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Evaluating nutrient circularity in integrated aquaculture systems: criteria and indicators

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ABSTRACT

Nutrient circularity is an application of circular economy principles that addresses issues such as nutrient accumulation or loss, and a shift away from fossil and synthetic fertilisers. The concept is increasingly being explored and is relevant for managing nutrients more sustainably in agri- and aquaculture systems, but the standards by which nutrient circularity can be evaluated require further clarification, and quantitative indicators should be established. Identifying the nutrient circularity performance of integrated aquaculture systems is particularly relevant to better understand how the combination of multiple and complementary species farmed or naturally present in these systems can upcycle nutrients from waste. The main objectives of this study were to improve understanding of nutrient circularity and clarify how to quantify it for (integrated) aquaculture systems. To this end, criteria for describing nutrient circularity were first defined based on a literature review, and quantitative indicators were then identified for each criterion to create an indicator framework. Finally, this framework was applied to three contrasting experimental integrated aquaculture systems (i.e. aquaponic, biofloc and polyculture pond) and their conventional monoculture system counterparts from previous studies to test its ability to compare nutrient circularity in aquaculture systems. Six complementary criteria (and 21 associated indicators) for describing nutrient circularity were identified: productivity, efficiency, self-sufficiency, recycling, regeneration, diversity and complementarity. These criteria, related to circularity principles, provided a clear framework for evaluation. Application of the framework indicated that the integrated systems evaluated usually outperformed conventional monoculture systems, which highlighted the potential of integrated systems to manage nutrients more sustainably. These contrasting integrated systems showed that different pathways (e.g., microbial loops, complementarity between farmed species) can be mobilised to create and (re-)cycle nutrients. Although relatively simple indicators were developed, lack of data prevented quantification of several indicators and thus a full comparison of the systems. Overall, this study helps clarify the concept of nutrient circularity and supports the development of integrated farming systems for more sustainable use of nutrients.

1. Introduction

Circular economy (CE) is currently considered a building block of policies in the European Union (European Commission, 2015), United States (EPA, 2024) and China (Chen, 2023) to combat climate change and environmental degradation. CE is an “umbrella strategy” (Moraga et al., 2019) that aggregates multiple concepts that aim to improve resource use and decrease waste and emissions compared to linear “make-use-dispose” systems. CE is now perceived as a powerful tool to address key obstacles facing current food systems (Jurgilevich et al., 2016), such as increasing food security, decreasing food losses and waste and decreasing pollution and pressure on natural and scarce resources. Depending on the local context and priorities, circular food systems may take various forms (Bonilla Cedrez et al., 2023; Hoogstra et al., 2024) and must question what is produced and consumed and how.

In this context, nutrient circularity is an application of CE principles

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to address more specific issues, such as nutrient accumulation or loss, and a shift away from fossil and synthetic fertilisers (Harder et al., 2021; Koppelmäki et al., 2021; van der Wiel et al., 2019). There is no common agreement on what nutrient circularity entails, but the concept goes beyond nutrient cycling (Koppelmäki et al., 2021). Spiller et al. (2024) defined nutrient circularity as a strategy that seeks to capture nutrients from point-source losses and by-products along the agri-food system and return them to agriculture to decrease dependence on primary nutrients (i.e. fossil phosphorus [P] and potassium, and synthesised nitrogen [N]). Nutrient circularity can include multiple and potentially antagonistic objectives, such as increased efficiency in the use of nutrient inputs, increased recycling of nutrients in waste products or increased nutrient self-sufficiency (Papangelou and Mathijs, 2021; Spiller et al., 2024; Velasco-Muñoz et al., 2021). Trade-offs between these objectives are possible, for example, when increased efficiency decreases waste and thus limits options for nutrient recycling (Spiller et al., 2024). The criteria (i.e. standards by which nutrient circularity can be evaluated) need to be clarified to design food systems that better reflect CE principles. Defining these criteria is also an initial step toward identifying circularity indicators that are currently lacking for food systems (Fassio and Chirilli, 2023) but essential for monitoring progress towards the CE.

Aquaculture is a key component of the global food system. In 2020, global aquaculture production represented 87.5 million t of aquatic animals (mainly as human food) and 35.1 million t of algae (for both food and non-food purposes; FAO, 2022). Most aquaculture animals are fed a nutritionally complete feed (e.g., commercial pellets) or supplemental feed (e.g., cereal by-products; FAO, 2022). Some aquaculture systems use fertilisers to stimulate the natural food web and provide natural food to the farmed animals. Like for crop and livestock systems, the use of inputs with high N and P concentrations and the release of aquaculture effluents in the environment can cause environmental problems such as eutrophication of water bodies (Price et al., 2015), degradation of benthic ecosystems (Hargrave, 2005), and greenhouse gas emissions. N and P emissions from the global food system are the main reason that humans exceed the planet's carrying capacity (Campbell et al., 2017).

The farm is a relevant level at which to estimate nutrient circularity in aquaculture. From a life cycle perspective, many environmental impacts, such as land use, energy use and climate change, are caused by off-farm processes (e.g., production of inputs; Bohnes et al., 2019), but most nutrient losses from aquaculture occur at the farm level. For example, Gephart et al. (2021) estimated that more than 87 % of N and 94 % of P emissions from fed aquaculture occur at the farm level. These nutrient losses consist mainly of solid (faeces) and dissolved (excretions) metabolic waste and uneaten feed. Metabolic losses can represent 51–90 % of the N and 60–83 % of the P consumed through feed by fish species of global importance (Dauda et al., 2019). Nutrient losses in uneaten feed can also be large but vary greatly among systems and are difficult to estimate (Ballester-Moltó et al., 2017; Chary et al., 2022). Ultimately, the fate of the nutrients not retained in aquatic products varies with systems technologies and management practices, potentially recycled by the natural food web as in ponds or extracted and treated in storage tanks or sewage treatment plants for RAS systems. In any case, there is a real interest in designing more circular aquaculture systems that reduce the import of nutrients, and reuse and/or recycle those are not retained by retained in the harvested products.

Integrated aquaculture systems are built to increase nutrient use by reusing outputs from one subsystem (taxa or rearing unit) which may have been wasted, as input for another subsystem (Edwards et al., 1988). Integrated aquaculture has been widely explored (Soto, 2009) and can take many forms, including the well-known Integrated Multi-Trophic Aquaculture (IMTA). In IMTA, multiple aquatic species from different trophic levels are farmed together, and extractive species (e.g., plants, invertebrates) use metabolic waste from fed species as nutrient sources. More generally, integrated aquaculture systems rely on complementarity among farmed and/or naturally present (e.g., microorganisms, food web) taxonomic groups in the system to transform and/or upcycle nutrients in "waste". These integrated systems are considered more resource-efficient than conventional aquaculture systems usually managed as monocultures, as they can produce more food with fewer external inputs. The complexity of aquaculture systems, characterised by more trophic levels and combinations than those of terrestrial livestock systems (Kolding et al., 2016), makes them an interesting subject for circularity-focused studies.

Many studies have examined the nutrient-use efficiency of IMTA, focussing on the potential nutrient uptake of extractive species (e.g., see the review of Nederlof et al. (2022)). These studies are useful for estimating the net nutrient balance of a system and quantifying potential advantages compared to a monoculture system. Recent studies developed other circularity indicators to assess IMTA (Checa et al., 2024) or aquaponic systems (Zhu et al., 2024). Surprisingly, however, few studies compared performances of conventional monoculture and other types of integrated aquaculture systems (e.g., biofloc, polyculture). Similarly, no studies have compared the performances of different types of integrated aquaculture systems.

The main objectives of this study were to improve understanding of nutrient circularity and clarify how to quantify it in aquaculture systems. To this end, we first defined criteria for describing nutrient circularity based on a literature review and then identified quantitative indicators for each criterion to create an indicator framework. Finally, we applied this framework to three contrasting integrated aquaculture systems and their conventional system counterparts to provide a proof of concept.

2. Materials and methods

2.1. Definition of circularity criteria and indicators

We used a two-steps method to build the indicator framework: i) defining the criteria of nutrient circularity ii) and defining indicators for each criterion. To define nutrient circularity criteria, we performed a literature review. The review included contributions from different research areas including studies defining CE principles (Ellen MacArthur Foundation, 2010; Geissdoerfer et al., 2017; Ghisellini et al., 2016; Morseletto, 2020; Muscat et al., 2021; Prieto-Sandoval et al., 2018), applying CE principles to agrifood systems(de Boer and Van Ittersum, 2018; Jurgilevich et al., 2016; Koppelmäki et al., 2021; Spiller et al., 2024; van der Wiel et al., 2019), and investigating nutrient circularity in aquaculture systems (Campanati et al., 2021; Chary et al., 2023; Checa et al., 2024; Lothmann and Sewilam, 2023; Zhu et al., 2024). This first review resulted in the definition of six criteria.

To identify potential nutrient circularity indicators, we extended our literature review to other studies defining and applying circularity metrics to agrifood sectors (Corona et al., 2019; Fassio and Chirilli, 2023; Poponi et al., 2022; van Loon et al., 2023; Velasco-Muñoz et al., 2021) and others defining sustainability indicators in aquaculture (Boyd et al., 2007; Le Féon et al., 2021; Lindblom et al., 2021; Stentiford et al., 2020; Valenti et al., 2018; Volpe et al., 2013). This extended review resulted in an extensive list of indicators, from which we selected best quality indicators based on five conditional factors.

- *Relevance*: The indicator is relevant for analysing the specific nutrient circularity criterion that it represents (MnE Expert, 2012)
- *Applicability*: The indicator is easy to apply, requires relatively few data and is easy to calculate (no need for specific software) (Lindblom et al., 2021; MnE Expert, 2012)
- *Clarity and unambiguity*: The indicator is easy to understand and interpret
- *Measurability*: The indicator is quantifiable and has a clear unit of measurement (MnE Expert, 2012)
- *Uniqueness*: The indicator is specific, has a clear meaning and scope and does not overlap with another indicator (MnE Expert, 2012)

These five conditional factors were score independently by each author for all indicators from 1 (poor) to 3 (excellent). The total score for each indicator, which equalled the mean of the authors' scores, was used to rank and then decrease the number of indicators.

2.2. Selection of case studies

As a proof of concept, the performance of integrated aquaculture systems was compared to that of their conventional monoculture aquaculture counterparts based on the final sub-set of nutrient circularity indicators. To this end, we limited the scope to published peer-reviewed studies that provided information on both types of systems simultaneously. This approach allowed us to analyse and compare three integrated aquaculture systems: an aquaponic system vs. monoculture in a recirculated aquaculture system (RAS; Monsees et al., 2017), a biofloc system vs. a clear water system (Luo et al., 2014) and a pond polyculture system vs. a pond monoculture system (Rahman et al., 2006). In these three studies, the conventional monoculture system was used as a control that had experimental conditions similar to those of the integrated system. A well-known example of integrated aquaculture is the IMTA practised in open-water sea cages (Chopin et al., 2012; Nederlof et al., 2022), but we did not consider it due to a lack of empirical studies that compared it directly to a monoculture counterpart.

The general characteristics of the three sets of aquaculture systems selected were diagrammed using the same graphical format (Figs. 1–3). As the studied systems were experimental configurations, they could not be considered representative of polyculture ponds, biofloc or aquaponic systems, nor of practices or performances of commercial farms. Nevertheless, they could be used as case studies for the application of circularity indicators. Data on nutrient (N and P) and biomass flows were taken as much as possible directly from the studies or estimated using simple mass-balance equations. Some external data (e.g., nutrient contents in fertilisers) from the literature were used to provide missing data.

2.2.1. Aquaponics vs. recirculated systems

An aquaponic system is defined as the combination of fish farming (or that of other aquatic animals), usually in a RAS, and plant production, in a hydroponic unit. The principle of aquaponics is to produce plant biomass from the dissolved nutrients released by the fish (Foucard et al., 2019). Nitrifying bacteria, either in a biofilter or throughout the system, are also present to transform ammonia into nitrate (i.e. nitrification), a form of N non-toxic to fish that plants can take up readily.

Monsees et al. (2017) compared the performances of a monoculture of Nile tilapia (*Oreochromis niloticus*) in RAS to those of two configurations of a tilapia/tomato aquaponic system (Fig. 1). For clarity, we used data from only one of the two configurations (system D). In their experiment, fish were fed commercial pellets for 154 days in 1.7 m^3 tanks. In both the RAS and aquaponic system, filtration units were used to remove suspended solids and increase nitrification. The hydroponic unit contained 0.68 m^2 of trays to grow tomatoes, and fertiliser with N, potassium, calcium and trace elements was supplied to increase their growth. Water reservoirs with one-way valves allowed water to circulate only from the fish tanks to the hydroponic unit (see Monsees et al. (2017) for details).

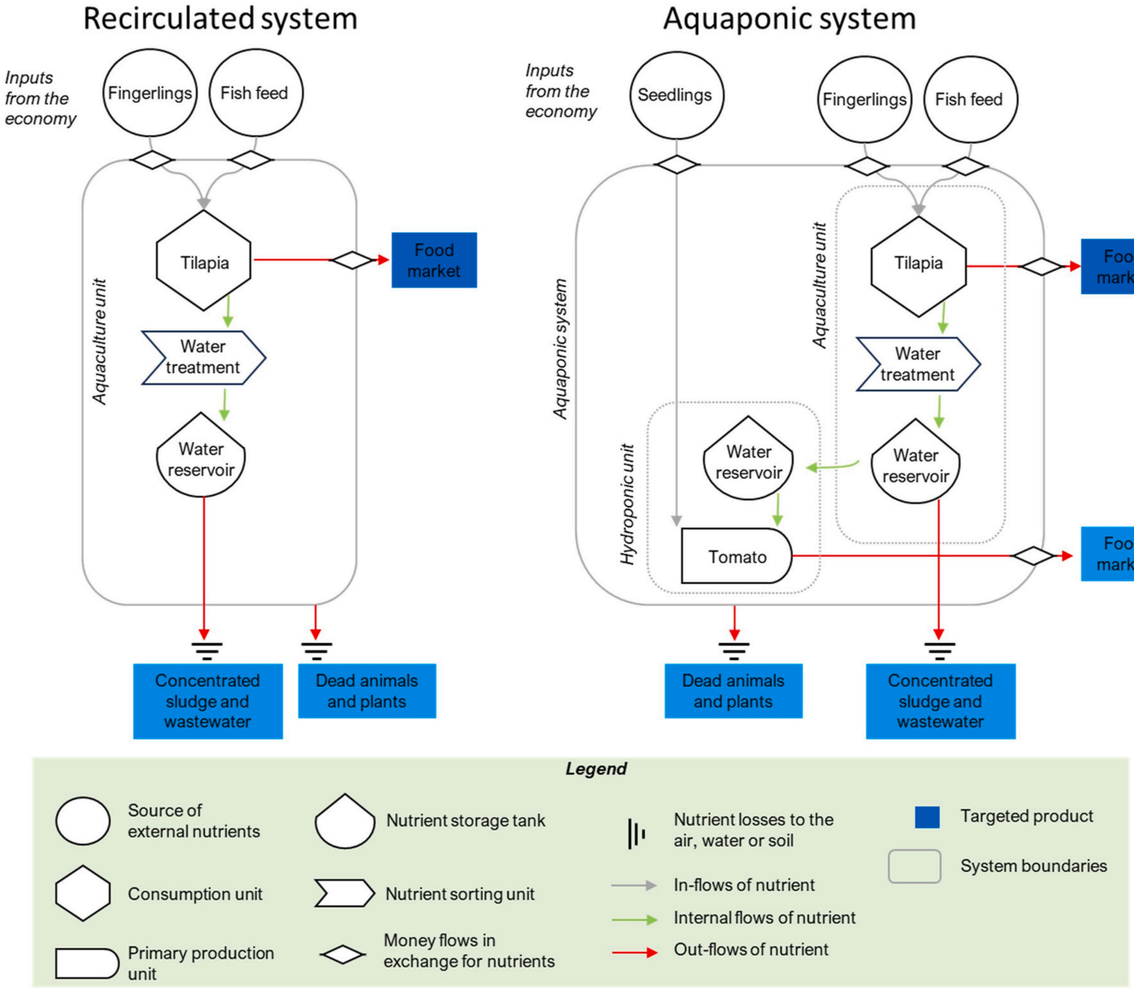

Fig. 1. Nutrient flows in the recirculated aquaculture system and aquaponic system.

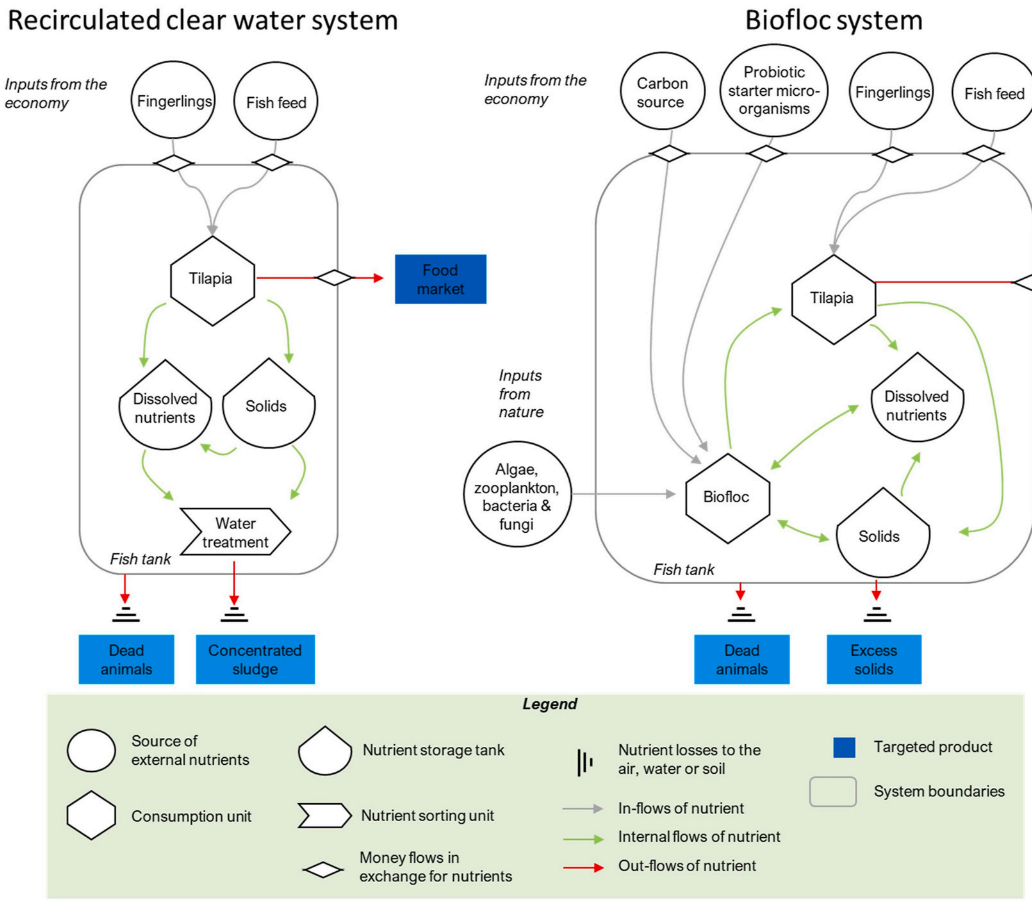

Fig. 2. Nutrient flows in the recirculated clear water and biofloc systems.

2.2.2. *Biofloc vs. clear water systems*

Biofloc technology is an aquaculture system implemented with little or no water exchange and with “green” (dominated by photoautotrophic organisms) or “brown” (dominated by heterotrophs) water. Biofloc technology uses the microbial community in the water to assimilate nutrient waste (in faeces, excretions and uneaten feed), converting it into microbial biomass, which can then be used as a supplemental or replacement food source for the farmed aquaculture animals. Biofloc systems generally rely on two main nutrient sources: a complete compound feed, designed to meet fish or shrimp nutrient requirements, and a carbon source, used to control the carbon:N ratio in the water and the growth of the desired microorganisms and plankton.

Luo et al. (2014) compared farmed Nile tilapia performances and nutrient emissions of a recirculated clear water system to those of an indoor biofloc system (Fig. 2). In their experiment, fish were fed commercial pellets for 87 days in 0.3 m^3 tanks. In the clear water system, water was filtered and renewed a mean of 9.6 times per day. In the biofloc system, the water-treatment units were closed, and sodium acetate was added to maintain an optimum carbon:N ratio for bacteria. The fish had constant access to the floc and could use it as supplemental feed. When the suspended solid concentration became too high, some water and floc were removed and allowed to settle, after which the water was returned to the tank. Water was continuously aerated in both the clear water and biofloc systems (see Luo et al. [2014] for details).

2.2.3. *Pond polyculture vs. pond monoculture*

In fish pond polyculture systems, species with compatible and complementary diets and behaviour are reared together to exploit multiple compartments of the pond (Milstein, 2005) to increase the system’s overall productivity (Thomas et al., 2021). Species are usually selected based on their trophic complementarity (e.g., herbivore with planktivory and omnivore species) and/or on their complementary use of spatial resources in the pond (e.g., water-column feeder and bottom feeder). Other forms of species complementarity, such as commensalism or mutualism, can be implemented and result in benefits for one or more of the species (e.g., better health conditions, improved water quality, increased food availability; Thomas et al., 2021).

Rahman et al. (2006) compared effects of introducing common carp or not into rohu (*Labeo rohita*) ponds on water quality and nutrient accumulation. Treatments included ponds with rohu alone (the control) and ponds with rohu and different stocking densities of carp. Supplementally fed and non-fed ponds were also compared. Associating carp with rohu is an example of commensalism in which carp foraging and burrowing in the pond bottom releases nutrients into the water, which stimulates primary production and increases food availability for the rohu. In our study, we used only the data from the fed rohu monoculture (stocked at 1.5 fish per m^{-2}) and the fed ponds with rohu and carp stocked at 1.5 and 0.5 fish per m^{-2}, respectively (Fig. 3). Both ponds were fed a complete compound feed and fertilised with cow manure, urea and synthetic P fertiliser. The fish were harvested after 137 days (see Rahman et al. (2006) for details).

3. Results and discussion

From the literature review, we identified six criteria: (i) productivity, (ii) efficiency, (iii) recycling, (iv) self-sufficiency, (v) ecosystem regeneration and (vi) species diversity and complementarity. We identified 32 potential indicators and ultimately selected 21 of them (Table 1) for the 6 criteria (see Table S1 for the indicators not selected). In this section, criteria are presented as well as relevant indicators to quantify them

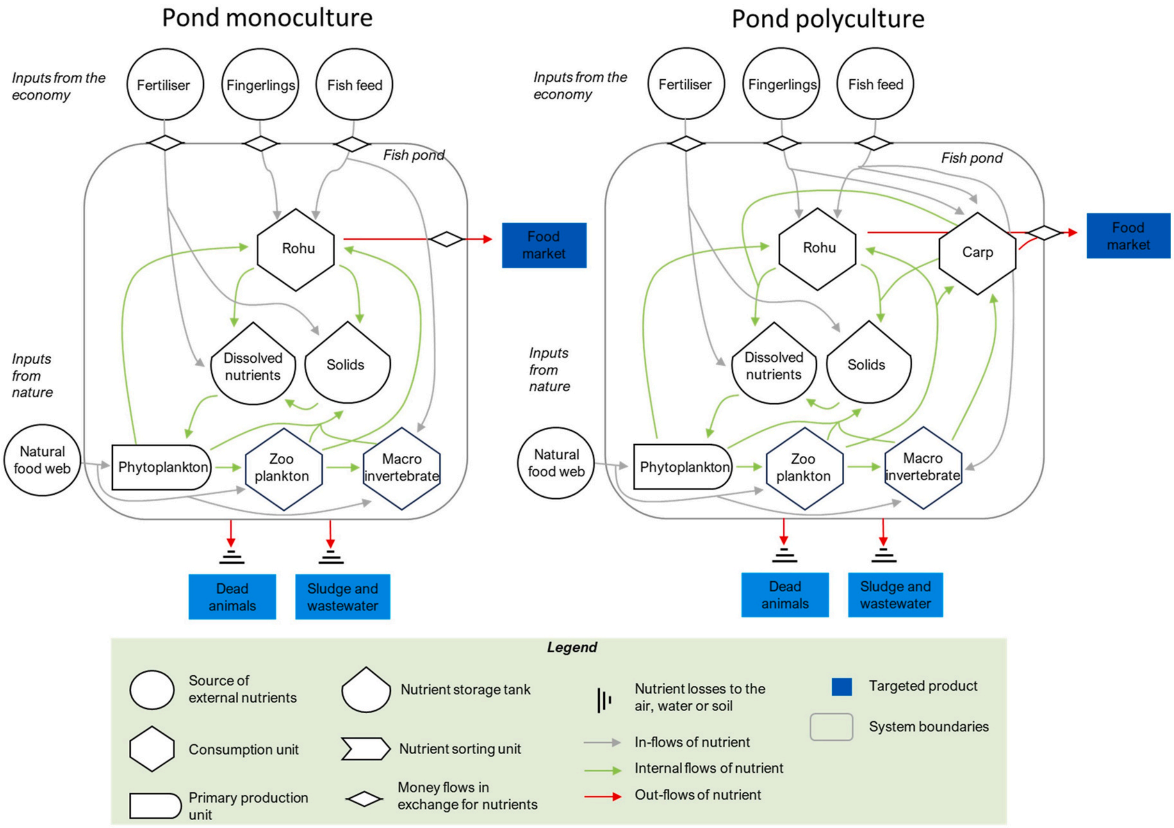

Fig. 3. Nutrient flows in the pond monoculture and polyculture systems.

(section 3.1, Table 1). Then, each integrated system is compared to its conventional monoculture counterpart by quantifying the indicators (section 3.2). Finally, the limitations of this study and avenues for further research are discussed (section 3.3).

3.1. *Criteria and indicators selected for describing nutrient circularity*

3.1.1. *Productivity*

The main objective of aquaculture is to produce and market food and non-food products (e.g., feed, pharmaceuticals, biomass for energy). Whereas system's profitability is often driven by one main product, a farm may also deliver co-products and generate wastes. In the context of integrated aquaculture, we refer to waste as "losses", including any matter that does not meet the requirements of the targeted (co-)product (s) and had little or no economic value. To evaluate productivity in aquaculture systems, commonly used indicators such as system yields, and other types of productivity were selected (Table 1). To allow for comparison with systems that produce more than fish (e.g., plants), these indicators were expressed per kg of food products.

Productivity indicators further include the food:non-food ratio, to accommodate circularity narratives (Chary et al., 2023; Muscat et al., 2021) which suggest that limited resources should be prioritised for basic human needs, i.e. prioritising food over feed production. This ratio is quantified as the relative quantities of food and non-food products harvested from a system. Final productivity indicator should refer to the ability to produce nutritious food (Stentiford et al., 2020). As nutrient composition varies greatly among aquatic foods (Golden et al., 2021), some species provide more nutrients important for human health. The nutrient-richness indicator (Table 1), accounts for nutrient (crude protein, EPA, DHA, vitamin A, B12, calcium, iodine, iron and zinc) density in the food products compared to daily requirements.

3.1.2. *Efficiency*

Higher efficiency is desired from both economic and ecological perspectives. Efficiency is a measure of production performance usually expressed as a ratio of the (targeted) products to the inputs (e.g., nutrients, land, water, energy) but it may also relate to the losses per unit of product. We selected the indicators animal mortality, nutrient losses (N and P emissions) and food losses (Table 1) to represent efficiency of (integrated) aquaculture systems.

Relating to the feed-food narrative (see 3.1.1) Chary et al. (2023) and de Boer and Van Ittersum (2018) highlight the inherent inefficiency of animal production systems relying on feed resources that are also suitable for direct human consumption. The human-edible-protein conversion ratio (HePCR) accounts for this as it estimates the quantity of human-edible ingredients in animal feed (Ertl et al., 2016; Laisse et al., 2018) and the net contribution of animal production systems to nutrient supplies.

3.1.3. *Recycling*

Achieving nutrient circularity requires closing nutrient and carbon cycles by recovering and (re)cycling unavoidable losses back into the bio-based system (Ghisellini et al., 2016; Prieto-Sandoval et al., 2018; Schreefel et al., 2020). Beyond farm level, this can be realised by treating the aquaculture system as a "digester" of food-system leftovers by using recycled products as inputs instead of virgin materials. We thereby suggest the relative fraction of by-products in feed as a recycling indicator, to evaluate nutrient circularity at the level of territory or food system.

Within a farm, nutrients can be recycled by stimulating internal cycling and reducing the flows that leave the system. In integrated aquaculture systems, nutrient exchange is stimulated by the presence of multiple complementary species. An indicator commonly used to estimate nutrient cycling in IMTA is the bioremediation index, which measure the efficiency with which extractive species exact waste

Table 1
Farm-level indicators used to quantify the nutrient circularity criteria selected for integrated aquaculture systems.

Criterion	Sub-criterion	Indicator	Unit	Description and rationale	Favourable values	References
Productivity	Overall production	Food yields	kg.m^{-3}	Biomass gain (in fresh matter) per unit volume of production containment	High	–
		Food productivity	kg.m^{-3}.yr^{-1}	Biomass gain (in fresh matter) per unit volume of production containment and unit time	High	–
	Specific production	Nutrient-richness	%	Mean percentage of daily requirements (for protein and 7 essential nutrients) met by a 100 g portion of the food product	High	Adapted from Golden et al. (2021)
		Food:non-food	kg.kg^{-1}	Mass of food produced per total mass of biomass produced. In food systems, food production should be prioritised over other functions (e.g., feed production).	Low	Adapted from Muscat et al. (2021)
Efficiency	Input-use efficiency	Nutrient-use efficiency (NUE)	%	Mass of nutrient recovered in the targeted product per mass of nutrient supplied	High	Valenti et al. (2018)
		Economic feed-conversion ratio (eFCR$_{food}$)	kg.kg^{-1}	Mass of external feed used per mass unit of food produced	Low	–
		Human-edible-protein conversion ratio (HePCR)	kg.kg^{-1}	Mass of human-edible protein (HeP) used in the animal feed per mass of HeP produced in the animal food product	Low	(Laisse et al., 2018; Wilkinson, 2011)
		Survival	%	Percentage of stocked animals harvested at the end of the production cycle	High	–
		Transformity	sej.J^{-1}	Total emergy flows in the inputs divided by the energy in the products	Low	Odum (1995)
	Losses	Food losses	%	Percentage of the harvested biomass wasted or lost before marketing	Low	–
		Nutrient emissions	kg.kg^{-1}	Nutrient emissions per kg of food products harvested	Low	–
(Re)cycling	Input or output recycling	Bioremediation	%	Percentage of nutrients (N or P) in the waste of fed species retained in extractive species	High	Adapted from Chary et al. (2020)
		By-products in feed	%	Percentage of feed-ingredient biomass derived from by-products	High	This study
		Output recycling	Yes/No	Recycling of some of the nutrients lost from the system (e.g., to produce fertilisers or feed)	Yes	This study
Self-sufficiency	Dependence on external inputs	Synthetic and fossil fertiliser dependence	%	Mass of phosphorus (P) or nitrogen (P) fertiliser from fossil or from synthetic sources per total mass of P or N in the inputs	Low	This study
		Nutrient self-sufficiency	%	Percentage of nutrients (N or P) in the feed used for the fed species produced by the farming system	High	This study
		Fish-in:fish-out ratio (FIFO)	kg.kg^{-1}	Mass of marine ingredients (fish meal and fish oil) required to produce 1 kg of farmed aquatic food	Low	–
		Forage-fish dependence ratio (FFDR)	kg.kg^{-1}	Mass of live fish from small demersal and pelagic fisheries in fish meal and fish oil needed to produce 1 kg of farmed aquatic food	Low	–
Regeneration	Nutrient balance	Import/export balance	kg nutrients.ha^{-1}	Nutrient output minus nutrient input (N or P)	Around 0	Phong et al. (2011)
Diversity and compl”ementarity	Complementarity	Trophic complementarity	Number	Number of trophic-level categories farmed in the system	High	–
		Extractive:fed biomass	kg.kg^{-1}	Biomass of extractive species harvested per kg of fed species harvested	Around 1 or higher	Adapted from Chary et al. (2020)

(Nederlof et al., 2022).

3.1.4. Self-sufficiency

Nutrient circularity is sometimes associated with the objective of decreasing dependence on external resources (e.g., feed, fertiliser) to reach (partial) self-sufficiency (de Boer and Van Ittersum, 2018; Schreefel et al., 2020; van der Wiel et al., 2019). Doing so can decrease the risks of fluctuating availability and/or prices of these inputs and is an important aspect of a farm's robustness and adaptation capacity. Furthermore, decreasing dependence on virgin materials such as fossil P or forage fish, decreases the environmental pressure of aquaculture systems on the resource ecosystems. We included a variety of indicators to estimate dependence on synthetic and fossil fertilisers (synthetic and fossil fertiliser dependence), forage fish (fish-in:fish-out ratio, forage-fish dependence ratio) and feed (feed self-sufficiency; Table 1).

3.1.5. Ecosystem regeneration

Ecosystem regeneration is a central principle of the CE (Ellen MacArthur Foundation, 2010; Morseletto, 2020; Muscat et al., 2021). A core objective of regenerative aquaculture is to develop aquaculture in the context of ecosystem functions and services (Alleway et al., 2019; Chary et al., 2023; Mizuta et al., 2023) to maintain conditions that support life-enhancing qualities of ecosystems. It implies, among other things, avoiding nutrient accumulation (e.g., of organic matter on the sediment in fed aquaculture) or depletion (e.g., of phytoplankton in bivalve aquaculture) in the system. As a regenerative indicator we followed Weitzman and Filgueira (2019), adding the measure that an aquaculture system should not import more nutrients than it exports or exceed the ecosystem's carrying capacity (i.e. assimilative and extractive capacity).

3.1.6. *Diversity and complementarity*

Diversity among food system components is not directly recognised as a key principle of circularity, but it is a way to use available resources more efficiently, which is necessary to optimise nutrient recirculation, and it helps increase ecosystem resilience (Dumont et al., 2014). Diversifying species in a farming system and promoting functional synergies are key concepts of integrated aquaculture systems. In the design of integrated aquaculture systems, emphasis is placed on the complementary ability of the selected species to exploit multiple trophic niches in the system. We included biomass ratio of extractive to fed species as an indicator, given that the ratio between trophic levels can strongly influence the system's ability to retain nutrients (Reid et al., 2020), as well as its management and economic model (Chary et al., 2020).

3.2. *Quantification of circularity indicators*

Due to a lack of data, only 15 of the 21 indicators selected could be quantified for the pond systems (the best documented), while even fewer could be quantified for the other systems. Results are presented per case study in Figs. 4–6 and all indicators' values are presented in supplementary materials (Table S2).

3.2.1. *Aquaponics system vs. RAS*

Most differences in the indicators between the aquaponic system and the RAS were driven by the additional plant production in the former. Fish growth rates were similar between the two systems. The aquaponic system had higher food yields (+67 %) than the RAS thanks to the additional production of tomatoes. The similar nutrient-richness score between the two systems, however, indicated that tomatoes produced in the aquaponic system did not supply substantial amount of key nutrients for human health. Noteworthy, tomatoes contain other nutrients and compounds (e.g., vitamins D, C and E, and carotenoids) not considered in the nutrient-richness score but also important for human health. Logically, the additional production of food (as tomatoes) in the aquaponic system also improved efficiency indicators such as the economic feed-conversion ratio and N-use efficiency and decreased N emissions by 29 % compared to that of the RAS. The additional biomass produced in the aquaponic system had a higher influence on these indicators than the N uptake by the tomatoes. Indeed, the tomatoes showed little potential for recycling nutrients from fish waste, as N bioremediation was extremely low (2 %) in the aquaponic system. This bioremediation percentage was similar to those observed for other aquaponic systems (e.g., Jaeger et al., 2019) but was particularly low given the extractive:fed biomass ratio of species in system (0.59). Increasing bioremediation to a meaningful percentage in the aquaponic system would imply producing much more tomato biomass than fish biomass in the system. Finally, the aquaponic system depended little (1 %) on N from synthetic fertiliser and hence performed similarly to the RAS (0 %). The addition of fertiliser to aquaponic systems can decrease nutrient uptake and create a trade-off with synthetic and fossil fertiliser dependence, but using fertiliser can be essential to maintain elemental stoichiometry, which strongly influences a system's ability to use nutrient inputs efficiently (van der Wiel et al., 2019). In summary, the aquaponic system had some higher productivity and efficiency indicators but little nutrient recycling.

3.2.2. *Biofloc system vs. clear water system*

The biofloc system had higher productivity, efficiency, recycling and self-sufficiency than the clear water system. The biofloc system had higher yields because its fish grew faster. Other studies observed better growth performances of tilapia in biofloc systems (e.g., Yu et al., 2023) than in clear water systems (e.g., Kishawy et al., 2020; Mirzakhani et al., 2019). The biofloc system also had higher N- and P-use efficiency and about one-half the N emissions per kg of fish produced than those of the clear water system. In biofloc systems, a decrease in nutrient losses can

Fig. 4. Productivity, recycling, efficiency, self-sufficiency and complementarity indicators estimated for the recirculated aquaculture system (RAS) and the aquaponic system (Aqua). See Table 1 for definitions of the indicator abbreviations.

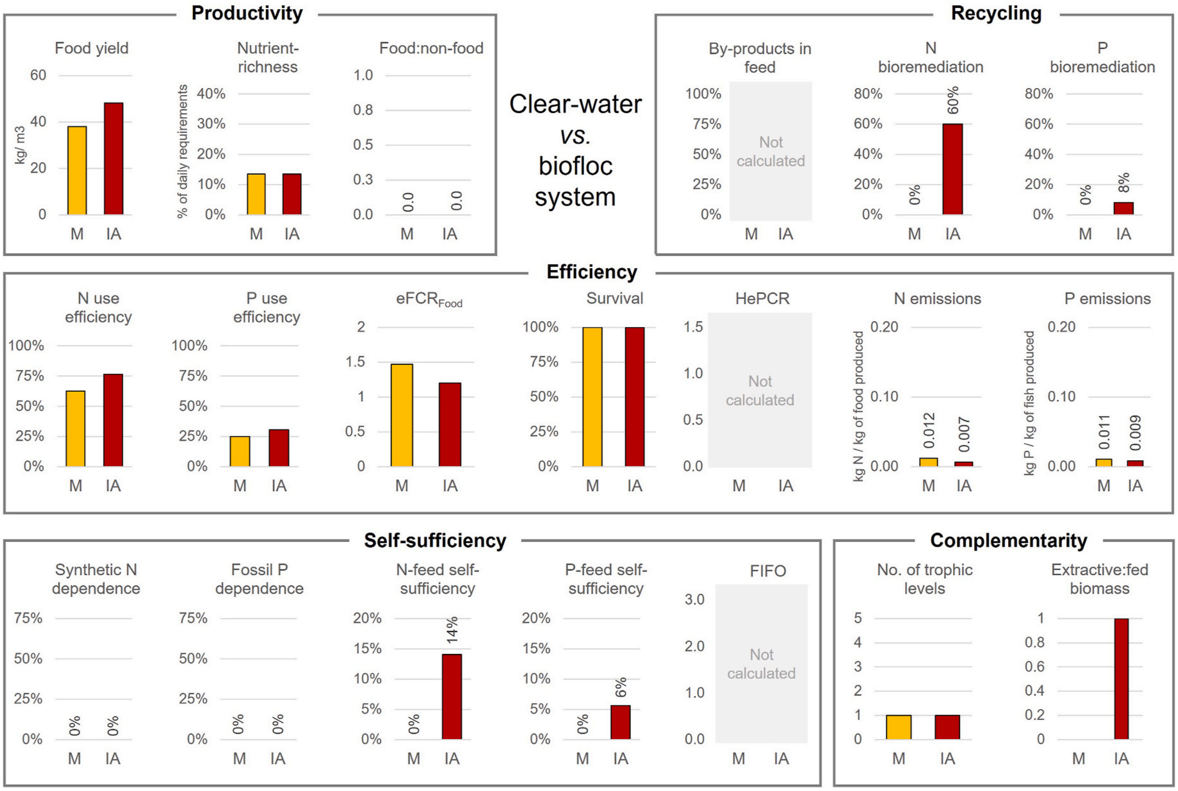

Fig. 5. Productivity, recycling, efficiency, self-sufficiency and complementarity indicators estimated for the clear-water recirculated aquaculture system (RAS) and the biofloc system. See Table 1 for definitions of the indicator abbreviations.

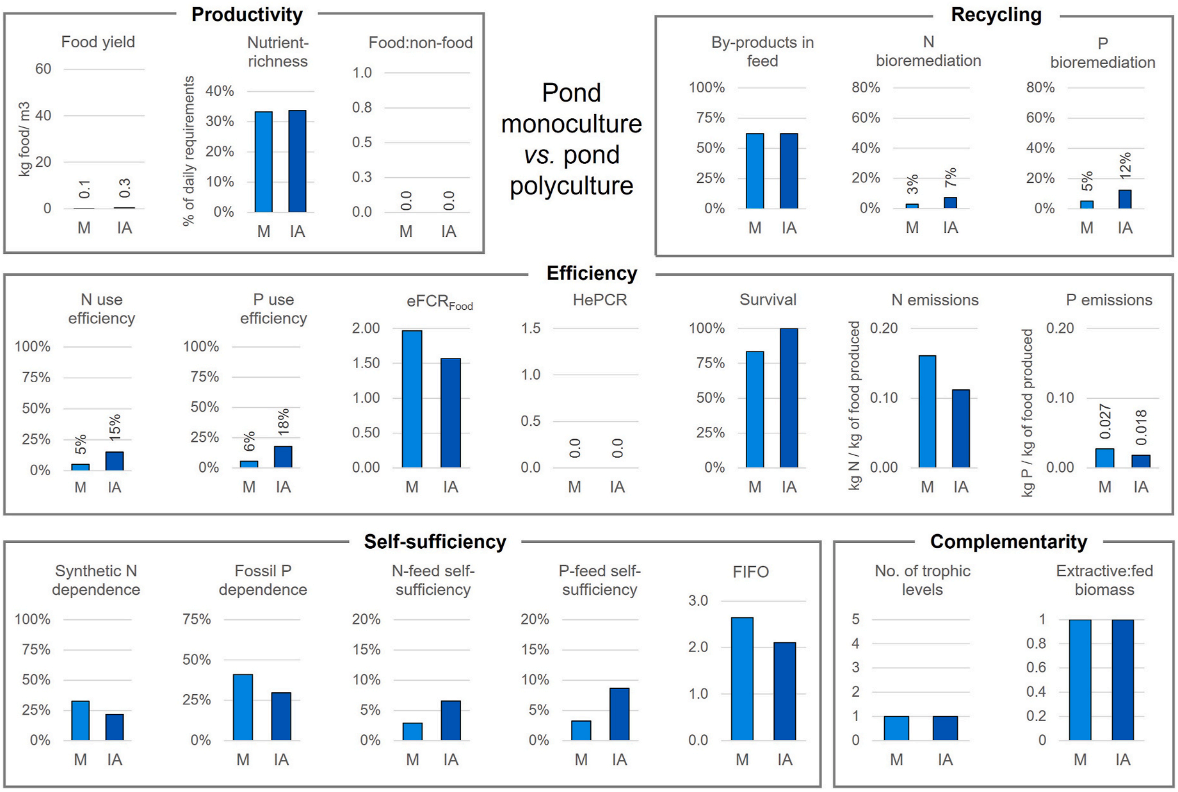

Fig. 6. Productivity, recycling, efficiency, self-sufficiency and complementarity indicators estimated for the monoculture system (Mono) and polyculture pond system (Poly). See Table 1 for definitions of the indicator abbreviations.

be explained by the floc's high palatability and functionality (e.g., stimulation of intestinal microbiota) as a feed supplement (McCusker et al., 2023). However, Luo et al. (2014) observed similar protein digestibility in the biofloc and clear water systems, suggesting that the biofloc system's higher growth was due to the consumption of floc and not to a better feed assimilation. As the biofloc system transformed much of the fish waste into flocs, most of which the fish consumed, we estimated that it had 60 % N bioremediation potential (vs. 0 % in the clear water system) and 14 % N feed self-sufficiency (vs. 0 % in the clear water system). The biofloc system is an interesting example of an integrated system that increases nutrient use while rearing only one trophic level.

3.2.3. Pond polyculture vs. pond monoculture

Yields were more than twice as high in the pond polyculture system than in the pond monoculture system, and differences in N- and P-use efficiencies between the two systems were even higher. These results indicate that carp effectively retain nutrients that rohu do not use. This higher efficiency was likely due more to carp consuming feed than to carp releasing nutrients through burrowing, as N- and P-use efficiencies were low in the monoculture system. Furthermore, gut content analysis performed by Rahman et al. (2006) revealed that carp fed mainly on feed, while rohu fed mainly on plankton. Consequently, when calculating the extractive:fed biomass ratio, we classified rohu and carp as both an extractive and fed species, which explains the ratio of 1 for the monoculture and polyculture systems. Classifying fish species as fed or extractive is not straightforward in pond systems, as many fish species are opportunistic and consume multiple food sources. In the monoculture and polyculture systems, N bioremediation was 3 and 7 % and P bioremediation 5 and 12 %, respectively. However, to obtain these estimates we had to make a series of assumptions about the proportion of ingested nutrients coming from natural sources and feed, and about the sources of nutrients (fertiliser or fish waste) used by the natural food web. Therefore, there is significant uncertainty in the calculation of N and P bioremediation. Both systems depended in part on synthetic N and fossil P, but the polyculture system had lower N and P dependence due to the additional production of carp. For the same reasons, co-culturing carp in the polyculture system increased the N and P feed self-sufficiency by 3 and 5 percentage points, respectively, compared to those estimated for the monoculture system (2.9 % and 3.2 %, respectively). The polyculture system had higher productivity, efficiency and self-sufficiency than the monoculture system, most likely due to the carp using the feed not eaten by the rohu.

3.2.4. Comparison of the biofloc, aquaponic and polyculture systems

Indicators were normalised and aggregated into a relative score for each criterion (Table S3) to demonstrate how the nutrient circularity of integrated systems can be compared (Fig. 7). Aggregating the indicators into five scores facilitated interpretation of the results. The aquaponic and pond polyculture systems had similar profiles, with a focus on productivity, efficiency and complementarity. In contrast, the biofloc system performed better than the other two at recycling and self-sufficiency. Because the recycling score was based only on the bioremediation indicator, it was highest for the biofloc system. This result indicates that besides the diversity and complementarity of farmed species in aquaculture systems, the microorganisms in can play an essential role in closing nutrient loops, in particular in biofloc systems. Complementarity indicators should be adapted to better reflect the potential role of non-farmed species, including microorganisms, in nutrient recycling. The biofloc system's higher score for self-sufficiency was due to its lack of fertiliser and use of biofloc as fish feed. The varying profiles of these integrated aquaculture systems confirm that these systems can implement several strategies to increase circularity. Although the present study was limited to three experimental systems, all pond polyculture, biofloc and aquaponic concepts can be translated into a variety of other aquaculture systems depending on the species chosen, environmental conditions and the design and management of the farm.

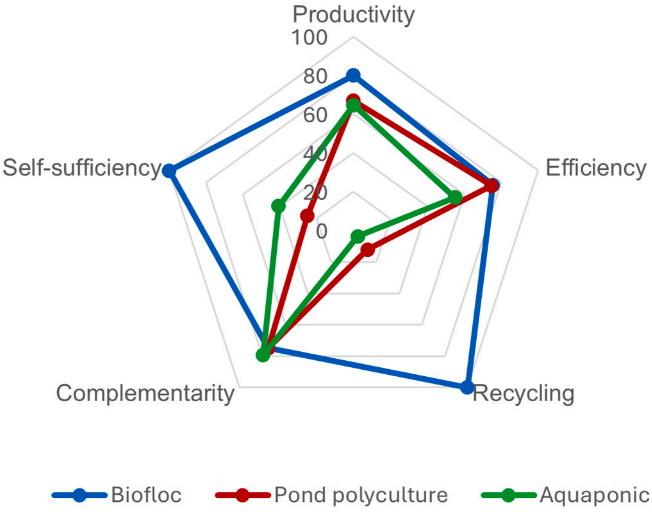

Fig. 7. Aggregated relative score for productivity, efficiency, recycling, self-sufficiency and complementarity indicators for the three integrated aquaculture systems. For each indicator, a score of 100 was set for the best-performing system. Other systems' scores were normalised as a function of the best-performing system. The aggregated relative score equals the mean of the score of each indicator for each criterion (Table S2). Only indicators for which values were calculated for all three systems were included.

3.3. General discussion

The lack of a common understanding of nutrient circularity stems in part from using the term both strictly, to refer to nutrient (re)cycling, and loosely, as a broader umbrella strategy (Moraga et al., 2019), as we did. In both cases, researchers agree on the need to consider multiple criteria simultaneously. For example, Velasco-Muñoz et al. (2021) concluded that indicators for circularity in agriculture should be able to combine multiple CE concepts, including efficient resource use, recycling or reuse, and regeneration of natural resources. Similarly, Spiller et al. (2024) recommended analysing circularity (in the sense of nutrient recycling), efficiency and self-sufficiency simultaneously to improve nutrient management in agri-food systems. Puech and Stark (2023), based on Bonaudo et al. (2014), identified self-sufficiency, productivity, efficiency and resilience as "emerging properties expected of sustainable agricultural systems". Our review identified six complementary criteria of nutrient circularity: productivity, efficiency, self-sufficiency, recycling, regeneration, diversity and complementarity. To avoid transforming circularity into another virtuous myth and to ensure that it is better understood and actionable for farmers and other stakeholders, we encourage researchers to avoid overusing the term "circular" and/or "circularity" and, when they do use it, to describe the criteria of interest clearly.

The selected indicators can contribute to the design of more environmentally sustainable aquaculture by providing stakeholders with valuable information on system and product performance. Farmers often use productivity and efficiency indicators, such as yields, survival rates, and eFCR, to monitor their performance and adapt management practices. In the future, farmers may also quantify self-sufficiency indicators, like nutrient self-sufficiency, to reduce risks associated with fertiliser/feed supply disruptions or price volatility. With increasing attention on feed-food conflicts (Barbieri et al., 2022; Breewood and Garnett, 2020), feed manufacturers are incentivised to adjust their formulations by reducing their reliance on food-grade and potentially human-edible resources. Indicators such as the percentage of by-products or the HePCR will therefore be useful for designing novel aquafeeds derived from the circular economy (Chary et al., 2024; Colombo and Turchini, 2021; van Riel et al., 2023). Certification bodies, such as the ASC, are already incorporating several of these indicators (e.g., FIFO, FFDR, NUE, survival, yield) into their certification schemes. Regulators also require data to monitor farm emissions (e.g., nitrogen and phosphorus) or to allocate subsidies linked to environmentally friendly practices (e.g., energy and fossil fuel usage). Ultimately, any indicator that measures the environmental performance and nutrient quality of products (e.g., nutrient richness score) can better inform consumers and encourage healthier and more responsible dietary choices.

As a proof of concept, the indicators selected were applied to three experimental integrated systems and their conventional monoculture counterparts. These comparisons indicated that integrated systems performed as well as or better than the conventional aquaculture systems. According to the indicators selected, integrated systems produced more per unit of nutrient and feed input, stimulated internal recycling and thus decreased the need for feed or emissions per kg of targeted product. In some cases, these systems also decreased the system's dependence on fossil P and synthetic N fertilisers. This result suggests that integrated aquaculture systems show great potential for more sustainable management of nutrients and confirms conclusions made about other integrated aquaculture systems (Checa et al., 2024; Nederlof et al., 2022). However, the three integrated systems did not contain more nutrients in their products or use more by-products in feed than their monoculture counterparts. Because the three integrated systems had higher values for distinct criteria, the six criteria and associated indicators seemed to be useful for providing a broad and nuanced perspective on potential benefits of integrated systems. Furthermore, a variety of integrated systems have been developed (Troell, 2009), and new systems that combine multiple concepts are also emerging. For example, aquaponics and biofloc technologies can be combined into FLOCponics systems (Pinho et al., 2022), and trophic efficiency in polyculture ponds can be increased further by adapting feed formulation to stimulate primary production, increasing food availability for fish (Kabir et al., 2020). This diversity of systems increases the chance of developing suitable integrated systems in contrasting contexts that differ in environment, species and availability of inputs and energy.

Most of the data required to calculate the indicators concerns the input and output flows over a production cycle and can easily be obtained, however, some key data are more rarely communicated. For example, exact feed formulation is often confidential and therefore rarely disclosed by feed manufacturers. Greater transparency regarding this data is needed to better calculate feed-related indicators (e.g. HePCR, FIFO, FFDR). Similarly, the proportion of feed actually consumed (and wasted) by the fish is generally unknown to farmers. Except in high-tech systems where feeding is automated and waste controlled via sensors and/or cameras (Føre et al., 2018), estimating precise feed intake is very difficult but essential to accurately estimate nutrient use efficiency and losses. Instead, the use of mathematical models, particularly bioenergetic models, can help estimate the amount of feed potentially wasted (Chary et al., 2022). Estimation of feed intake and feed waste with modelling is less time and money consuming than direct measurements and has a higher generalisation potential. The development of "turnkey" models tailored to different systems and species is therefore crucial, both for optimising practices and for more accurately estimating farm performance. Future studies on integrated systems should also report more often data about energy use. Indeed, recycling nutrients in integrated systems can increase energy use significantly (Greenfeld et al., 2022) due to the need for more energy to circulate water between system components (e.g., in aquaponics). Communicating energy use data will allow the calculation of other important indicators such as product's transformity which represents the cumulative energy resource used during a product's life cycle divided by the available energy in a product (Odum, 1995). It is a strong indicator of the efficiency of a production system, and quantifying it is particularly important, as it can highlight potential trade-offs with circularity. Finally, more transparency is also needed regarding other aspects such as the quality and fate of aquaculture effluents, and the nutritional quality of aquatic products.

The recycling and regeneration criteria would benefit from additional clear, applicable and quantifiable indicators. This study's process for evaluating indicators resulted in selecting only one indicator (i.e., import/export balance for nutrients) for regeneration, which turned out to be impossible to quantify for the three case studies selected. Calculating an import/export balance for nutrients implies estimating independently all nutrient flows that enter and leave the aquaculture system, but this is rarely done for aquaculture systems in contrast to livestock systems (Godinot et al., 2015). The nutrient contribution from nature (e.g., the food web, ambient nutrients in the water, precipitation) is often ignored (Dalbem Barbosa et al., 2024), and nutrients in the sludge are usually subtracted from nutrients in inputs and products. However, estimating the import/export balance is key to determining whether a production system contributes to an ecosystem's nutrient enrichment or depletion and does not exceed the ecosystem's ecological carrying capacity. These criteria are specifically relevant for (integrated) aquaculture systems that interact directly with the surrounding ecosystem, such as IMTA systems in open-water environments, which we did not consider due to a lack of data. A traditional mass-balance approach is usually used to estimate nutrient-retention efficiencies in such systems (Checa et al., 2024; Nederlof et al., 2022), ignoring complex interactions with nature, including temporal and spatial connectivity. Other aspects of the regeneration criterion included the ecosystem services provided by the production system to sequester carbon, enhance biodiversity or more generally maintain or restore the health and resilience of ecosystems. These aspects are particularly difficult to quantify, and the two indicators identified to estimate ecological risks and benefits (Table S1) can be used only as imperfect proxies. Similar difficulties were encountered when defining applicable and clear recycling indicators. New indicators, such as the cycling index or the cycle count (Steinmetz et al., 2021; van Loon et al., 2023), are being developed as the interest in nutrient circularity increases, but quantifying them requires detailed description of all internal flows in the system (green arrows in Figs. 1–3), and interpreting them is not straightforward. Ecological network analysis, ecotrophic modelling and equivalent methods are better suited to quantify these indicators than the nutrient mass-balance approach.

The proposed circularity indicator framework is not without limitations. The value of some of the selected indicators can be influenced by subjective methodological choices. The way in which system boundaries and sub-systems are defined can affect the outcomes of (re)cycling and self-sufficiency, or regeneration indicators. In some systems, such as open-water cages, farm boundaries are particularly difficult to define, especially if we want to consider the changes in productivity of downstream ecosystems. For example, in these systems, should wild fish feeding on fish faeces and uneaten feed be considered part of the farm's sub-system or excluded? Similarly, should ambient nutrients in the water be accounted for as internal or external flows? The lack of consensus on how to define key parameters for some indicators can also introduce uncertainty into the results. For example, outcomes of the HePCR which assesses feed-food competition can vary significantly according to which feed ingredients are considered "human edible" or not (Chary et al., 2024). To address these limitations, we recommend greater transparency and clarity regarding the definition of system boundaries (i.e., as proposed in Figs. 1–3) and the assumptions used in the calculation of the indicators. Furthermore, uncertainty should further be incorporated in the calculation of circularity indicators in future studies.

The present study explored nutrient circularity at production system level. Managing nutrient flows at this level is relevant in aquaculture because most losses occur there. It is also practical, as the system's components are generally close enough to each other to facilitate exchanges. However, circularity is a multi-level concept (Figge et al., 2023) that can be assessed from smaller (e.g., field, rearing unit) to larger (e.g., landscape, territory, region; de Boer and Van Ittersum, 2018; Koppelmäki et al., 2021) spatial (and temporal) levels. There is likely no optimal level at which nutrients should be recycled, but instead complementary pathways that remain context-specific (de Boer and Van Ittersum, 2018). Considering circularity at the territorial or regional level has the potential to connect aquaculture systems to multiple sectors and actors that can act as nutrient suppliers, nutrient sinks or both (Fig. S1). For example, aquaculture can reuse agri-food waste and by-products from food processing (e.g., dried distillers' grain, mustard cake, wheat bran) as feed (Prabakusuma et al., 2023), while fish-processing by-products can be processed into fish meal and oil and used as feed for other aquaculture species or terrestrial livestock (Fraga-Corral et al., 2022). Studying nutrient circularity at the regional level uses indicators relatively similar to those we selected (e.g., Corona et al., 2019; Parchomenko et al., 2019). An increasing number of studies have analysed nutrient circularity in agrifood systems at the regional level (e.g., Fleitas Girett et al., 2023; Tamsma et al., 2024; Vingerhoets et al., 2023), but they often overlook aquaculture systems. A few studies highlighted the strong contribution of aquaculture and fish production to certain regional agri-food systems, particularly in China (Yang et al., 2020; Zhang et al., 2022). Depending on the number of farms and their locations, available local nutrient resources and degree of integration of agricultural sectors, aquaculture systems can play a crucial role in the circularity and sustainability of agri-food systems.

4. Conclusion

This study developed six complementary criteria – productivity, efficiency, self-sufficiency, recycling, regeneration, diversity and complementarity – and 21 associated indicators to assess nutrient circularity in aquaculture systems. As a proof of concept, we applied these indicators to three selected case studies of integrated and conventional aquaculture systems to compare their performances and test the indicators' relevance and usefulness. The experimental integrated systems usually outperformed their conventional monoculture counterparts. Among the three integrated systems, the biofloc system performed better at self-sufficiency and recycling than the aquaponic and pond polyculture systems but worse at complementarity. Although relatively simple indicators were developed, a lack of data was a major constraint that prevented quantification of several indicators and a full comparison of the systems. In particular, simple and quantifiable indicators to evaluate regeneration are lacking. This study helps clarify the concept of nutrient circularity in aquaculture and supports the development of integrated farming systems for more sustainable use of nutrients. Future studies are needed to apply the indicator framework to other integrated aquaculture systems, including IMTA. The performances of diverse conventional and integrated systems should also be reviewed to provide reference value ranges for the indicators and to compare them with environmental thresholds, based on local and global carrying capacities. Ultimately, our indicator framework should be used in combination with a broader list of sustainability indicators as circularity may cause environmental (e.g., water use, land use; Cobo et al., 2018), economic (e.g., cost of recovering and recycling nutrients), technical (e.g., more complex management) or welfare (e.g., pathogen spill-over) trade-offs.

CRediT authorship contribution statement

Killian Chary: Writing – review & editing, Writing – original draft, Visualization, Project administration, Formal analysis, Data curation, Conceptualization. **Christophe Jaeger:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Henrice M. Jansen:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Souhil Harchaoui:** Writing – review & editing, Visualization. **Joël Aubin:** Writing – review & editing, Visualization, Formal analysis, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

Data used in this study are available in the supplementary materials.

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