.gu.se/digitalAssets/1536/1536133_publication-emergy-use-in-aquaculture.pdf)

156. Badiola M, Basurko OC, Piedrahita R, Hundley P, Mendiola D. Energy use in recirculating aquaculture systems (RAS): a review. *Aquac Eng.* 2018;81:57-70. doi:[10.1016/J.AQUAENG.2018.03.003](https://doi.org/10.1016/J.AQUAENG.2018.03.003)
157. Badiola M, Mendiola D, Bostock J. Recirculating aquaculture systems (RAS) analysis: Main issues on management and future challenges. *Aquac Eng.* 2012;51:26-35. doi:[10.1016/j.aquaeng.2012.07.004](https://doi.org/10.1016/j.aquaeng.2012.07.004)
158. Halpern BS, Frazier M, Verstaen J, et al. The environmental footprint of global food production. *Nat Sustain.* 2022;5:1027-1039. doi:[10.1038/s41893-022-00965-x](https://doi.org/10.1038/s41893-022-00965-x)
159. Vo TTE, Ko H, Huh JH, Park N. Overview of solar energy for aquaculture: the potential and future trends. *Energies.* 2021;14(21):6923. doi:[10.3390/en14216923](https://doi.org/10.3390/en14216923)
160. Golden CD, Koehn JZ, Shepon A, et al. Aquatic foods to nourish nations. *Nature.* 2021;598(7880):315-320. doi:[10.1038/s41586-021-03917-1](https://doi.org/10.1038/s41586-021-03917-1)
161. Gephart JA, Golden CD. Environmental and nutritional double bottom lines in aquaculture. *One Earth.* 2022;5(4):324-328. doi:[10.1016/J.ONEEAR.2022.03.018](https://doi.org/10.1016/J.ONEEAR.2022.03.018)
162. Van Zanten HHE, Herrero M, Van Hal O, et al. Defining a land boundary for sustainable livestock consumption. *Glob Chang Biol.* 2018;24(9):4185-4194. doi:[10.1111/GCB.14321](https://doi.org/10.1111/GCB.14321)
163. Malcorps W, Newton RW, Sprague M, Glencross BD, Little DC. Nutritional characterisation of European aquaculture processing by-products to facilitate strategic utilisation. *Front Sustain Food Syst.* 2021;5:378. doi:[10.3389/fsufs.2021.720595](https://doi.org/10.3389/fsufs.2021.720595)
164. Engle CR, McNevin A, Racine P, et al. Economics of sustainable intensification of aquaculture: evidence from shrimp farms in Vietnam and Thailand. *J World Aquac Soc.* 2017;48(2):227-239. doi:[10.1111/JWAS.12423](https://doi.org/10.1111/JWAS.12423)
165. Garnett T, Mathewson S, Angelides P, Borthwick F. *Policies and Actions to Shift Eating Patterns: What Works? A Review of the Evidence of the Effectiveness of Interventions Aimed at Shifting Diets in More Sustainable and Healthy Directions.* FCRN; 2015.
166. The Norwegian Ministry of Finance. *Proposition to the Storting 78 LS - Resource Rent Tax on Aquaculture.* Støre Government; 2023.
167. Hicks CC, Gephart JA, Koehn JZ, et al. Rights and representation support justice across aquatic food systems. *Nat Food.* 2022;3(10):851-861. doi:[10.1038/s43016-022-00618-4](https://doi.org/10.1038/s43016-022-00618-4)
168. Short RE, Gelcich S, Little DC, et al. Harnessing the diversity of small-scale actors is key to the future of aquatic food systems. *Nat Food.* 2021;2(9):733-741. doi:[10.1038/s43016-021-00363-0](https://doi.org/10.1038/s43016-021-00363-0)
169. Geissdoerfer M, Morioka SN, de Carvalho MM, Evans S. Business models and supply chains for the circular economy. *J Clean Prod.* 2018;190:712-721. doi:[10.1016/j.jclepro.2018.04.159](https://doi.org/10.1016/j.jclepro.2018.04.159)
170. Fletcher CA, St Clair R, Sharmina M. Seafood businesses' resilience can benefit from circular economy principles. *Nat Food.* 2021;2(4):228-232. doi:[10.1038/s43016-021-00262-4](https://doi.org/10.1038/s43016-021-00262-4)
171. Leung TLF, Bates AE. More rapid and severe disease outbreaks for aquaculture at the tropics: implications for food security. *J Appl Ecol.* 2013;50(1):215-222. doi:[10.1111/1365-2644.12017](https://doi.org/10.1111/1365-2644.12017)
172. Boyd CE, D'Abramo LR, Glencross BD, et al. Achieving sustainable aquaculture: historical and current perspectives and future needs and challenges. *J World Aquac Soc.* 2020;51(3):578-633. doi:[10.1111/JWAS.12714](https://doi.org/10.1111/JWAS.12714)
173. Thomas JBE, Sinha R, Strand Å, et al. Marine biomass for a circular blue-green bioeconomy? A life cycle perspective on closing nitrogen and phosphorus land-marine loops. *J Ind Ecol.* 2021;26:2136-2153. doi:[10.1111/JIEC.13177](https://doi.org/10.1111/JIEC.13177)
174. Garrett RD, Ryschawy J, Bell LW, et al. Drivers of decoupling and recoupling of crop and livestock systems at farm and territorial scales. *Ecol Soc.* 2020;25(1):24. doi:[10.5751/ES-11412-250124](https://doi.org/10.5751/ES-11412-250124)
175. Costa-Pierce BA, Chopin T. The hype, fantasies and realities of aquaculture development globally and in its new geographies. *World Aquac.* 2021;52(2):23-35.

#### SUPPORTING INFORMATION

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

**How to cite this article:** Chary K, van Riel A-J, Muscat A, et al. Transforming sustainable aquaculture by applying circularity principles. *Rev Aquac.* 2023;1-18. doi:[10.1111/raq.12860](https://doi.org/10.1111/raq.12860)