Bioresource Technology 450 (2026) 134470

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Review

# On how to make aquaponics more circular

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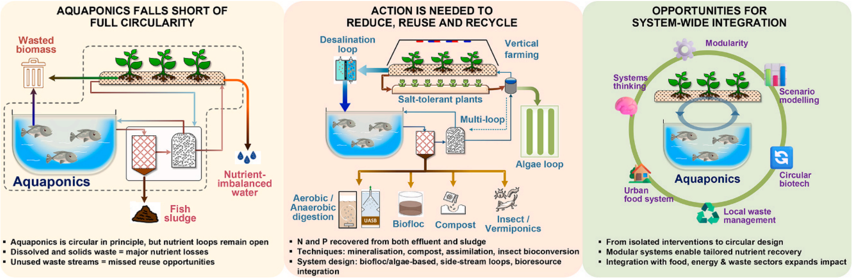
## HIGHLIGHTS

- Quantify nutrient fluxes and evaluate strategies for more circular aquaponics.
- Map nitrogen and phosphorus flows across systems and pinpoint loss hotspots.
- Integrate dissolved nutrient recycling with value recovery from solid side streams.
- Decision-oriented synthesis linking circularity to design targets and trade-offs.
- Distil system-level guidelines for configuring scalable multi-loop aquaponic layouts.

## GRAPHICAL ABSTRACT



- Aquaponics is circular in principle, but nutrient loops remain open
- Dissolved and solids waste = major nutrient losses
- Unused waste streams = missed reuse opportunities

- N and P recovered from both effluent and sludge
- Techniques: mineralisation, compost, assimilation, insect bioconversion
- System design: biofloc/algae-based, side-stream loops, bioresource integration

- From isolated interventions to circular design
- Modular systems enable tailored nutrient recovery
- Integration with food, energy & waste sectors expands impact

## ARTICLE INFO

*Keywords:*
Integrated food systems
Circularity
Closed-loop farming
Waste valorisation
Nutrient fluxes
Food-water-energy-environment nexus

## ABSTRACT

Aquaponics is a recognised food system for its circular nutrient management potentiality, as it redirects aquaculture waste into plant production. However, current practices still fall short of closing nutrient loops, with substantial losses occurring through dissolved effluents and solid waste. This review examines strategies to reduce losses, recover nutrients, internally recycle dissolved streams, and valorise solid side streams in aquaponics, with particular attention to nitrogen and phosphorus due to their dual role as essential, and often limiting, inputs in aquaculture and plant production as well as key pollutants with major eutrophication potential. First, we identify the fate of dissolved and solid nutrients from both aquaculture and hydroponic subsystems. Second, we evaluate strategies to recover these nutrients, exploring opportunities to recycle dissolved nutrients and water, reuse solid waste, and reduce system-wide impacts. Third, we discuss the importance of integrating these processes at a system level and reflect on how current innovations can be better aligned with circular bioeconomy principles. Our synthesis concluded that while the integration of these strategies into

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https://doi.org/10.1016/j.biortech.2026.134470
Received 1 November 2025; Received in revised form 2 January 2026; Accepted 19 March 2026

optimally efficient, circular aquaponic systems is an ongoing challenge, several key nutrient recovery technologies are themselves well-established and have been successfully implemented. Addressing the gap in knowledge and industry practice will require systems thinking, deeper cross-disciplinary collaboration, and applied research that goes beyond isolated interventions.

## 1. Introduction

Climate change and food security are increasingly interlinked challenges for global food production systems (Rosenzweig et al., 2020), particularly in aquaculture, where production is both highly climate-sensitive and a potential source of environmental pressure. Climate change, coupled with unsustainable resource exploitation, is resulting in numerous modifications of global and local environments, including rising temperatures, ocean acidification, and increased frequency of extreme events (Reynolds et al., 2007). These changes pose significant risks to global food production systems, threatening food security for millions of people (FAO et al., 2021). In this context, aquaponics (AP) has emerged as a food production system explicitly designed to address resource inefficiencies and environmental impacts in aquaculture by coupling fish and plant production through internal nutrient recycling (Baganz et al., 2021a; Verreth et al., 2023). Traditional aquaculture systems, like pond and cage culture systems, can be directly impacted by, but also often directly contribute to, climate change-related phenomena. When they are not well planned and managed, aquaculture activities can be responsible for nutrient rich effluent discharge, habitat destruction, and the depletion of wild fish stocks (Galappaththi et al., 2020), driving public concern and interest in circular food production systems.

Aquaponics is inherently aligned with the concept of a circular economy, as it reduces waste from fish farming, recycles it through microbial activity, and reuses it for plant cultivation, enhancing resource use efficiency (Okomoda et al., 2023; Yep and Zheng, 2019). By integrating aquaculture into local soilless horticulture systems, AP also directly links climate mitigation and food-security objectives through reduced water demand, lower nutrient losses, and shorter supply chains, reducing transport-related carbon emissions and year-round nutritious food (Körner et al., 2021). However, aquaponics falls short of functioning as a fully closed-loop system. Nutrient supply and demand mismatches between fish and crops (Gebauer et al., 2023), salt accumulation in closed loops, and underutilised solid side streams still cause avoidable losses and costs (Nhut et al., 2019; Schumann and Brinker, 2020; Van Rijn, 2013). Addressing these gaps requires a comprehensive understanding of nutrient input–output flows, so that more targeted and effective strategies can be developed and integrated at the system level.

This review presents an in-depth and critical analysis of recovery strategies of dissolved and solid nutrients in aquaponic systems. Situated within the circular bioeconomy framework, an emerging focal point in aquaponics research, the review differs from prior overviews by adopting a circularity-first perspective that synthesises reported nutrient fluxes and loss points across coupled, decoupled, and multi-loop layouts and relates these to system-level design frameworks and operating set-points. We integrate strategies for dissolved nutrient optimisation, valorisation of solid side-streams, and operational salt management within a single systems framework, linking circular economy principles to measurable indicators of performance and cost, and we harmonise terminology and system boundaries to support comparability, guide retrofits, and enable scale-up. We focus on nitrogen (N) and phosphorus (P) as the most relevant input and waste in aquaponics, structured into three sections: (i) identification of the fate of dissolved and solid nutrients within the aquaculture and hydroponics subsystems; (ii) presentation of emerging and underutilised strategies for recycling dissolved nutrients and reusing solid wastes, with the aim of improving nutrient use efficiency and reducing losses; and, (iii) discussion of the key challenges associated with implementing these strategies in practice, highlighting the need for system-level integration, improved technical feasibility, and broader alignment with circular bioeconomy principles to ensure their long-term viability and impact.

This study adopts a narrative review approach structured conceptually around nutrient pathways, loss points, and system configurations. The main nutrient recovery and recycling strategies currently discussed and applied in aquaponics were first identified based on expert consultation and the authors' direct research experience in aquaponic, hydroponic, and waste-reuse systems. Literature was identified through Web of Science and Scopus, complemented by Google Scholar and targeted searches of FAO, EU and national technical reports, using combinations of keywords such as "aquaponics", "recirculating aquaculture", "fish sludge", "anaerobic digestion", "aerobic mineralisation", "microaerophilic assimilation", "biofloc", "insect bioconversion", "circularity", "nutrient recovery", and "technoeconomic assessment". The primary time window was 2000–2025, with earlier seminal work included where relevant (Fig. 1). The manuscript is organised into seven subsequent sections, as follows: Sections 2 and 3 summarise key aquaponics concepts and provide the background needed to interpret nutrient fluxes and recovery strategies, with Section 2 focusing on system definitions and configurations and Section 3 delving into nutrient inputs, transformations, and outputs in conventional aquaponics. Section 4 characterises the main pathways for dissolved and solid nutrient loss in the aquaculture and hydroponics subsystems; Sections 5 and 6 synthesise recycling and valorisation options for dissolved and solid streams, respectively; and Sections 7 and 8 provide a system level discussion and outline future perspectives on aligning aquaponics with circular bioeconomy principles.

## 2. Nutrient fluxes in aquaponics

Aquaponics has undergone numerous definitions and re-interpretations over the past 20 years, with subtle variations introduced by each author, likely shaped by their unique perspectives, viewpoints, and research objectives (Table 1) (Baganz et al., 2021b; Goddek et al., 2019; Palm et al., 2023, 2018; Rakocy et al., 2011). Aquaponics, being fundamentally aimed at resource-saving, has been receiving increased attention as a food production system and farming method with high sustainability potentials (Baganz et al., 2021b; David et al., 2022). For instance, recent experimental and modelling work on multi-loop, near zero discharge aquaponic systems has shown that they can operate with very high water use efficiency. A coupled aquaponic system with anaerobic digestion in an arid climate required only 14–38 L of supplementary water per kg of lettuce, corresponding to daily water additions of about 1–3% of total system volume (Zhu et al., 2024). Another important benefit of aquaponics is the reduction of pollution generation, by providing an alternative for transforming nutrient-rich wastewater from fish production into valuable plant fertiliser (Campanati et al., 2021). Furthermore, aquaponics practices can achieve economic savings by improving resource efficiency and optimising land use (Greenfeld et al., 2018). These benefits, either real, expected, or potential, have positioned aquaponics as a promising circular food production technology, attracting growing scientific interest across a wide array of research areas over the past 20 years (Fig. 1).

The configuration of the system is a key determinant of both the pathways and magnitude of nutrient flows in aquaponics, as well as the feasibility of recovery strategies (Table 1). In general, most systems comprise tanks for aquatic organisms and mechanical and biological filters, forming a recirculating aquaculture system (RAS) that is then

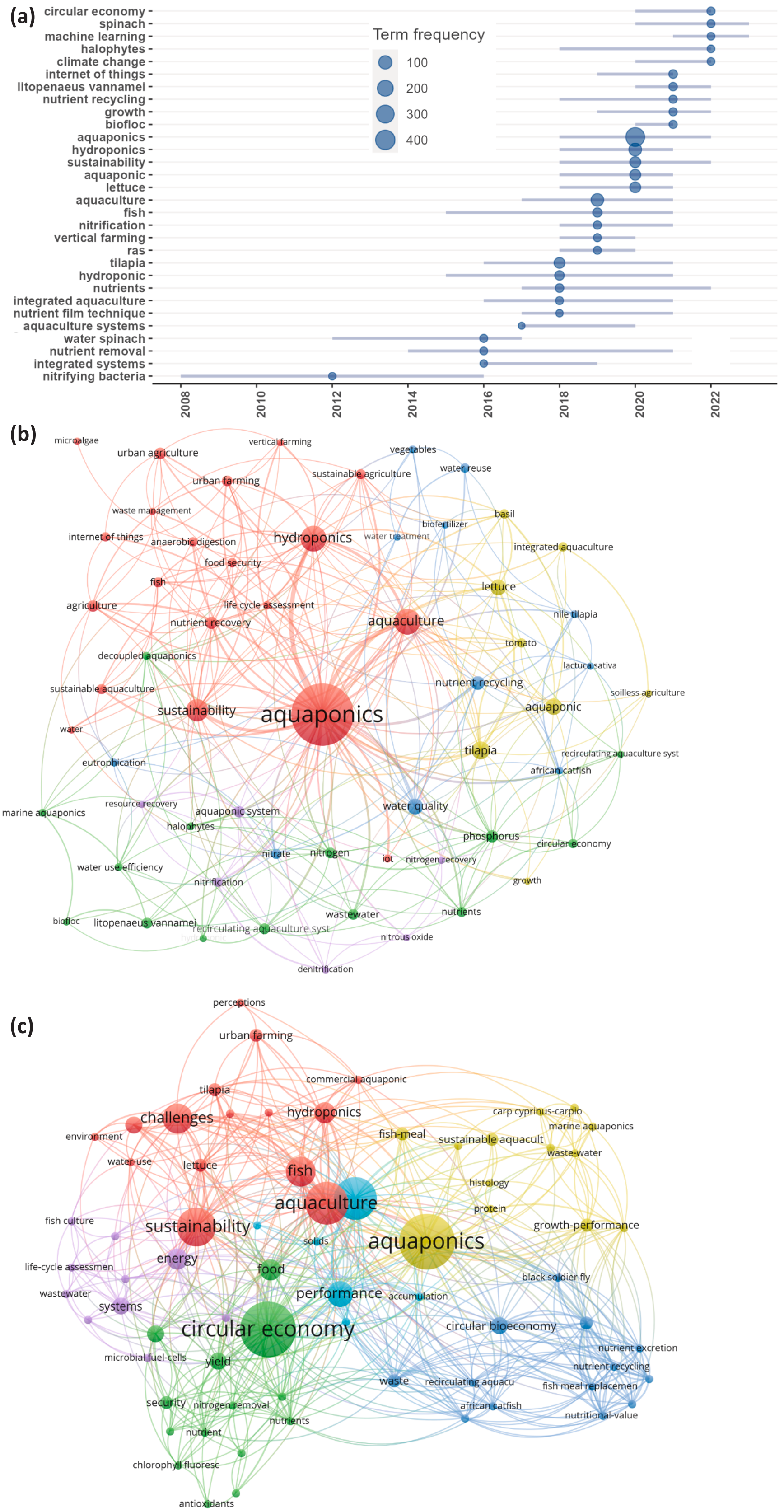

**Fig. 1.** Key focus areas in aquaponics research over the last 20 years (2004–2023): (a) trending research themes over the year of most prominent topics in aquaponics; (b) visualization map of high-frequency research in nutrient recovery and strategies; and (c) circular bioeconomy of aquaponics.

connected to a hydroponics unit for plant production (Baganz et al., 2021a; Martinez-Cordova et al., 2023). System layouts vary depending on local geography, climate, production goals, and market demands (Goddek and Körner, 2019; Pinho et al., 2021). In coupled systems, aquaculture and hydroponics subsystems are linked in a single-loop water recirculating cycle, requiring all organisms to share the same water and environmental conditions, often resulting in trade-offs and suboptimal performance for both plants and fish (Palm et al., 2023). Decoupled systems allow for directional flow from fish to plants, enabling independent control of water quality and nutrient supplementation (Monsees et al., 2017b; Zhu et al., 2024). More complex multi-loop designs go further by incorporating additional treatment or cultivation steps to enhance nutrient recovery and reuse, and are increasingly proposed as system innovations to improve aquaponics circularity (Baganz et al., 2021a; Pinho et al., 2022). In this review, we refer to ‘conventional aquaponics’ as single loop coupled systems, where aquaculture and hydroponics compartments are permanently connected through a shared water and nutrient cycle (Fig. 2), and use this configuration as a reference point for discussing nutrient recycling strategies, because it represents the most widespread configuration in practice (Baganz et al., 2021a; Palm et al., 2023). This configuration offers the clearest physical expression of circularity, with water and nutrients literally recirculating between compartments. Importantly, this apparent physical circularity does not equate to full functional circularity, as shown in the next subsections, where nutrient imbalances, losses, and system constraints become evident.

Before delving into the specific technical options for optimising nutrient recovery and reuse in aquaponics, and thereby improving system circularity, it is first important to establish a general understanding of nutrient dynamics, covering inputs, transformations, and outputs.

### 2.1. Influx

The nutrient influx into conventional aquaponics comprises mainly seedlings (juvenile fish and plants), aquafeed, plant fertiliser supplementation, and water, which can have different origin and may contain different trace minerals (Fig. 3a). Aquafeed serves as the primary source of nutrients, and its composition and quantity depend on the cultured species, their nutritional requirements, their physiological and development status, and on farm feeding management (Goddek et al., 2019; Roy et al., 2022). For instance, tilapia in the growth-out phase cultured in RAS are fed with aquafeed typically containing 35–40% crude protein, equivalent to 6% N and 1–1.5% P (Table 1) (Mabroke et al., 2019; Pinho et al., 2017; Zappernick et al., 2022), while marine shrimp are fed with 36–45% crude protein and 0.5–1.5% P (He et al., 2022). The feed is tailored to meet the nutritional requirements of the target organism, and the resulting wastes are a function of the quantity of uneaten feed and excretions, such as faecal solids and dissolved excretory products (mainly ammonia from gills). The concentrations and ratios of nutrients in these solid and dissolved excretions are governed by digestive, absorptive and catabolic processes in the fish, and are therefore strongly influenced by feed formulation and composition, species and life stage, physiological status, environmental conditions and on-farm feeding and water management (Lall and Lewis-McCrea, 2007; Lunda et al., 2019; Shaw et al., 2022). Given the variation in species raised in aquaponics and their unique nutritional needs, empirical studies of commercial recirculating aquaculture systems and aquaponic facilities report that the composition of the resulting nutrient-rich effluents varies widely and rarely matches the concentrations and ratios recommended for standard hydroponic nutrient solutions,

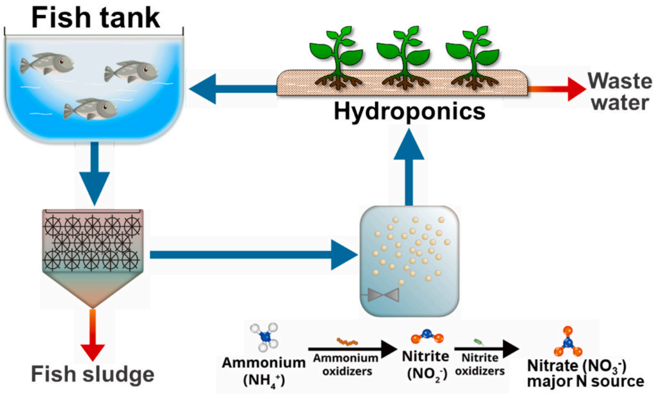

**Fig. 2.** Basic technical system design of conventional aquaponic systems with fish tank, solid filter, biofilter, and hydroponics units.

**Table 1**
Waste reuse, nutrient use efficiency and trends of nutrients in different typical of aquaponic systems.

| System type | Fish | Plant | NUE-N (%) | NUE-P (%) | Trends of nutrients over time | Nutrient balance strategy | Location | Reference |
|---|---|---|---|---|---|---|---|---|
| Coupled AP (UVI); DWC | Tilapia | Basil | 35–53 | 28–45 | N accumulation | Add nutrients; discharge | Virgin Islands (US) | Bailey and Ferrarezi, 2017; Rakocy et al., 2011 |
| Decoupled, Media-filled bed | Eurasian perch | Tomato; cucumber | 50–69 | 52–55 | N accumulation | Fertiliser | Switzerland | Graber and Junge, 2009 |
| Decoupled AP; DWC | Tilapia | Tomato | 34–41 | 20–30 | Stable | Plant fish ratio | Hawaii (US) | Wongkiew et al., 2017 |
| Decoupled AP; NFT | Tilapia | Lettuce; tomato | 60–68 | 50–55 | N accumulation; P depletion | Fertiliser; discharge | Zürich | Goddek et al., 2019; Schmautz et al., 2021 |
| Coupled and decoupled AP; NFT | Tilapia | Lettuce | 55–60 | 45–50 | N accumulation; P depletion | Fertiliser; water exchange | Germany | Monsees et al., 2017b, 2019 |
| Saline AP | European sea bass; shrimp | Samphire; agretti; quinoa | 25–72 | 20–50 | Salinity; nutrient accumulation | Discharge; nutrient supplement | Florida (US) | Doncato and Costa, 2021; Spradlin and Saha, 2022 |
| Vertical AP; living wall | Tilapia; catfish | Spinach; basil; chicory | 20–60 | 20–40 | Nutrient depletion | Fertiliser; water exchange | London (UK) | Ahmed and Turchini, 2021; Avgoustaki and Xydis, 2020; Khandaker and Kotzen, 2018 |
| Decoupled AP; FLOCponics | Tilapia | Lettuce | 48–64 | – | N scarcity | Add fertiliser; discharge | Brazil | Pinho et al., 2021, 2022 |
| Zero waste coupled AP; AD; DWC | Catfish | Lettuce; tomato | 84–90 | 73–80 | Stable | K and Iron nutrients | Israel | Zhu et al., 2021, 2022b; Zhu, 2023 |

NUE-N: Nutrient use efficiency of nitrogen; NUE-P: Nutrient use efficiency of phosphorus; AP: Aquaponics; DWC: Deep water culture. NFT: Nutrient film technique. AD: Anaerobic digestion.

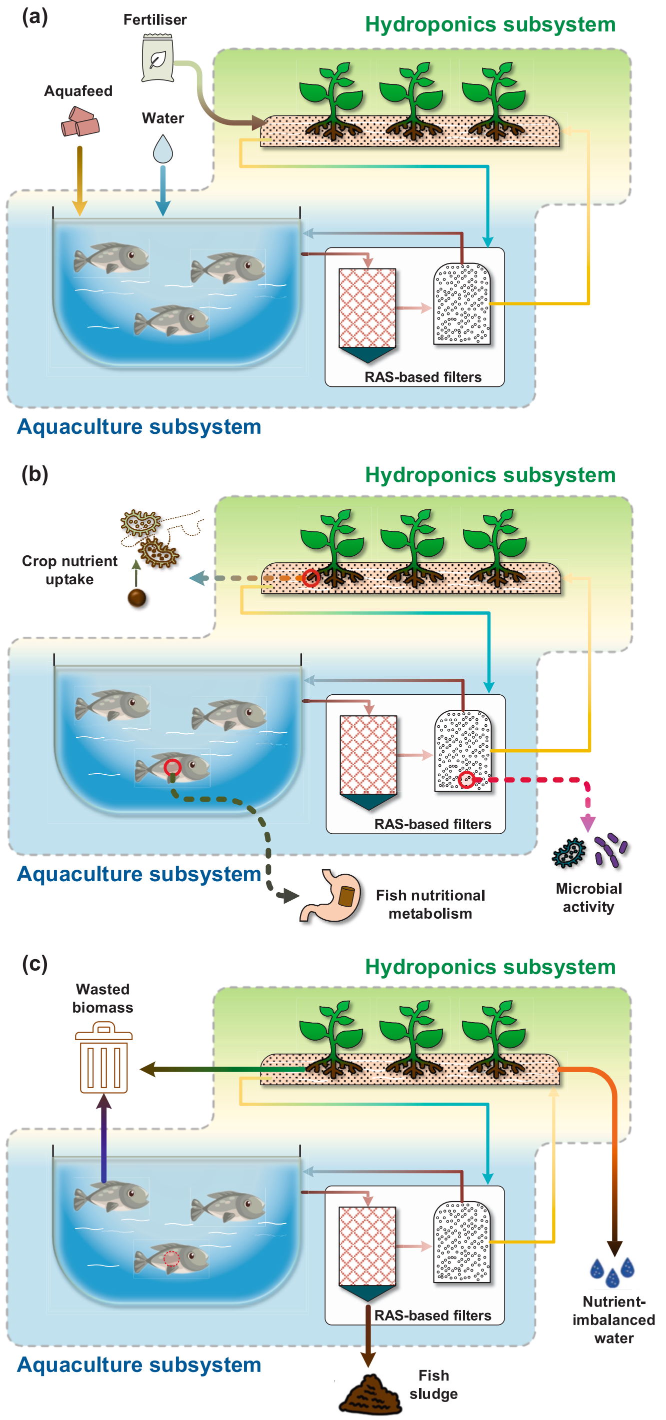

**Fig. 3.** Representation of nutrient fluxes in conventional aquaponics: (a) influx; (b) transformation; and (c) outflux.

particularly for K, Ca, Fe and several micronutrients (Patloková and Pokluda, 2024; Shaw et al., 2023; Zhu et al., 2024). Aquaponic crops also display significant variation in nutritional needs (leafy crops vs. fruiting crops). Therefore, supplementation of specific nutrients is often necessary to balance and complement fish waste products to achieve optimal nutrient inputs for plant growth. Such supplementation, often in the form of inorganic fertilisers or targeted organic/foliar amendments, is now well documented in coupled and decoupled aquaponic systems (Monsees et al., 2017b, 2019; Pinho et al., 2024). Table 1 presents the varying needs for supplementation across case studies, highlighting differences in fertiliser inputs and nutrient management approaches according to system design, location, and target species.

## 2.2. Transformations

Nutrients undergo a series of transformations, unfolding through various steps and pathways, including feed utilisation by reared aquatic animals, microbial activity, and crop nutrient uptake. The process begins with feed intake by fish, which is affected by feed management and feed quality, but typically most (~95%) of the administered aquafeed is eaten. Then the process continues through digestion and absorption of nutrients by the fish and the fish intestinal microbiota, and then undigested nutrients, coupled with excreted catabolic products, are released as waste in liquid or solid forms (faeces, urine, gills, and surface excretions) into the system (Zhu et al., 2022b). Subsequently, the discharged nutrients pass through additional transformations when they enter the water body and are further transformed by assimilation and metabolic pathways of the abundant microbiome present in the water body itself, on the tanks and pipe surfaces, and in the appositely designed filters and biofilters, which form the aquaculture subsystem (Li et al., 2024a; Schmautz et al., 2022). From there, nutrients are transported to the hydroponic subsystem and delivered into the plant root zone. Microbial processes further transform nutrients, and plant roots absorb them via passive diffusion and active transport, partly driven by leaf transpiration (Maucieri et al., 2018; Mitchell, 2022). A key feature of aquaponics is its reliance on certain bacteria and their metabolic processes, such as the biological nitrification process, whereby ammonium nitrogen ($NH_4^+$-N) excreted by fish is transformed into nitrate ($NO_3^-$) (Fig. 3b), which plants readily assimilate (Zhang et al., 2024).

In addition to N, a number of other nutrients, including macronutrients, such as P, K, Ca, Mg, S, and micronutrients, such as Fe, B, Zn, Mn, Cu, and Mo, are required for plant metabolism, and their uptake involves several key processes such as root absorption and root transport (Resh, 2016). Accordingly, microorganisms in aquaponic systems play several crucial roles in transforming nutrients beyond nitrogen. Heterotrophic and plant associated microbes decompose organic matter from uneaten feed, faeces and plant residues and mineralise organic and particulate phosphorus via extracellular phosphatases and phosphate-solubilising bacteria, thereby releasing orthophosphate into the water column (Cerozi and Fitzsimmons, 2017; Eck et al., 2019; Luo, 2023). In low oxygen compartments such as biofilters, sludge collectors and root associated biofilms, sulphate reducing and sulphur oxidising bacteria drive sulphur cycling by reducing sulphate to sulphide and deoxidising sulphide, processes that influence alkalinity, redox conditions and potential sulphide accumulation in aquaculture and aquaponic units (Jørgensen et al., 2019; Zhang et al., 2020). Microbial communities also mediate iron cycling: Fe(II)-oxidising and Fe(III)-reducing bacteria, together with plant growth promoting microorganisms that produce siderophores, control iron speciation and chelation in biofilters and the rhizosphere and thus contribute both to iron limitation and to improved Fe bioavailability for aquaponic crops (Bartelme et al., 2018; Kasozi et al., 2019). Importantly, pH of the water in the hydroponic subsystem is also a fundamental factor determining the availability of dissolved nutrients for plant absorption. Therefore, monitoring and regulating environmental nutrients and water parameters, through tracking pH, electrical conductivity (EC), and nutrient concentrations, are all important steps for preventing nutrient imbalances or deficiencies in aquaponics systems (Goddek et al., 2019).

## 2.3. Outflux

In terms of nutrient outflow, two conceptually very different outputs can be considered: the harvested biomass of fish and plants represents positive marketable outputs (Fig. 3c); whereas, fish sludge (solid and liquid portions), non-traditionally marketable biomass (e.g., mortalities and inedible parts of fish or plants), and water discharged from the hydroponics subsystem to balance the excess of specific nutrients, are considered nutrient losses or negative outputs, which we can refer to as outflux. As such, it is evident that a highly efficient aquaponic system should maximise the concentration and recovery of nutrients into the positive, marketable outputs, and simultaneously minimise the negative outflux.

Importantly, however, what is here referred to as the negative outflux or outputs does not represent a definitive endpoint, but rather it is a potentially underutilised pool of recoverable nutrients. Fish sludge, plant residues, and discharged water all contain valuable macro- and micronutrients that, embracing better circularity principles, could be redirected into productive uses within or beyond the system. Enhancing the overall nutrient use efficiency of aquaponic systems therefore requires not only reducing losses, but also identifying opportunities for nutrient recovery and recirculation. To support this, the next section characterises in more detail the main nutrient loss pathways within each subsystem of conventional aquaponics, thereby laying the foundation for evaluating targeted recovery strategies. The aquaponic systems summarised in Table 1 illustrate diverse strategies for managing such outputs, from water discharge and sludge removal to integration with nutrient recovery units, highlighting both the challenges and opportunities for improving overall circularity.

Across the aquaponic and RAS case studies compiled in Table 2, feed-N retention in harvested fish and plants consistently occupies a relatively narrow band, with most systems clustering between roughly one quarter and one half of total N input, while the remaining N is split between dissolved losses in the water column and solid wastes requiring treatment. Phosphorus retention in biomass tends to be slightly higher, but a substantial fraction still accumulates in sludge. These patterns are remarkably robust across species and configurations and highlight two design implications: (i) even well-managed aquaponic systems will generate significant N and P side streams that must be addressed by complementary recovery technologies, and (ii) improvements in circularity are likely to depend more on how these side streams are treated and reintegrated than on marginal gains in feed conversion alone.

## 3. Nutrient losses in conventional aquaponics

### 3.1. Aquaculture subsystem wastes

Aquaculture effluents contain dissolved and particulate nutrients originating from feed and animal waste, with their composition influenced by diet, feeding practices, and the physiology of the cultured species (Stentiford et al., 2020), and their variable composition is reported in Table 2. N and P are key components of nutrient loss in aquaculture, and they are also the two nutrients directly associated with risks of generating eutrophic systems (Yogev et al., 2018). RAS systems, in particular, produce highly concentrated wastes (Fig. 4), but have much lower discharge rates than other aquaculture systems such as flow-through raceways, earthen ponds, or cage systems (Ahmed and Turchini, 2021; Boyd and McNevin, 2015). Most N loss in RAS occurs in dissolved form (60–90%). Initially, this N is primarily in the form of ammonia, which, depending on water pH, can be toxic to many aquatic organisms at concentrations above 1 mg/L (Preena et al., 2021). After undergoing biological transformations, as described earlier, it is converted to nitrate, which is less toxic and represents the preferred nitrogen form for uptake by many plant species (Zhu et al., 2021). As for P, the portion lost in soluble form is variable, ranging from 15% to 75% of its input, with a considerable amount being trapped in the solid fraction (Luo, 2023).

In aquaponics, the highly concentrated dissolved effluent from the RAS subsystem is repurposed by means of being redirected to the hydroponics subsystem. Whilst the concept is elegant, simple, and very logical, in practice, nonetheless, not all dissolved nutrients discharged from the RAS are typically fully reused and assimilated by the growing plants, mostly due to how the aquaponic system is designed and nutrient management operations in the hydroponics subsystem (Tellbüscher et al., 2024). The variability in dissolved nutrient concentrations and the degree of nutrient recycling across systems is reflected in the broad ranges reported for total N, P, and other key elements in effluent streams across different species in Table 2. While universal operating set-points

**Table 2**

Composition (ranges and averages) of nutrient resources (dissolved nutrients, fish sludge, and plant waste) from aquaponic systems with typical fish and crops.

| Renewable nutrients from aquaponics | | TN | TP | K | Na | Ca | Mg | Reference |
|---|---|---|---|---|---|---|---|---|
| *Aquaculture part (mg/L)* | | | | | | | | |
| Tilapia | Effluent* | 31–172<br>(94) | 4.2–34<br>(18) | 10–24<br>(15) | 42–55<br>(46) | 32–73<br>(49) | 28–63<br>(41) | Boyd and McNevin, 2015; Timmons et al., 2018; Zappernick et al., 2022 |
| | Fish sludge | 266–417<br>(338) | 82–116<br>(94.4) | 134–176<br>(145.2) | 61–80<br>(69) | 112–165<br>(133.4) | 19–28<br>(24.0) | Mirzoyan et al., 2010 |
| | Biomass waste** (%) | 7.9–12.4<br>(9.6) | 0.5–1.0<br>(0.7) | 0.2–0.5<br>(0.4) | 0.1–0.3<br>(0.2) | 0.1–0.4<br>(0.2) | 0.1–0.2<br>(0.1) | Timmons et al., 2018; Zappernick et al., 2022 |
| Catfish | Effluent | 64–115<br>(85.7) | 13–27<br>(18.8) | 42–93<br>(67.4) | 54–77<br>(63) | 55–76<br>(65.8) | 11–17<br>(14.3) | Calone et al., 2019 |
| | Fish sludge | 188–394<br>(285) | 96–148<br>(112) | 114–181<br>(144) | 69–79<br>(74) | 133–171<br>(151) | 24–30<br>(26.1) | Yogev et al., 2017; Zhu, 2023 |
| | Biomass waste (%) | 8.5–10.4<br>(9.7) | 2.0–3.5<br>(2.6) | 0.5–1.1<br>(0.8) | 0.2–0.3<br>(0.2) | 3.2–5.7<br>(4.1) | 0.1–0.2<br>(0.1) | Zhu et al., 2022b; Zhu, 2023 |
| Trout | Effluent | 26–67<br>(38.7) | 4–18<br>(8.7) | 21–32<br>(25.4) | 89–91<br>(90) | 84–98<br>(87.1) | 3–14<br>(5.7) | Forchino et al., 2017; Petrea et al., 2014 |
| | Fish sludge | 94–112<br>(96.0) | 42–66<br>(48.1) | 15–29<br>(23.1) | 92–124<br>(115) | 44–67<br>(59.8) | 12–15<br>(13.1) | Meriac et al., 2015; Papatryphon et al., 2005 |
| | Biomass waste (%) | 8.6–12.4<br>(11.2) | 0.8–1.1<br>(1.0) | 1.8–2.1<br>(1.9) | 0.4–1.4<br>(0.9) | 0.1–0.2<br>(0.1) | 0.1–0.2<br>(0.1) | Jung and Lovitt, 2011; Papatryphon et al., 2005; Petrea et al., 2014 |
| *Hydroponics part* | | | | | | | | |
| Plant waste*** | Tomato (%) | 3.0–3.3<br>(3.16) | 1.0–1.1<br>(1.05) | 3.4–3.6<br>(3.6) | 0.3–0.5<br>(0.4) | 8.1–8.3<br>(8.2) | 1.3–1.6<br>(1.4) | Zhu et al., 2022a |
| | Lettuce (%) | 3.6–3.9<br>(3.8) | 0.8–1.0<br>(0.8) | 2.1–2.3<br>(2.3) | 0.6–0.7<br>(0.6) | 2.0–2.4<br>(2.1) | 0.4–0.5<br>(0.5) | Zhu et al., 2021 |
| Discharge wastewater (mg/L) | | 48–494<br>(270) | 13–106<br>(35) | 63–270<br>(131) | 86–162<br>(125) | 104–282<br>(134) | 7–69<br>(25) | Kwon et al., 2021; Richa et al., 2020 |

Note: * Input for the hydroponics subsystem.
**Biomass waste from dead fish and inedible biomass (% dry weight).
***Plant waste is reported on a % dry weight basis.

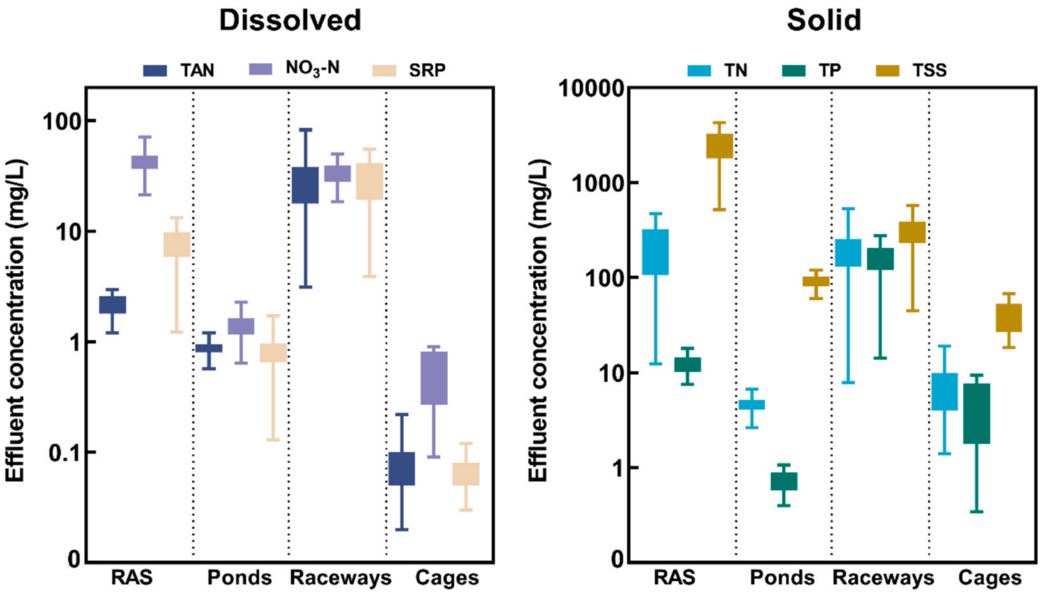

**Fig. 4.** Dissolved and solid effluents (log10 scale y-axis) in wastewater discharged by different intensive farming systems (RAS, ponds, raceways, cages). Data was gathered and extracted from 158 published case studies, which were analysed and presented here. A log10 scale was used for the large range of concentrations. RAS: Recirculating Aquaculture System. TAN: Total Ammonia Nitrogen. $NO_3$-N: Nitrate-Nitrogen. SRP: Soluble Reactive Phosphorus. TN: Total Nitrogen. TP: Total Phosphorus. TSS: Total Suspended Solids.

are difficult to define due to climate and biological variability, the nutrient concentration ranges presented in Table 2 provide the quantitative boundaries necessary for sizing recovery units and establishing mass balance targets during system design.

Solid waste, on the other hand, is another significant part of aquaculture subsystem waste, but the nutrients trapped in fish sludge are not directly bioavailable for plants. Typically, aquaculture sludge contains 10–30% of total N and 30–80% of total P from uneaten food and faeces (Timmons et al., 2018) (Fig. 4). The type of feed, as well as feed management and fish physiological conditions, affect the consistency, quantity, and form of solids in the waste (Boyd and McNevin, 2015). The nature of the solids also determines their behaviour in the system. Settleable solids (>100 μm) sink to the bottom of the water column and are more easily removed compared to suspended solids (30–100 μm), which are consequently considered as major pollutants (Campanati et al., 2021). These suspended solids can cause bacterial proliferation, leading to reduced hygienic conditions, which can be harmful to the farmed animals as they affect gill function and facilitate pathogen infections (Stentiford et al., 2020), and also can be responsible for clogging filtration units and biofilters. The high nutrient concentration of fish sludge observed in Table 2, especially for N, P, K, and Ca, confirms the potential value of these solids if recovered and valorised through appropriate post-treatment or reuse strategies. For instance, to manage these impacts and unlock the potential of solid waste, effective sludge thickening methods can reduce effluent volume for practical storage, off-site transport, composting, and further concentrate nutrients for other applications.

In addition to feed and excretion related nutrient losses, nutrients are also commonly lost from the system due to mortality, the inedible portions of aquaculture products, and biological processes such as the shedding of fish scales or shrimp exoskeletons during moulting. These losses represent not only a waste of resources but also potential environmental pollutants (Lopes et al., 2022). Not all aquatic species survive intensive aquaculture, and the survival rate can significantly vary due to environmental conditions, fish species, and disease outbreaks (FAO, 2024). For instance, the survival rate for catfish is about 95–100% (Zhu et al., 2022b), 89–98% for tilapia, and 85–91% for rainbow trout (Barrett et al., 2019). Salmon, known for its particular requirements, has both a lower and broader range of survival rates from 60 to 85% (Overton et al., 2019). Except for carcasses, the inedible portions of fish, including the head, viscera, skin, scales, and bones, constitute 20–50% of the total weight of the whole fish, representing a significant proportion that requires effective management and utilisation strategies (FAO, 2024; FAO et al., 2022). The relevance of these organic residues is further highlighted in Table 2, where biomass waste from inedible fish parts and mortalities is quantified across species, indicating an often overlooked but recoverable source of nutrients. Therefore, as it will be described later in *Section 6* of this article, it seems necessary to explore existing and novel strategies for addressing these nutrient losses too, so that valorising and reusing these wastes can enhance nutrient recovery and contribute to a more circular aquaponic system.

### 3.2. *Hydroponics subsystem wastes*

Hydroponics produce significant amounts of waste, including inedible parts of plants like leaves, stems, roots, and spoiled fruits, which potentially lead to severe water and soil pollution (Alexander et al., 2017). Each ton of harvested products in a fruit or vegetable crop, such as tomato yields approximately 5.5 tons of post-harvest residues (FAO et al., 2021). The elemental composition of plant wastes has been relatively constant at 5–15% of dry matter. On average, the concentrations of carbon (C), N, and P has been reported as approximately 40%, 5%, and 1%, respectively (Zhu et al., 2021), and these wastes have been reported to contain a noteworthy concentration of minerals and micronutrients, such as Mg, Ca, S, and Fe (Zhu et al., 2022a). Table 2 illustrates the typical ranges and average values of these nutrients in plant residues for commonly grown crops like tomato and lettuce, confirming the substantial recovery potential embedded in hydroponic biomass waste.

Although some of this plant waste is repurposed, for instance, as animal feed, a large portion remains unutilised and is instead burned, composted, or sent to landfill. These disposal routes often lead to inefficient nutrient use, environmental degradation, and social or logistical issues (Alexander et al., 2017). Furthermore, the presence of natural toxic compounds in some plant residues, such as tomatine and solanine in tomato waste, can further complicate safe reuse options (Ohyama et al., 2013). In light of these challenges, onsite treatment strategies that allow for nutrient and energy recovery offer a potentially sustainable alternative. However, the feasibility of such solutions depends on factors like waste type, climate, available technologies, and local market conditions (Xu et al., 2018).

In addition to solid plant residues, hydroponics systems also generate significant volumes of wastewater, which present their own set of management challenges. This wastewater often contains elevated concentrations of N (80–600 mg/L) and P (10–100 mg/L), making it a potential environmental pollutant if not properly treated (Richa et al., 2020). Wastewater discharge from hydroponics, either in standalone systems or in integrated ones as aquaponics, is typically the result of challenges with nutrient imbalance required for plant development and growth. While optimising N and P levels is a primary reason for discharge (Tarigan et al., 2021), another major driver for wastewater discharge is the accumulation of sodium (Na), especially in freshwater aquaponic systems (Lastiri et al., 2018). Na is critical because it is an element not utilised by most cultured plants (Suhl et al., 2016). In aquaponics, this accumulation arises from the fish production process, either through the intentional addition of salts to mitigate nitrite toxicity or disease outbreaks, or from the Na content present in commercially available fish feed (Yep et al., 2020). When such nutrient-rich wastewater is discharged without treatment, particularly with elevated levels of $NO_3^-$, N, P, and Na, it can contaminate the environment, impacting soil, surface, and groundwater quality through eutrophication, and ultimately posing risks to human health (Kwon et al., 2021).

## 4. Recycling dissolved nutrients

The primary challenge in terms of dissolved nutrient losses in conventional one-loop aquaponic systems lies in effectively balancing nutrients for plant growth without harming fish health. Cultured aquatic animals and plants have different, almost opposite requirements. While fish culture operates at the lowest possible nutrient levels in the water, plants require minimum concentrations of N and P (along with other twelve essential nutrients) maintained at specific intra-nutrient ratios for optimum growth. Ideally, recycling strategies involve a combined dual approach (Table 3): (i) adapting processes in fish culture and feed nutrition not only focusing on fish performance but to also deliver more balanced nutrients for subsequent plant uptake; and (ii) further recycling effluent discharged from the hydroponic subsystems, which might be too high in nutrients for direct reutilization into fish culture, or as input for additional cocultures. For instance, the latter can be achieved by changing the system design and adding additional subsystems into the conventional aquaponic setup composed of RAS and hydroponics, such as microalgae bioreactors, or redirecting some of the effluents for producing salt-tolerant plants when the issue is linked to Na accumulation.

A series of strategies for nutrient optimisation and recycling within aquaponic systems, designed to enhance plant growth and improve waste management, have been studied and proposed by several authors, as summarised in Table 3. Key approaches used by researchers include: i) balancing inorganic nutrients, such as by diluting aquaculture effluents and adding essential nutrients (e.g., P and Fe) for improved plant uptake; ii) tailored fish diets and feed innovations, including protein-rich ingredients, enzymes, and biofloc products, to support nutrient efficiency, minimizing nitrogen output while boosting nutrient absorption and reuse; iii) improved nutrient recycling through salt-tolerant plants or algae integration into the system; and, iv) advanced filtration methods, which maximize nutrient retention and water reuse under varied conditions. These latter innovative wastewater treatments can include aerobic and anaerobic processing, contributing to efficient nutrient recovery, while desalination and constructed wetlands could enable sustainable water cycling (Table 3). All these methods collectively promote a more balanced, resource-efficient system that aligns aquaculture with productive hydroponic cultivation.

**Table 3**
Summary of strategies for optimising and recycling dissolved nutrients in aquaponics with rationale and references.

| Dissolved nutrient optimisation | Recycling strategies | Rationale | References |
|---|---|---|---|
| Inorganic nutrient balance | Dilution of aquaculture effluent;<br>Addition of nutrients (P, K, Fe) | Achieve nutrient mass balance for optimal plant growth | Goddek et al., 2019; Monsees et al., 2019; Zhu et al., 2025b |
| Excess nutrients in the fish culture | Tailored aquaponics fish diets with adding P and Fe | Enhance nutrient fluxes in the fish effluent | Colt and Schuur, 2021; Roy et al., 2022 |
| | Protein ingredients rich in nutrients essential for plant growth, such as P and Fe | Ensure fish excrete nutrients balanced with essential nutrients for plant growth | Gebauer et al., 2023; Shaw et al., 2022; Siqwepu et al., 2020 |
| | Easily digestible protein-based ingredients | Improve nutrient absorption and reduce nitrogen in RAS effluent | Roy et al., 2022 |
| | Additional enzymes, feed pre-treatments, or specific microorganisms in feed | Enhance the digestibility and bioavailability of specific nutrients like P | da Cerozi and Fitzsimmons, 2016; Boyd and McNevin, 2015 |
| | Biotechnology use:<br>−insects<br>−algae<br>−biofloc-based products | Improve nutrient reuse and reduce unwanted nutrients like Na in fish effluent | Alfiko et al., 2022; Deng et al., 2021b; Nayak et al., 2023; Pinho et al., 2022; Spradlin and Saha, 2022 |
| Hydroponics culture | Cultivation of salt-tolerant plant species in additional loops | Reuse nutrients even in saline conditions | Gunning et al., 2016 |
| | Incorporation of algae and duckweed loops | High nutrient use efficiency even in high salt solution | Egloff et al., 2018; Guttman et al., 2018; Tarigan et al., 2021 |
| Wastewater from fish sludge | Dewatering and sand filtration to separate water | Return water to systems through physical filtration | Boyd and McNevin, 2015; Timmons et al., 2018 |
| | Single-stage process for nutrient recovery | Reuse water and produce biofloc via microbial processes | Li et al., 2024a, 2024b, 2024c |
| | Anaerobic digestion | Remove solid and reuse supernatant | Monsees et al., 2017a; Zhu et al., 2025a; Zhu et al., 2024 |
| | Aerobic mineralisation | Reduce organic by using oxygen-dependent microorganisms | Boxman et al., 2018; Khiari et al., 2019; Monsees et al., 2017a |
| Wastewater from hydroponics | Desalination/distillation processes | Remove excess salts and enable water reuse | Goddek et al., 2019; Goddek and Körner, 2019; Zhu et al., 2025c |
| | Cultivation of microalgae or algae | Remove excess nutrients | Richa et al., 2020 |
| | Constructed wetlands | Naturally treatment by using plants and microbes to remove contaminants | Saravanan et al., 2021 |

### *4.1. Strategies within the fish culture*

RAS wastewater contains high concentrations of nitrogenous compounds, ideally in the form of nitrate. Consequently, the ratio of total N to other nutrients is significantly higher than in standard hydroponic nutrient solutions formulated to meet plant needs. For example, the N:P ratio in the water of tilapia RAS is around 5.3 (Table 2), while in a lettuce culture, the standard and recommended ratio is approximately 3.2 (Zhu et al., 2023). As such, balancing the nutrients in fish water to suit plant requirements is needed, and this is sometimes achieved by diluting the fish water (reducing the N concentration) before directing it to hydroponic subsystems, and/or by supplementing this adjusted solution with missing nutrients using inorganic fertilisers (Baganz et al., 2021a). However, diluting the RAS effluent is neither the most waste-efficient nor a circular-based solution. Therefore, one of the primary strategies for optimising dissolved nutrient recycling in aquaponics, particularly from a fish culture perspective, involves maximising the efficiency of aquafeed and exploring circular ingredients for aquafeed formulation (Colt and Schuur, 2021; Roy et al., 2022; Shaw et al., 2022).

Tailored aquaponics fish diets have been evaluated in recent years, aiming to fine-tune the nutrient composition of the aquafeed, ensuring that fish excrete waste balanced with essential nutrients for plant growth (Robaina et al., 2019). Modified aquaponics feed formulations have generally taken two main approaches: first, they have been designed to enhance nutrient fluxes through the incorporation of dietary additives like K or P, which are commonly limiting nutrients in the fish effluent and highly required by the plants (Siqwepu et al., 2020). From a commercial and operational perspective, the viability of adding specific nutrients as inedible feed additives, compared to directly introducing them into the water as fertiliser, likely depends on the scale and context of the operation (Shaw et al., 2022). While both approaches can ultimately supply limiting nutrients to plants, routing nutrients through fish that do not require them for growth deliberately generates a secondary waste stream for plant use (Jones et al., 2024). Consequently, whether this approach represents a functionally circular improvement or an added inefficiency remains a subject of ongoing research. In practice, a more operationally flexible approach currently used in many systems is to measure nutrient levels in the fish water, or to use reference elements such as N to infer others, and to supplement only the nutrients that are limiting for the hydroponic subsystem (Robaina et al., 2019). Comparative cost-effectiveness assessments of tailored feed formulations versus direct water supplementation remain a critical gap in the literature, particularly given that the economic trade-offs between feed-derived nutrients and inorganic fertilizers are complex and vary across regions and system designs (Colt and Schuur, 2021).

Alternatively, some authors propose that aquaponics aquafeed formulation should focus on the digestibility of protein-based ingredients by fish (Roy et al., 2022). This approach suggests either: (i) selecting easily digestible ingredients to enhance nutrient absorption and reduce nitrogen in RAS effluent, an objective common to all aquafeed; or (ii) using protein ingredients rich in nutrients essential for plant growth, such as P and Fe (Gebauer et al., 2023; Shaw et al., 2022). Enhancing the digestibility of N by fish and the bioavailability of specific nutrients like P in the water can be achieved through methods other than changing the formulation, such as the inclusion of additional enzymes, feed pre-treatments, or specific microorganisms directly in the feed (da Cerozi and Fitzsimmons, 2016; Boyd and McNevin, 2015). Regarding the scalability of these strategies, distinct challenges exist. From a feed formulation and manufacturing perspective, the large-scale adoption of aquaponics-tailored feeds would require dedicated reformulation and separate production lines, which is a potential barrier for a global industry currently structured around high-volume, standardised aquafeed markets (Shaw et al., 2022). However, feasibility may be significantly higher in niche markets or local contexts. Strategies such as the use of micronutrient premixes, regional milling, or on-farm feed production could allow for the implementation of tailored formulations without requiring systemic changes to global commodity chains.

In contrast, broadening the boundaries of circularity from the production system to the input level, by valorising by-products and non-human food streams as aquafeed ingredients, appears more compatible with existing circular feed trends and established ingredient supply chains (Colombo et al., 2023). These circular ingredients can partially substitute for traditional fish meal, which often introduces unwanted nutrients like sodium into fish effluent when reused for plant production (Spradlin and Saha, 2022). Examples of circular ingredients under investigation include insect, algae, and biofloc-based products, which can be produced from system waste and, in some cases, reintroduced into aquafeed (Alfiko et al., 2022; Deng et al., 2021b; Nayak et al., 2023). Nonetheless, further research is still needed to identify which by-products, nutrient profiles, and inclusion rates would be commercially realistic, nutritionally adequate, and operationally compatible with aquaponic systems.

Another strategy for optimising nutrient recycling in aquaculture, applicable to aquaponics, is the use of biofloc technology to recycle excess dissolved nutrients (Dauda, 2020; Khanjani and Sharifinia, 2020). In biofloc-based systems, microbial communities grow within fish tanks (*in situ* biofloc), converting dissolved and suspended nutrients into bacterial biomass, effectively reducing excess nitrogen, which the fish can consume (Crab et al., 2012; Khanjani et al., 2022). A system variation known as FLOCponics replaces the traditional RAS unit with a biofloc-based fish culture, using its effluent as a direct water and nutrient source for hydroponic plants (Pinho et al., 2022). In FLOCponics, biofilters are not required, as microbial aggregates simultaneously manage water quality, cycle nutrients, and degrade suspended solids (Khanjani et al., 2022; Pinheiro et al., 2020; Pinho et al., 2017). Previous research has shown that the effluent from FLOCponics systems is rich in microbial biomass and nutrients, and can support crops like leafy greens, which benefit from the combined organic and mineral nutrient supply (Pinho et al., 2022; Martinez-Cordova et al., 2023). However, challenges such as managing suspended solids and maintaining sufficient light penetration in hydroponic units must be addressed, particularly when the system is run in a conventional coupled layout (Pinho et al., 2022, 2023).

### 4.2. Strategies within the plant culture

In an aquaponics setup, most of the wastewater actually originates from the plant production stage, as the aquaculture subsystem is essentially positioned upstream, and the system as a whole should be designed to direct all effluent from the aquaculture subsystem into the hydroponics subsystem. In conventional aquaponics layouts, the physical separation between aquaculture and hydroponics is not possible and wastewater discharges are the result of incomplete uptake of nutrients by the plants. As a result, excess nutrients, salts (e.g., Na), and residual water gradually accumulate and must be discharged, leading to the loss of about 28% of N and 20% of P from the total input through hydroponics-linked wastewater (Kwon et al., 2021; Zhu et al., 2023). Various recycling technologies, such as desalination, activated carbon, and constructed wetlands, have been studied to reuse wastewater (Saravanan et al., 2021). Algae or duckweed cultivation offers a natural method for treating nutrient-rich wastewater, absorbing nutrients, and making the water reusable for plant cultivation, thus conserving freshwater and nutrients while preventing pollution (Egloff et al., 2018; Guttman et al., 2018; Tarigan et al., 2021). Microalgae-based treatments, particularly with *Dunaliella salina* and *Chlorella vulgaris*, have shown potential for near-total nutrient recycling and zero discharge (Richa et al., 2020). Another strategy is to reconfigure the system layout to incorporate compartments for salt-tolerant plants (as *Sesuvium portulacastrum* and *Batis maritima*) or co-cultures that can utilise specific nutrient fractions (Gunning et al., 2016; Verma et al., 2023).

Building on this, expanding nutrient recovery through additional production loops, such as the aforementioned algal bioreactors, microbial treatments, or salt-tolerant crop compartments that receive wastewater from the hydroponics subsystem, has gained increasing attention as a way to manage high-load effluent streams associated with hydroponic production and move more effectively toward closing nutrient cycles. These so-called multi-loop configurations offer modularity and flexibility by routing water through separate biological or technological units before discharge or reuse. Algae-based loops, in particular, have demonstrated high nutrient uptake rates and strong potential for integration into closed-loop systems. For instance, studies have reported over 90% removal efficiency for nitrate and phosphorus under optimised conditions (Richa et al., 2020), and a modelling work in Indonesia showed that integrating duckweed cultivation in freshwater aquaponics improved N, P, and water use efficiencies by 10%, 18%, and 31%, respectively (Tarigan et al., 2021). When harvested, algae biomass can be valorised as fertiliser, feed ingredient, or bioenergy source, enhancing system circularity. Cascaded hydroponics subsystems are another example, which route nutrient-rich water sequentially through different plant types and have also been explored in standalone hydroponics to maximise nutrient recovery while broadening the range of outputs (Gunning et al., 2016; Naounoulis et al., 2024), and could be effectively adapted for aquaponics to enhance nutrient use efficiency.

Decoupled aquaponic systems, characterised by their unidirectional water flow, are especially compatible with these approaches, as they allow separate control over each loop's conditions and facilitate the integration of specialised side-stream processes (Baganz et al., 2021a,b), including the ones expanded on in the next section for solid waste treatment. At the same time, decoupling does not automatically make a system more circular. Comparative studies of coupled, decoupled and hydroponic configurations show that decoupled layouts commonly rely on considerable mineral fertiliser inputs and can exhibit nutrient-use efficiencies similar to hydroponics when fish sludge is not further valorised. In line with recent work on circular aquaponics, we therefore view decoupled systems as an architectural opportunity to integrate targeted recovery loops, rather than as inherently superior designs; their contribution to circularity must be evaluated by full nutrient mass balances and the share of plant nutrition that is supplied by fish-derived resources.

## 5. Reusing solid wastes from aquaponics

All solid wastes from aquaponics, especially fish sludge and plant biomass waste, are valuable nutrient sources that could be reintroduced into the integrated system to promote circularity (Table 4). As shown in Fig. 2, RAS subsystems typically generate large quantities of solid sludge, the primary solid waste in aquaponics, presenting an ongoing challenge for system operations. Total solids generation in RAS varies widely, ranging from under 100 kg to over 600 kg per ton of fish production (Van Rijn, 2013). It is therefore manifest that the proper management of these solid wastes is crucial for nutrient recovery, and thus is also crucial for the overall sustainability of the system.

### 5.1. *Anaerobic digestion*

Anaerobic digestion (AD) offers a well-established biological pathway to mobilise these nutrients, enabling their recovery and reuse within or beyond the aquaponic loop. AD is widely used for waste stabilisation and mass reduction due to its operational simplicity, low costs, potential biogas production as an energy source, and the generation of inorganic materials (e.g., minerals) as fertilisers (Kumar and Tuohy, 2018) (Table 5). Around three decades ago, anaerobic sludge treatment in RAS was pioneered, with the first early reports on freshwater RAS sludge (Kugelman and van Gorder, 1991; Lanari and Franci, 1998), followed by marine (Chen et al., 1997) and brackish water operations (Mirzoyan et al., 2010). Recently, the use of Upflow Anaerobic Sludge Blanket (UASB) technology was suggested for RAS sludge treatment, with biogas production as an alternative energy source (Fig. 5) (Zhu et al., 2022b).

Few studies have shown the effectiveness of UASB for solids treatment in pilot-scale saline and marine aquaculture systems, highlighting its potential in aquaponics (Yogev et al., 2017). The UASB system enabled high water recirculation rates (>99%) and reduced sludge

**Table 4**
A summary of the most common technologies for treating aquaponics solid wastes and the nutrients and by-products they can recover.

| Waste stream | Possible technologies | By products | Recover potential | Advantage | Disadvantage | References |
|---|---|---|---|---|---|---|
| Fish sludge | Anaerobic digestion | Biogas; fertiliser (supernatant) | 87–94% N; 55–71% P; 100% water | Onsite treatment; high recovery potential | Long start-up process | Estevez et al., 2014; Mirzoyan et al., 2010; Zhu et al., 2022b |
| | Aerobic mineralization | Fertiliser | 90–98% N; 50–80% P; 100% K | Low maintenance; increasing nutrient capture | Higher energy consumption | Goddek et al., 2019; Khiari et al., 2019; Monsees et al., 2017a |
| | Assimilation (*Ex-situ* biofloc) | High protein biofloc | 40% crude protein | Valuable by-product; Low cost | High require maintenance | Nayak et al., 2023; Yogev and Gross, 2019 |
| | Composting | Compost | 55–99% N; 69–100% P; 100% K | Reduces water requirement | Requires large amounts of C-rich, dry materials | Wu and Song, 2021 |
| | Insect bioconversion | Protein, fertiliser (frass) | 65–90% N (as protein and fertiliser); 60–80% C; 65–95% S | Rapid bioconversion | Requires dewatering or a dry material | Hu et al., 2026; Rossi et al., 2023 |
| Plant wastes | Anaerobic digestion | Biogas; fertiliser (supernatant) | 70–80% N;58–72% P; TN ~ 700 mg/L; TP ~ 80 mg/L | Nutrient reuse; renewable energy | Requiring pretreatment | Zhu et al., 2021, 2022a |
| | Composting | Compost | 20–86% P | Low-cost and simple technology | Requires a *N*-rich waste | Lopes et al., 2020b; de Bertoldi et al., 1996 |
| | Insect bioconversion | Protein, fertiliser (frass) | >45% crude protein; 50–80% N | Larvae can reduce pesticide contamination | Low bioconversion efficiency and requires pre-treatment | Lalander et al., 2019; Lindberg et al., 2022 |
| | Biomass conversion | Biofuels, bioplastics | 50–90% organic matter | Valuable products; cleaner biofuels | High cost; complex process | Chandra et al., 2012 |
| Fish carcasses | Composting | Compost | 40–60% N; 50–73% P | Low-cost and simple technology | Time-demanding; high land use | Lopes et al., 2020a, 2020b |
| | Insect bioconversion | Protein, fertiliser (frass) | 55–99% N; 69–100% P; 100% K | Fast bioconversion and high recovery potential | †High infrastructure investments and energy consumption | Hu et al., 2024, 2026; Lalander et al., 2019; Parodi et al., 2020 |
| | Hydrothermal carbonization | Biochar, fertiliser, gas ($H_2$, $CH_4$) | 85–100% N;55–90%P; 78–96%K | Highly effective | High capital investment | Mau et al., 2019 |

† Depending on the setup and location.

**Table 5**

Comparative evaluation of technologies for valorization of solid wastes in aquaponics systems.

| Technology | TRL (1–9) | Nutrient recovery efficiency (%) (N / P / K)* | Energy demand (kWh/ t wet waste) † | Capital cost (USD/t/yr capacity) ‡ | Operational complexity | GHG emissions (kg $CO_2$-eq/t wet waste) § | Strengths & limitations for aquaponics |
|---|---|---|---|---|---|---|---|
| Anaerobic digestion | 8–9 (mature for sludge & manure; pilots with fish sludge) | N: ~20–50; P: ~60–90; K: ~70–95 retained in digestate / liquor | ~50–100 (electricity); often net energy-positive due to 300–600 kWh $t^{-1}$ biogas | Medium (300–800 for small plants; lower at large scale) | High – requires heating, gas handling, safety, skilled operation | ~50–400; can become net climate-beneficial | Combines energy recovery with nutrient recycling and treats wet mixed wastes; high CAPEX, co-substrate needs and effluent polishing limit use on small stand-alone farms. |
| Aerobic mineralization | 6–7 (demonstrated for aquaponic sludge) | N: ~20–40; P: ~50–80; K: ~70–90 mobilised into liquid phase | ~100–400 (aeration-dominated) | Medium–high (tanks + blowers; below full AD systems) | Medium – control of aeration, foaming, sludge age | ~100–300 ($CO_2$ from respiration; some $N_2O$) | Provides a nutrient-rich liquid for dosing hydroponic loops; energy-intensive aeration and N losses mean benefits depend on tight design and matching to plant demand. |
| Biofloc-based assimilation | 7–8 (commercial in shrimp; pilots in RAS/aquaponics) | TAN removal ~ 70–90; ~10–30 of N captured in microbial biomass; P: ~40–70 in flocs; K largely conserved | ~100–500 (intensive aeration and mixing) | Medium (reactors, aeration, harvesting equipment) | Medium–high – demanding control of C/N, DO, solids concentration | ~150–400; dominated by respiration $CO_2$ and $N_2O$ | Converts dissolved N and solids into protein-rich biomass fish can use; high oxygen demand and fine solids require strong separation to avoid degrading hydroponic water quality. |
| Microaerophilic assimilation | 5–6 (pilot-scale proof-of-concept) | TAN removal ~ 89; nitrate ~ 100; most P retained in biomass | ~80–200 (microaerophilic aeration; somewhat lower than fully aerobic nitrification–denitrification) | Medium (additional side-reactor, mixers, control) | High – tight control of DO and C/N; requires advanced monitoring | ~100–250 ($CO_2$ from respiration; limited empirical $N_2O$ data) | Converts dissolved N and solids into high-value microbial protein while off-loading the main RAS; still experimental and must be validated for long-term stability, fish performance and plant nutrient matching. |
| Composting & vermicomposting | 8–9 (widely implemented; vermi well established) | N: ~30–60 (losses via $NH_3/N_2O$); P: ~70–95; K: ~70–95 retained | ~10–50 (turning, ventilation; vermi typically at lower end) | Low–medium (pads / windrows); medium for in-vessel systems | Low–medium – moisture and C/N management; vermi adds biological sensitivity | ~200–600; vermicomposting often reduces $CH_4$ | Produces stable, marketable fertiliser and valorises mixed fish–plant residues; slow, land-demanding and off-loop, best as a complementary outlet rather than the main nutrient-return route. |
| Insect bioconversion (BSFL / mealworm) | 6–8 (rapidly scaling; several industrial plants) | N: ~30–60 into larvae + frass; P: ~40–70 (mostly in frass); K: largely in frass; strongly substrate-dependent | ~20–100 (climate control, aeration, drying/processing) | Medium–high (rearing halls, climate systems, processing lines) | High – requires continuous husbandry, hygiene, and process control | ~50–250; often lower than compost/AD | Generates high-value protein and fertiliser, attractive as a side-stream; current substrate regulations and risk of diverting nutrients away from plants constrain its role in circular aquaponics. |
| Hydrothermal carbonization | 4–6 (demo/pilot; few full-scale plants) | P: >80–95 in hydrochar; N: ~20–50 (rest in process water/ off-gas); K: mainly in process liquor | ~500–1000 (thermal), partially recoverable via heat integration | High (pressure reactors, heat recovery, downstream handling) | High – high-pressure operation, corrosion control, management of hydrochar and process water | ~100–500; can be favourable | Densifies P-rich solids into transportable slow-release fertiliser and can couple with energy recovery; high CAPEX, energy use and TRL make it mainly suitable for large clusters, not single farms. |
| Direct land application | 9 (routine practice where permitted) | Relative agronomic efficiency typically N: ~50–80; P: ~60–90 | <10–20 (pumping, transport, spreading) | Very low (storage and spreading equipment) | Low – mainly logistics, timing with crop calendars | ~50–200; limited processing emissions | Very simple, low-cost way to recycle nutrients at landscape scale; exports nutrients from the recirculating system and is hard to apply in urban/vertical farms, offering limited on-site circularity. |

Note:

AD: Anaerobic digestion; BSFL: Black soldier fly larvae; CAPEX: Capital expenditure; GHG:Greenhouse gas; TRL: Technological Readiness Level.

Methodological note: Data were compiled from recent reviews, experimental studies and life-cycle assessments on fish sludge, aquaculture sludge and related organic wastes, with priority given to aquaponics-specific work where available. All references from the context and Table 3 and 4.

* Nutrient recovery figures refer to approximate ranges reported for aquaculture sludge, sewage sludge, and comparable organic wastes; actual performance depends on feed composition, operating conditions, and downstream management.

† Energy demand values combine indicative electricity and, where relevant, thermal inputs; they are meant as order-of-magnitude guidance rather than plant-specific design values.

‡ Capital costs are indicative and highly scale- and context-dependent; ranges are derived from techno-economic assessments of sludge and organic waste treatment plants.

§ GHG ranges are compiled from life-cycle assessments and direct emission studies and may shift substantially when credits for displaced fertilisers, energy, or feeds are included.

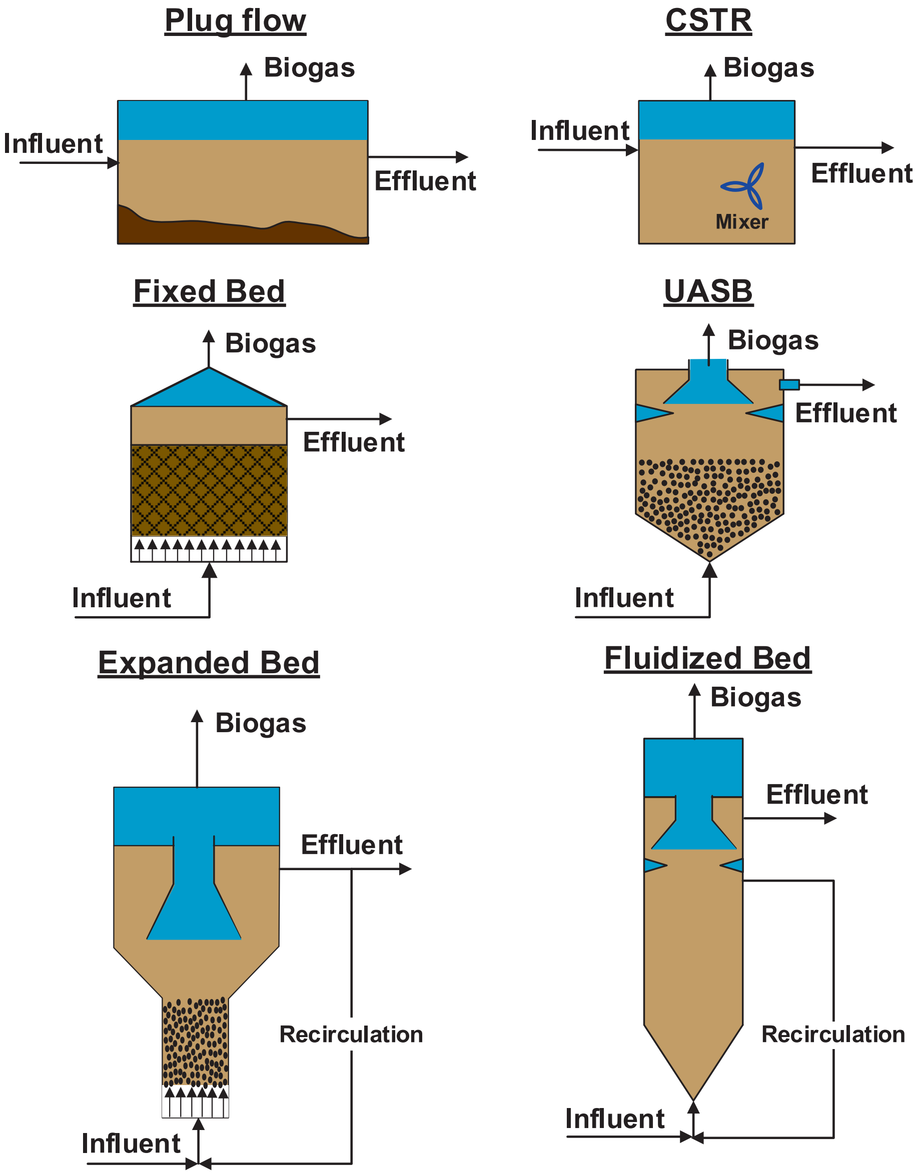

**Fig. 5.** Schematic representation of anaerobic bioreactors for aquaponics solid wastes, modified from previous studies (Goddek et al., 2019; Lin et al., 2013; Xu et al., 2018; Zhu et al., 2021, 2022a, 2025a). CSTR: Completely Stirred Tank Reactor; UASB: Upflow Anaerobic Sludge Blanket Reactor.

production (<8%) compared to typical RAS without onsite solids treatment (Zhu, 2023). The amount of UASB recovered energy was shown to contribute up to 12% of the total RAS energy demand (Zhu et al., 2022b). Additionally, implementing UASB in aquaponics allowed the recovery of up to 50% more nutrients, such as N and P, released into the water as a result of solid biodegradation (Zhu et al., 2024).

In contrast to the decanting process used in UASB, an alternative, and highly advanced, option is the implementation of Anaerobic Membrane Bioreactor (AnMBR), which uses the microfiltration or ultrafiltration membrane constructed typically from polymeric materials or ceramics, to separate solids from the liquid (Lin et al., 2013). Sludge fermentation takes place in a simple anaerobic tank, and then effluents exit through the membrane with a pore size of 0.1–0.5 μm, which retains microorganisms within the tank for subsequent, continuous fermentation processes (Kumar and Tuohy, 2018). AnMBR provides high-quality effluent with most nutrients retained in a form available for plant uptake, along with short hydraulic retention time (HRT), effective pathogen removal, and a small system footprint (Grossman et al., 2019). However, AnMBR is characterized by a series of limitations, with the most significant being the high operational costs due to membrane maintenance to prevent biofouling and a high $CO_2$ fraction (30–50%) in biogas, which limits its use and contributes to greenhouse gas (GHG) emissions (Harb et al., 2015).

A conceptual solution that has been proposed for integrating anaerobic digestion with nutrient recovery in aquaponics is to operate sludge treatment in two sequential stages under different pH conditions. In the first stage, the digester is maintained near neutral pH to favour methanogenesis and remove most of the biodegradable carbon as biogas, thereby stabilising the sludge (Jankowska et al., 2015). In a subsequent low pH stage, acidification promotes the dissolution of P and Ca bearing precipitates and other mineral phases, increasing the concentration of plant available ions in the liquid phase (Goddek et al., 2018; Jung and Lovitt, 2011). In theory, removing most of the carbon in the first stage should also limit the formation of volatile fatty acids during the low pH step (De Korte et al., 2026; Zhu et al., 2023). However, to our knowledge this ‘high pH-low pH’ configuration has not yet been demonstrated in pilot or full-scale aquaponic systems, and should therefore be regarded as a promising design hypothesis that merits targeted experimental validation rather than an established solution.

### 5.2. Aerobic mineralisation

Aerobic mineralisation facilitates the oxidation of the fish sludge, which consequently releases nutrients such as N, P, K, Ca, Mg, and S, along with micronutrients like Fe, Mn, Zn, Co, B, and Mo, into the water in ionic forms (Zhang et al., 2021). The duration of each mineralisation cycle can range from 5 to 30 days, depending on factors such as the system setup, organic load, and the desired nutrient profile (Khiari et al., 2019). A 29-day retention period for aerobic mineralisation on fish sludge from two aquaculture systems achieved significant nutrient recovery (Rakocy et al., 2011). The reduction in pH during the process is a key factor in nutrient release, as many nutrients are initially bound in forms such as calcium phosphates (Zhang et al., 2021). Approximately 78% of phosphate in the aquaculture system can be retained in sludge, with about 50% of the phosphate being acid soluble, demonstrating the potential of mineralisation units for nutrient recovery in aquaponics (Monsees et al., 2017a). However, the relatively long retention time poses a challenge for integration into tightly recirculating loops, particularly in commercial systems where space and turnaround time are limiting factors. Accommodating a 29-day mineralisation cycle within the main system would require large buffer tanks and additional infrastructure, which may not always be economically or spatially feasible. To address this, aerobic mineralisers can be operated as decoupled, batch-mode units, independent of the main water loop. In this configuration, fish sludge is processed separately, and only the supernatant, once nutrient remineralisation reaches a maximum or target level, is periodically reintroduced into the aquaponic system. This approach avoids continuous water volume retention while still enabling nutrient recovery and reuse.

The optimal pH for organic breakdown by microorganisms is between 6 and 8, and differs from the optimal pH for promoting nutrient leaching, which is generally below 5.5 (Goddek et al., 2019). Therefore, the process can be divided into two phases: organic reduction near neutral pH and nutrient leaching under acidic conditions. While this staged approach enhances nutrient solubilisation, it further extends the total processing time, making batch operation and decoupling even more relevant for practical implementation.

Aerobic mineralisation has several advantages, including low maintenance, ease of operation, and no subsequent reoxygenation (Schmautz et al., 2021). The nutrient-rich water produced can be directly applied to plants, ideally managed by an automated system to properly regulate nutrient levels. However, unlike anaerobic mineralisation, aerobic processes do not produce methane, and the continuous aeration required leads to higher energy consumption (Luo, 2023) (Table 5). Despite these limitations, some commercial aquaponics farms have already adopted aerobic mineralisation in decoupled batch configurations, demonstrating its practical viability when space, energy use, and nutrient delivery are carefully balanced. Such configurations have been observed by the authors (SMP and ZZ, personal communication) during site visits to farms in Brazil (São Paulo State), South Africa (Western Cape province), USA (Indiana), Italy (Bologna), China (Hangzhou), and Israel (Negev), where aerobic mineralisers were implemented outside the main recirculating loop.

### 5.3. Microaerophilic assimilation

Microaerophilic assimilation is another emerging *ex-situ* strategy for treating solid wastes, particularly fish sludge, in aquaponic systems (Yogev and Gross, 2019). It is based on the principle of microbial assimilation, in which total $NH_3$-N and organic C from uneaten feed and faeces, supplemented with additional carbon sources (e.g., food waste), are converted into microbial biomass under low-oxygen (microaerophilic) conditions (Nayak et al., 2023). This approach builds on the concept of biofloc technology, where microbial communities transform dissolved nutrients into protein-rich biomass (Avnimelech et al., 1994). However, it differs in two key ways: (i) microaerophilic assimilation is operated *ex situ*, in a dedicated side-stream reactor, whereas biofloc systems are typically run *in situ* within the fish tank; and, (ii) it requires significantly less aeration, offering substantial energy savings.

In this configuration, a portion of the fish effluent and suspended solids is diverted to a side-stream reactor, where heterotrophic bacteria assimilate N and organic matter into microbial biomass (Deng et al., 2021a), which supports high-density aquaculture and enables the cultivation of a broader range of fish species (beyond species such as tilapia and catfish). Operating under low-oxygen conditions suppresses nitrification while enabling efficient nutrient conversion (Wang et al., 2024). The system has been shown to reduce energy consumption by up to 75% compared to fully aerobic microbial assimilation processes (Yogev and Gross, 2019) (Table 5).

Microaerophilic reactors have been tested in RAS-based aquaponic systems, where the post-treated effluent is reintroduced into the main loop (Yogev and Gross, 2019). However, early implementations resulted in the unintended release of microbial flocs back into the recirculating system, increasing total suspended solids (TSS) and compromising water clarity, which is particularly detrimental for high-density aquaculture and high-value fish species. Unlike *in situ* biofloc systems, which are specifically designed to accommodate suspended microbial biomass (Li et al., 2024a, 2024b, 2024c; Zhu et al., 2025b), conventional RAS-based aquaponic systems are generally not equipped to handle high solids loads, making this a significant operational challenge. To address this limitation, a membrane-based microaerophilic reactor was recently developed, integrating ultrafiltration to retain microbial biomass within the treatment unit while allowing only clarified water to return to the main loop (Fig. 6) (Sharma et al., 2024). In a pilot scale RAS, integrating a microaerophilic assimilation side reactor reduced the return of fine solids and dissolved nitrogen to the fish tanks and enabled near-zero discharge operation (Yogev and Gross, 2019), but this approach is still at the proof-of-concept stage. Accordingly, in the context of aquaponics it should be regarded as an emerging strategy that may help limit solids recirculation and enhance nutrient recovery yet requires further long-term and commercial scale validation.

### 5.4. Composting

Beyond the in-system solid reuse strategies presented above, organic solids can also be processed externally to recover nutrients in forms suitable for terrestrial application, with composting being one of the more traditional approaches. Composting refers to the controlled biological decomposition of biodegradable solid waste under aerobic conditions, transforming it into a safe and mature compost for multiple uses (de Bertoldi et al., 1996). While aquaculture waste (including carcasses, feed remains, and others) has been thoroughly studied for its potential to be treated by thermophilic composting (Lopes et al., 2020a,b, 2022), the most abundant waste in aquaponic systems (sludge) has not yet received the same attention, even though the existing data indicate promising results for composting. In a study comparing the efficiency of pond and RAS sludge derived from catfish production composted with rice straw, the enormous potential of RAS sludge was shown, as RAS sludge efficiently generated a high-quality and nutrient-rich fertiliser for agriculture, with 1.4% N, 1.1% P, and 11.3% K (Nhut et al., 2019). The authors suggested that almost 1 kg of high-quality compost could be obtained for each kg of fish produced, enabling the recovery of significant amounts of nutrients and organic matter from the production. Even though composting aquaponics sludge has one important drawback, which is the need for dewatering (water content typically $> 90\%$), adopting this process can be highly advantageous due to its easy handling, low land use and cost, even being performed within the production site (Wu and Song, 2021). However, it might have a negative impact on the efficiency of water reuse or production costs.

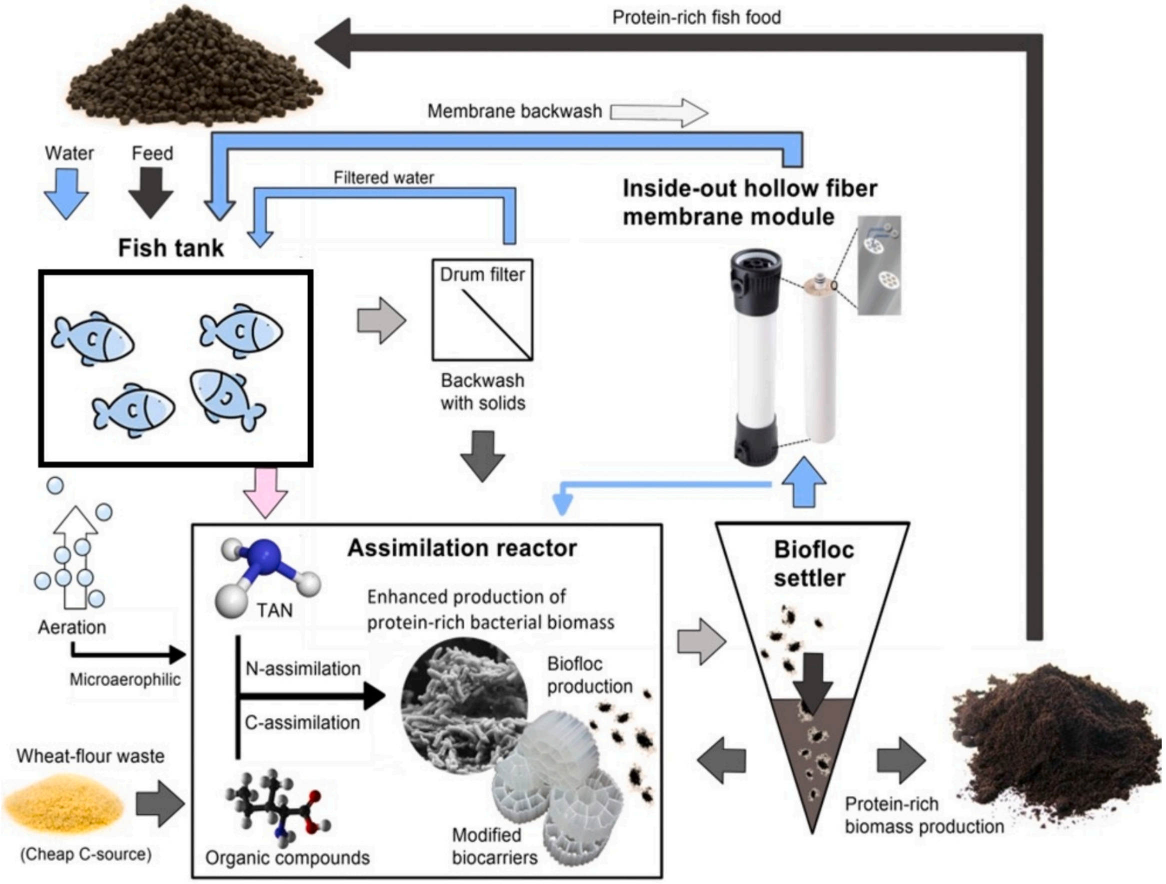

**Fig. 6.** A novel microaerophilic assimilation system that assimilated fish solid waste and TAN into protein-rich microbial biomass.

### 5.5. *Biowaste treatment with insects*

A novel and effective technology for treating solid waste is bioconverting it through the use of insects. Insects, especially the abundantly studied black soldier fly (*Hermetia illucens*) larvae (BSFL), can thrive in substrates of highly variable nutritional compositions (Lalander et al., 2019). Accordingly, BSFL have been proven effective in bioconverting a series of different aquaculture waste streams, from fish carcasses (Hu et al., 2026; Lopes et al., 2020a,b), to sludge collected in a drum filter of an RAS used in salmon production (Schmitt et al., 2019). This process enables the production of high-quality protein (larval biomass with > 45% crude protein, dry matter basis), essential amino acids (Lalander et al., 2019), and fatty acids (Ewald et al., 2020), that could be recirculated back to aquaculture production, replacing the pressure on fishmeal and soybean meal use, as well as organic fertilisers for crop production (Lopes et al., 2022).

The use of BSFL and other insects as aquafeed ingredients has been increasingly reported as promising; however, many bottlenecks remain before they are utilised in large volumes in aquaculture (Colombo et al., 2023). In addition to technical challenges, regulatory barriers also limit the potential of insect-based solutions. In the EU, for example, insects are classified as livestock, which prohibits their rearing on animal-derived waste streams such as aquaculture sludge or fish offal. This policy restriction has sustainability implications. Life cycle assessment studies show that, under current European feed legislation where larvae are fed mainly on feed-grade plant materials or high-value co-products, the climate impact of insect meal per unit protein can be comparable to or even higher than that of fishmeal or soybean meal because substrate production dominates the footprint (Beyers et al., 2023; Bosch et al., 2019; Smetana et al., 2023) (Table 5). These studies further indicate that using low-opportunity organic residues and animal by-products as substrates, materials that are presently restricted or tightly regulated, substantially improves the greenhouse gas profile of insect production and its contribution to waste valorisation (Beyers et al., 2023; Bosch et al., 2019). These findings suggest that, provided food and feed safety is ensured, carefully expanding the range of permissible substrates could be crucial to improving the environmental performance of insect farming and aligning insect bioconversion with the circularity ambitions of aquaculture. Considering the potential of insects as tools for waste management, feed production, and promoting true circularity, their use in sustainable aquaculture must continue to be investigated, particularly in connection with evolving regulatory frameworks through collaboration between researchers, industry, and policymakers.

### 5.6. *Land application*

Fish sludge generated in aquaculture and aquaponic systems has characteristics that make it a promising input for direct land application, particularly as a nutrient source for crop production. For instance, a detailed assessment of sludge from an Atlantic salmon farm in Chile, which produced 200 tonnes of salmon and generated 1–2 $m^3$ of sludge per day, found the material met sanitary and environmental safety standards for land application (Madariaga and Marín, 2017). However, the composition of fish sludge is highly variable and influenced by system inputs, including feed type, water source, cultured species, and management practices. As such, its toxicological and nutrient profiles, particularly the presence of heavy metals, pathogens, and excess nutrients, must be carefully assessed prior to land application (Zhang et al., 2023; Zhu et al., 2025a).

One notable challenge associated with directing solid waste to land application is the salinity of sludge, particularly from marine-based systems, which can lead to salt accumulation in soils and, over time, reduce soil fertility and crop productivity (Li et al., 2022). In contrast, sludge from freshwater aquaponic systems generally contains lower salt concentrations and is therefore more suitable for agricultural use. Nevertheless, nutrient imbalances and residual contaminants may still require pre-treatment or conditioning before application.

Despite these challenges, land application remains the most common destination for sludge in commercial aquaculture, underscoring advancing research and practice to further unlock the potential as a nutrient-recycling solution. For example, Norwegian marine aquaculture alone discharges approximately 14,000 tonnes of P and 27,000 tonnes of N annually into surrounding waters (Brod and Øgaard, 2021). Given that Norway contributes just 2% of global aquaculture production (FAO, 2024), these figures not only underscore the magnitude of nutrient loss from aquaculture globally but also reinforce the urgent need to improve solid waste treatment and nutrient recovery strategies across the aquatic-based food production sector.

While land application may not directly close the nutrient loop within an aquaponic system, it plays an important role when considered through a broader food systems perspective. Crops grown using these recovered nutrients could, in turn, serve as inputs, such as feed ingredients, for aquaponics or other forms of livestock production. In this way, land application is not merely a waste management endpoint; it is a potential connector between aquatic and terrestrial systems, offering a bridge toward more integrated, circular food networks.

## 6. Discussion

Despite the strong conceptual alignment between aquaponics and circular economy principles, current systems often remain only partially circular, particularly when considering the full potential for nutrient utilisation. The strategies reviewed in this paper represent a growing body of research aimed at minimising these losses and enhancing nutrient use efficiency across aquaponic systems. However, embedding these strategies into commercially viable and operationally robust systems remains a major challenge. This discussion critically evaluates the systemic nature of nutrient recovery barriers, highlighting gaps and contradictions in current research, and exploring how aquaponics can more effectively align with circular bioeconomy goals in both design and practice.

Across the systems and technologies reviewed, a few quantitative indicators emerge as particularly useful for judging circularity and system performance: (i) nutrient use efficiency for N, P and K, defined as the fraction of feed-derived nutrients harvested in fish and plants; (ii) the share of plant-essential nutrients supplied by internal sources (fish wastes, recovered sludges, side-stream biomasses) versus external mineral fertilisers; (iii) water-use efficiency (kg product per $m^3$ freshwater input); (iv) energy intensity (kWh per kg fish and plant biomass); and (v) specific capital and operating costs for key recovery units. Table 2 summarises typical ranges of N and P losses in conventional and multi-loop aquaponic layouts, while Table 5 compares solid-waste valorisation technologies in terms of nutrient recovery, energy demand, capital cost, scalability and operational complexity. Together, these mass-balance ranges and comparative metrics are intended to support practitioners in selecting combinations of layouts and recovery options that fit their circularity targets.

### 6.1. *Integrating nutrient recovery strategies: A system-wide challenge*

One of the central challenges highlighted by this review is that nutrient transformation and recovery processes in aquaponics, such as nitrification, sludge mineralisation, anaerobic digestion, electrochemical recovery, microbial or algal cultivation (Sharma et al., 2024), are still often designed and evaluated as stand-alone units, even though they are hydraulically and biogeochemically interconnected. This fragmentation risks optimising individual components while missing opportunities to close nutrient loops at the system level. To advance functional circularity, aquaponics research needs to move from component-centric optimisation towards integrated multi-loop layouts in which side-stream processes operate at their own optimal pH, redox conditions and hydraulic retention times, while maintaining suitable water quality for fish and plants (Zhang et al., 2025). Decoupled and multi-loop configurations can provide this additional degree of freedom by treating sludge and concentrate streams outside the main fish loop, which facilitates the practical integration of batch aerobic or anaerobic mineralisers, UASB reactors and other specialised recovery technologies that would be difficult to operate within a single-loop layout (Baganz et al., 2021a; Monsees et al., 2019).

Environmental and biosystems modelling research has been attempting to address this gap through dynamic modelling approaches based on deterministic mass balances, which simulate nutrient flows and evaluate the resource efficiency of aquaponics configurations under varying conditions (Dijkgraaf et al., 2019; Jansen and Keesman, 2022; Karimanzira et al., 2016; Lastiri et al., 2018, 2016; Pinho et al., 2022; Tarigan et al., 2021; Zhu, 2023; Zhu et al., 2025c). These models enable the identification of bottlenecks and imbalances across systems and subsystems and can support design decisions that maximise nutrient reuse. While often theoretical or limited to experimental settings, these studies provide essential conceptual scaffolding and a systems-thinking perspective, and position aquaponics not as a sequence of isolated operations but as an interconnected network of biological and technical processes. This review reinforces the need for future work to combine these modelling insights with empirical validation in operational contexts, bridging the gap between conceptual or modelled circular system design and commercial-scale practice.

Regardless of system layout, and though the technical feasibility of nutrient recovery strategies has been demonstrated, at least in isolation, their practical integration remains limited, especially in commercial farms. While some operations employ composting, mineralisation, or bioconversion, the extent to which these are holistically integrated into system operations is largely undocumented. Real-world data on performance, feasibility, and scalability remain scarce. This gap stems in part from weak connections between researchers and practitioners. On-farm experimentation is often driven by trial and error, tailored to site-specific or seasonal constraints, whereas researchers typically test individual interventions at laboratory scale under idealised conditions. As a result, many innovations struggle to move beyond the prototype stage. Bridging this gap will require deeper collaboration and participatory research that includes producers in the co-design of nutrient recovery processes. Despite promising advances, the translation of nutrient recovery strategies from concept to commercial reality faces substantial hurdles. Technical complexities, such as system compatibility, control precision, and maintenance demands, often limit practical adoption. Economic barriers, including capital costs, uncertain returns, and labour requirements, further constrain uptake, particularly for small or resource-limited operators. Regulatory ambiguity regarding waste classification, water discharge, and novel products like microbial biomass adds further complication.

### 6.2. *Opportunities for broader circular bioeconomy alignment*

Numerous nutrient recovery strategies in aquaponics have been proposed and revised in this review; however, a persistent challenge lies in evaluating their actual efficiency and involved trade-offs. Most studies to date focus on isolated processes and technical performance indicators, typically reporting short-term nutrient recovery rates or pollutant reductions, but rarely examining the systemic implications of implementing these interventions within functioning aquaponic systems. For example, anaerobic digestion of fish sludge has demonstrated nutrient solubilisation efficiencies exceeding 50% for N and P (Li et al., 2025b, 2025a; Zhu et al., 2024), yet its stringent process control demands, accumulation of metabolic byproducts, and risk of biogas leakage cannot be overlooked. Similarly, aerobic mineralisation is praised for producing nutrient-rich fertiliser with minimal operational complexity (Monsees et al., 2017a), but its long retention times, environmental sensitivity, and high aeration requirements may negatively affect overall system energy performance, highlighting the need to explore more energy-efficient alternatives. All the implementation challenges highlighted in this review underscore the need for a more systemic perspective, one that considers aquaponics not merely as a biological interface but as an integrated sociotechnical system. Future efforts should consider policy engagement, cost benefit analysis, technoeconomic analysis (TEA), and adaptive governance to complement technical innovation. Embedding nutrient recovery within broader transition pathways toward circular bioeconomies will require not just better technologies, but also better alignment of incentives, institutions, and knowledge networks.

To meaningfully progress with the nutrient recovery strategies, it seems that it is essential to adopt multi-criteria evaluation frameworks that consider not only nutrient recovery efficiency, but also cost-effectiveness, operational feasibility, energy demand, system compatibility, and long-term environmental impacts. In practice, these dimensions are characterised by inherent trade-offs, including, for example, energy demand versus nutrient recovery rate (e.g. low-energy anaerobic digestion versus energy-intensive aerobic mineralisation or desalination-based reuse), capital and infrastructure costs versus operational simplicity (e.g. AnMBR and microaerophilic reactors versus low-tech batch mineralisers or composting), process control requirements versus system robustness (e.g. tightly controlled UASB and saline hydroponic loops versus passive constructed wetlands or land-based sludge reuse), and maximising internal nutrient reuse versus expanding the boundaries of circularity beyond the system itself (e.g. full in-loop nutrient recycling versus exporting sludge for land application, insect bioconversion, or external composting). However, very few studies have applied a more comprehensive approach specifically to nutrient recovery, highlighting that a significant research gap exists. Addressing this gap requires adopting, as a general principle for targeting improvements in aquaponics circularity, an iterative, case-by-case systems framework in which system boundaries are explicitly defined, mass and energy flows are quantified through modelling, and existing and alternative recovery scenarios are evaluated through multi-criteria and sensitivity analyses. The weighting of these multi-criteria indicators, which should consider operational efficiency, environmental sustainability, and socio-economic dimensions, is highly case-specific. In some contexts where, for example, electricity is inexpensive and sourced from renewable, low-emissions systems, more energy-intensive recovery options may be feasible, whereas in other contexts a balance between accepting lower circularity and avoiding high energy or capital inputs may be more appropriate. In essence, such iterative evaluation, supported by feedback between modelling and operation, should always systematically underpin practical design and management decisions toward functional circularity rather than purely theoretical closure, and toward solutions that are realistic and feasible in the longer term, where circularity and sustainability objectives can be jointly met.

As emphasised throughout this paper, aquaponics holds strong potential to contribute meaningfully to the circular bioeconomy. Yet, this contribution must extend beyond internal nutrient cycling. Looking from a broader viewpoint, aquaponics should be envisioned and evolve as a platform capable of integrating with other food, waste, and energy systems. For instance, fish sludge and plant residues could be co-processed with urban or agricultural biowaste to produce bioenergy or organic fertilisers. Likewise, microbial or insect biomass generated from waste treatments could be valorised as protein-rich feed inputs for aquaculture or terrestrial livestock (Colombo et al., 2023; de Korte et al., 2024; Lopes et al., 2022). These interconnections may enable aquaponics to create added value across sectors for local communities and contribute to more regenerative and resilient regional food systems.

Realising this broader potential requires greater alignment between researchers, practitioners, and policymakers. Supporting on-farm innovation, fostering data sharing, and enabling regulatory frameworks that recognise and promote nutrient reuse from aquaponic waste streams will be critical. Only through such collaborative and cross-sectoral efforts can aquaponics move from the promising niche it is today to an integrated pillar within the circular bioeconomy.

### 6.3. *Future perspectives*

Looking ahead, future research must move beyond isolated interventions and prioritise commercial-scale validation of concrete multi-loop layouts, for example systems that (i) integrate sludge mineralisation or anaerobic digestion as a primary nutrient source for the hydroponic unit, (ii) operate with near zero discharge of water and solids, and (iii) rely on internal waste derived fertilisers, insect or algal side streams to minimise external mineral fertiliser inputs, while applying robust evaluation frameworks. Realising the full potential of aquaponics as a contributor to circular bioeconomy transitions will require a strategic and action-oriented research agenda. Priorities should include co-developing pilot projects with industry stakeholders, embedding nutrient recovery within broader food, energy, and waste systems, and fostering interdisciplinary approaches that span engineering, microbiology, economics, and policy. Investment in decision support tools and scenario modelling can help translate systems thinking into practical guidance for diverse farming contexts. Finally, targeted policy interventions such as incentives for nutrient valorisation, clearer regulatory pathways for by-products, and support for innovation clusters will be essential to bridge the gap between experimental promise and commercial implementation. The next phase for aquaponics therefore lies not only in technical optimisation, but in strengthening the institutional, regulatory, and infrastructural conditions required to enable circularity to scale meaningfully across real farming systems.

## 7. Conclusions

This review provided a critical synthesis of strategies to reduce, reuse, and recycle N and P in aquaponics, focusing on both dissolved and solid nutrient streams. Through this, it identified key points of nutrient loss and highlighted a range of emerging and underutilised approaches aimed at improving nutrient recovery efficiency. While the review categorised these strategies individually, the discussion placed them within a broader systems perspective, emphasising the importance of integration, trade-off evaluation, and alignment with circular bioeconomy goals. The relevance of this review lies in bridging a persistent disconnect; although many recovery strategies are technically promising, they are rarely integrated into aquaponics as interconnected systems. The discussion demonstrated that closing nutrient loops is not simply a matter of adding recovery technologies, but of redesigning systems to support their interaction, sequencing, and synchronisation. Importantly, this work highlights how aquaponics can act not only as a circular system in itself, but as a node within broader circular food, waste, and energy networks.

## CRediT authorship contribution statement

**Ze Zhu:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Sara M Pinho:** Writing – original draft, Visualization, Validation, Methodology, Conceptualization. **Oliver Körner:** Writing – original draft, Data curation. **Giovanni M Turchini:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Ivã Guidini Lopes:** . **Paul B Brown:** Writing – review & editing, Supervision, Funding acquisition. **Zhangying Ye:** Writing – review & editing, Resources. **Jian Zhao:** Writing – review & editing, Resources. **Guozhi Luo:** Writing – review & editing, Resources. **Hendrik Monsees:** Writing – original draft, Data curation. **Karel J Keesman:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Amit Gross:** Writing – review &

editing, Supervision, Project administration, Funding acquisition.

## Funding

(i) European Union's Horizon 2020 and ERA-NET Cofund No 862555; (ii) Federal Ministry of Food and Agriculture of Germany No 2821ERA20C; (iii) Dutch Ministry of Agriculture, Nature and Food Quality No. 1400011944; (iv) EU PRIMA – FrontAgNexus Grant Agreement No 2242; (v) German Research Foundation (DFG) No. 516754420; (vi) Purdue University, College of Agriculture, Accelerating Giant Leaps: Agriculture's Intersection with Computing, Analytics, and OneHealth.

## 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.

## Acknowledgements

This work is part of the Blue-Cycling project that has received funding from the EU's Horizon 2020 research and innovation program under grant agreement No. 862555 within the 2019 Joint Call of the ERA-NET Cofund on Food Systems and Climate, the Federal Ministry of Food and Agriculture of Germany with grant No 2821ERA20C, the Dutch Ministry of Agriculture, Nature and Food Quality No. 1400011944. This work is partially supported by the PRIMA program under grant agreement No. 2242, project FrontAg Nexus. The PRIMA program is supported by the European Union. BELMONT Forum project AquaponicsOpti funded through the German Research Foundation (DFG) with grant number 516754420. Purdue University College of Agriculture, Accelerating Giant Leaps: Agriculture's Intersection with Computing, Analytics, and OneHealth. This work was supported by the USDA National Institute of Food and Agriculture, Award #2023-68012-39001.

## Data availability

Data will be made available on request.

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