RESEARCH REPORT

Pathways for Circular Aquaculture and Resource-Efficient Food Production

Eunice Modupe Epebinu, Susanne Bodach, Solomie Gebrezgabher, and
Tosin Somorin

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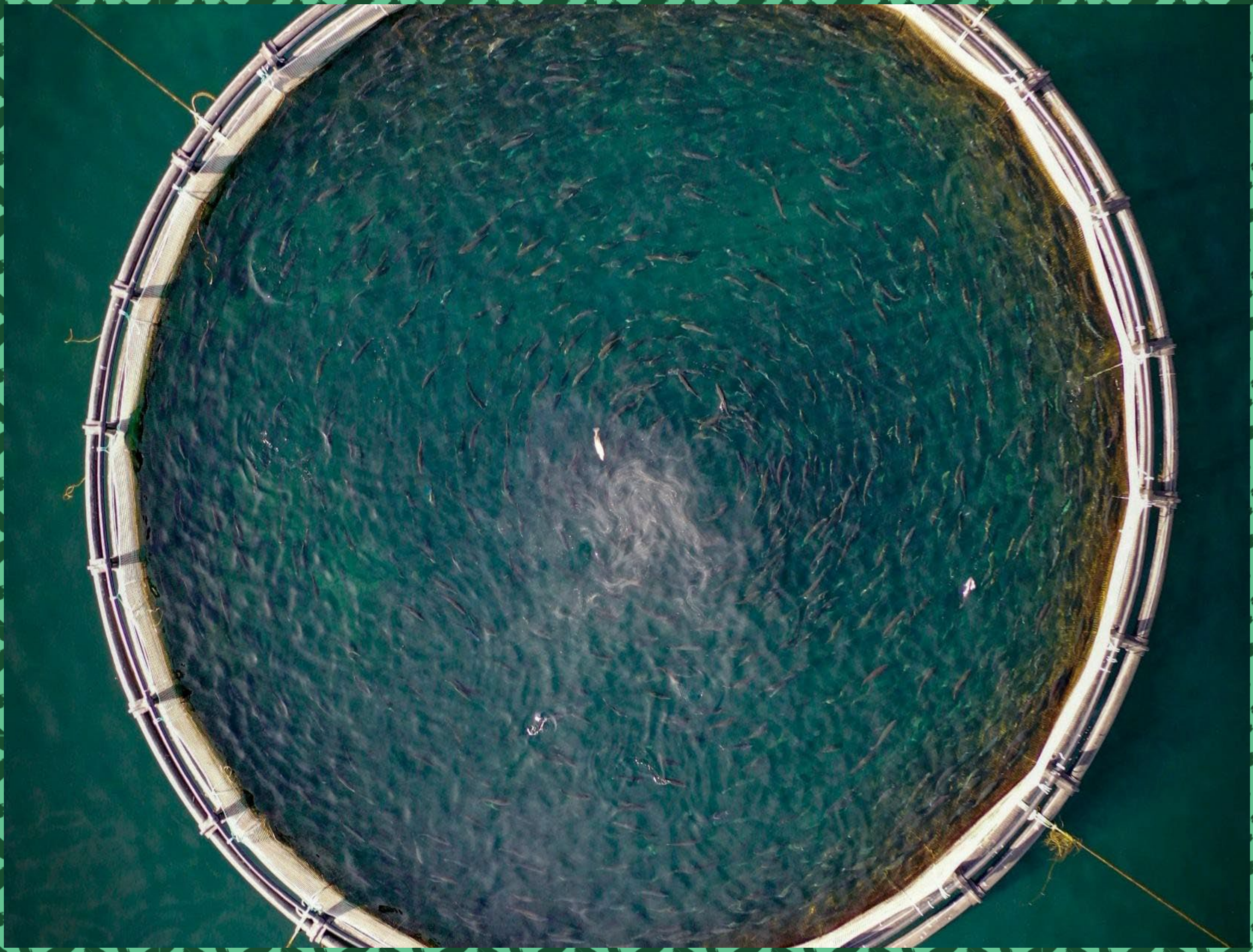

The authors

Eunice Modupe Epebinu, Intern, International Water Management Institute (IWMI), Accra, Ghana
Susanne Bodach, Research Group Leader - Integrated Circular Economy Transformations, IWMI, Colombo, Sri Lanka
Solomie Gebrezgabher, Senior Researcher - Economics, IWMI, Accra Ghana
Tosin Somorin – Researcher - Circular Economy and Waste Management, IWMI, Accra, Ghana

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Contents

List of Figures

List of Tables

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1. Background

Aquaculture is one of the fastest-growing food production sectors globally and plays an increasingly critical role in food and nutrition security, livelihoods, and economic development (Verdegem et al., 2023; Boyd et al., 2022). In 2022, global aquaculture production reached

130.9 million tonnes, with an estimated farm-gate value of USD 312.8 billion; aquaculture also accounted for 51% of global aquatic animal production and employed approximately 22 million people (FAO, 2024). While this growth is essential for meeting rising demand for aquatic foods, it has also been accompanied by increasing pressures on water resources, higher nutrient losses, and the generation of wastewater and solid by-products, particularly in more intensive production systems (Campanati et al., 2022). These challenges are exacerbated in linear production models characterized by high feed inputs, limited water exchange, and weak integration between production and waste management processes. Such systems have high water, feed, and energy inputs, and they dispose of nutrient-rich effluents and by-products as waste rather than systematically recovering and reusing them as productive resources (Boyd et al., 2022; Chary et al., 2024; Kurniawan et al., 2025). This linear paradigm not only undermines environmental integrity but also results in the loss of valuable nutrients.

To address these limitations, the circular economy (CE) has emerged as a promising approach for rethinking aquaculture development beyond incremental efficiency gains. CE approaches aim to replace linear “take–make–dispose” models with regenerative systems that close material, nutrient, and energy loops while safeguarding ecosystem integrity (Chary et al., 2024; Kurniawan et al., 2025; Osei et al., 2025). This calls for a paradigm shift: moving beyond efficiency gains toward the systemic integration of production, treatment, and recovery processes across spatial and temporal scales, as well as a conceptual shift in how aquaculture systems are designed, managed, and evaluated (Greene et al., 2022; Kurniawan et al., 2025). It emphasizes not only waste reduction and recycling but also prioritizes biomass for essential human needs, avoiding non-essential resource use, and regenerating aquatic and connected agroecosystems (Campanati et al., 2022; Chary et al., 2024). Within aquaculture, this entails reconfiguring production systems to enable nutrient recovery, water reuse, and the integration of complementary biological processes.

Recent reviews highlight that many elements of circular aquaculture are already present in practice, including nutrient recycling, by-product reuse, and integrated production systems (Campanati et al., 2022; Verdegem et al., 2023; Zhang et al., 2023). Despite this growing body of work, the transition from isolated circular practices to fully integrated circular aquaculture systems remains uneven and poorly operationalized, particularly in low- and middle-income countries (LMICs). In these contexts, much of the existing literature and practice has been driven by the imperative to expand aquaculture production and livelihoods, with comparatively limited attention to whether emerging systems are sustainable in terms of resource use, waste generation, and ecosystem impacts. Expansion strategies often prioritize productivity and income generation, while the interactions among production typologies, hydraulic regimes, waste streams, and treatment pathways are poorly addressed. Consequently, there is a paucity of system-level frameworks that embed sustainability at the core of aquaculture development and coherently link system design with water reuse, nutrient recovery, and biomass valorization options. This gap constrains both research for development and practical decision-making, making it difficult for practitioners, planners, and policymakers to identify context-appropriate circular pathways.

Against this background, this report aims to provide a synthesis of circular aquaculture by: (i) classifying dominant aquaculture production systems in relation to their water use, nutrient dynamics, and waste generation profiles; (ii) mapping key pathways for water reuse, nutrient recovery, and by-product valorization within and beyond aquaculture systems; and (iii) evaluating the circular potential and limitations of different system configurations and treatment approaches, with particular attention to applicability in LMIC settings. By doing so, it seeks to bridge the gap between conceptual understanding and operational system design, offering a structured basis for advancing circular aquaculture in practice.

2. Methodology

This study adopts a scoping review approach to map and synthesize existing evidence on aquaculture wastewater management and circular aquaculture systems. Rather than aiming for exhaustive coverage or effect-size estimation, the review focuses on identifying dominant concepts, system typologies, treatment pathways, and research gaps across diverse production contexts. The review draws on peer-reviewed literature and selected grey sources addressing aquaculture wastewater treatment, resource recovery, and the management of aquaculture wastewater and by-products. Studies were included based on their relevance to aquaculture systems, wastewater and by-product management, resource recovery efficiency, and system-level sustainability. No restrictions were placed on publication year or geographic scope to enable broad conceptual coverage. Additional sources were identified through snowballing by screening the reference lists of key papers. This ensures representation of both mature technological pathways and emerging, context-specific innovations that may not yet be widely captured in formal reviews, especially those in resource-constrained settings.

The review draws on 104 publications, including peer-reviewed articles, FAO reports, and selected grey literature. The evidence base spans all major aquaculture regions, with strong representation from Asia and Europe, as well as studies from Africa, North America, South America, and cross-regional/global analyses. Extracted information was analysed qualitatively to: (i) classify aquaculture production systems and examine their implications for water use, nutrient retention, and waste generation; (ii) identify dominant pathways for water reuse, nutrient recovery, and biomass valorization within aquaculture systems and across linked food, agriculture, and energy systems; and (iii) assess the circular performance, opportunities, and limitations of different aquaculture systems and treatment approaches. Analysis prioritised system-level relationships between production intensity, hydraulic regimes, waste characteristics, and treatment requirements, enabling comparison across systems and configurations.

This scoping approach provides a preliminary yet structured foundation for understanding how circular principles are currently being applied within aquaculture systems. It does not seek to rank technologies or prescribe optimal solutions, but rather to map the landscape of existing approaches, reveal dominant design logics, and highlight where evidence is concentrated or absent. By establishing the literature around system typologies, waste streams, and recovery pathways, the review clarifies how production intensity, hydraulic regimes, and waste characteristics shape treatment needs and circular opportunities across different aquaculture configurations. The resulting framework supports evidence-informed system design, highlights priority areas for innovation, and provides a conceptual basis for guiding future research, policy, and investment toward scalable, resource-efficient aquaculture wastewater solutions within a broader circular bioeconomy. The system typologies, operational characteristics, wastewater profiles, circularity indicators, and treatment pathways identified through this scoping review are established in Tables 1–6 (see Appendix A)

3. Typologies and Characteristics of Aquaculture Systems

There is a wide diversity of fish farming methods in aquaculture, many of which have contributed to supplementing capture fisheries and reducing pressure on wild stocks. Early classifications distinguish *water-based systems*, such as cages and pens, from *land-based systems*, including rainfed and irrigated ponds, tanks, and raceways (Baluyut, 1989). Aquaculture systems are also commonly categorized by farming intensity, ranging from *extensive* and *semi-intensive* configurations that rely partly on natural productivity to *intensive systems* characterized by high stocking densities, formulated feeds, aeration, energy inputs, and tightly managed production environments (FAO, 2007).

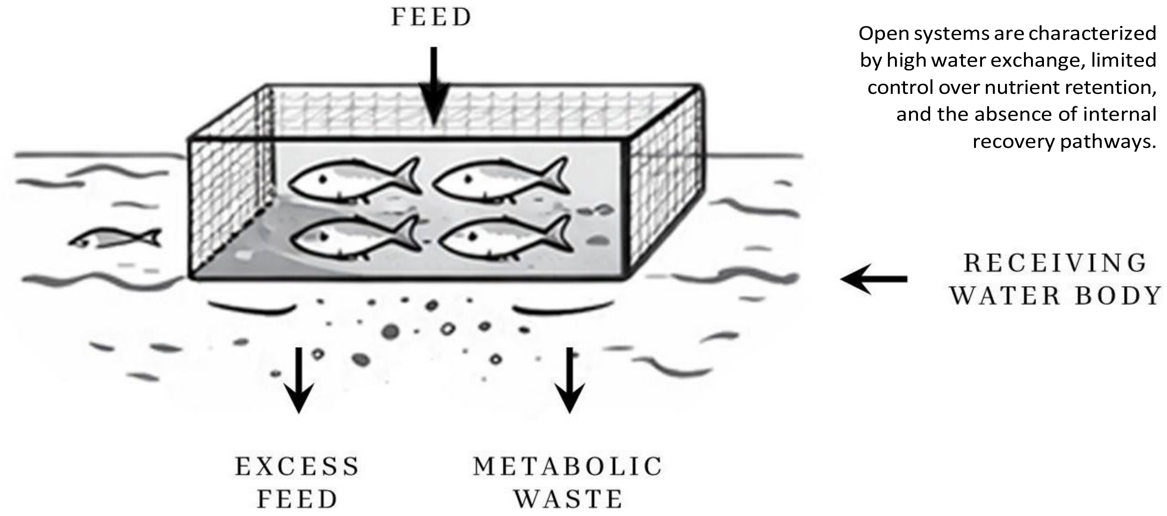
More recent classifications integrate these dimensions into structurally and functionally coherent typologies. Tidwell (2012) distinguishes four broad system types: open, semi-closed, closed, and hybrid systems. *Open systems* include cages and pens; *semi-closed systems* encompass ponds and raceways; *closed systems* comprise recirculating aquaculture systems (RAS) and biofloc-based systems; and *hybrid systems* integrate features of multiple approaches, such as aquaponics, in-pond raceways, split-pond, and partitioned-pond systems. Building on these structural typologies, Verdegem et al. (2023) advance a systems perspective that situates aquaculture along intersecting gradients of fed versus extractive production, inland versus marine environments, and degrees of control over water and nutrient flows. *Fed systems*, dominated by finfish and crustaceans, range from extensive ponds to super-intensive biofloc, partitioned pond, raceway, and RAS configurations. *Extractive systems*, principally mollusks and seaweeds, operate in open coastal environments, using bottom culture, rafts, nets, ropes, and ambient nutrients rather than formulated feeds.

Together, these aquaculture typologies reveal aquaculture as a spectrum, ranging from open, low-control systems embedded in natural ecosystems to highly controlled, closed-loop production environments. However, they differ fundamentally in operational practices, including the degree of water exchange, the intensity of stocking and feeding, the accumulation and management of pollutants, the complexity of treatment and control technologies, the capacity for nutrient recovery, and the magnitude and nature of their environmental interactions with surrounding ecosystems (Liu et al., 2024). These distinctions shape not only production efficiency but also affect where and how waste streams can be intercepted, treated, and valorized within and beyond the farm boundary.

3.1. Open Systems

Open systems are characterized by the continuous or periodic exchange of water with surrounding natural water bodies, such as rivers, lakes, reservoirs, and coastal environments (Figure 1). These free water exchanges allow oxygen to diffuse and waste to be dispersed, while enabling the release of nutrients and organic matter into the ambient ecosystem. Common examples include cage culture, open raceways, and flow-through pond systems (FAO, 2007; Tidwell, 2012; Masser, 2012). These systems depend largely on ambient environmental conditions for temperature regulation, oxygen supply, and dilution of metabolic wastes. In these systems, water quality is largely governed by ambient environmental conditions rather than internal processes. Nutrients originating from uneaten feed, metabolic waste, and excreta are discharged directly into receiving waters, where dilution and natural assimilation processes regulate their fate (Tidwell, 2012). As a result, nutrient retention within the production unit is limited, and most nutrient inputs are not recovered for reuse.

Furthermore, evidence indicates that open systems depend heavily on the assimilative capacity of the surrounding environment. When site conditions are suitable, such as adequate water exchange, depth, and flow, environmental impacts may be moderated. However, where carrying capacity is exceeded or hydrodynamic conditions are constrained, nutrient accumulation and environmental degradation may occur (FAO, 2007; Boyd et al., 2020; Verdegem et al., 2023). Despite these limitations, open systems remain widely used due to their simplicity. They can support partial circularity when combined with complementary treatment or integration strategies. For example, flow-through systems, including cages and net pens, can be combined with supplementary treatment measures, such as sedimentation ponds, to reduce solid and nutrient loads prior to discharge. While such integrations improve environmental performance, circular outcomes remain highly dependent on site-specific conditions, system design, and operational management.



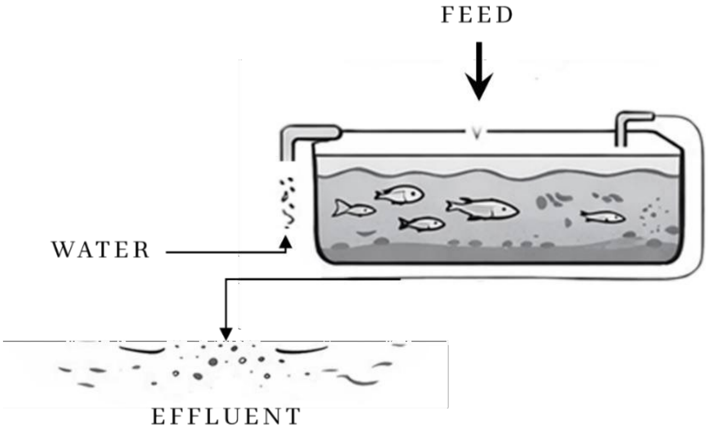
Open systems are characterized by high water exchange, limited control over nutrient retention, and the absence of internal recovery pathways.

Figure 1. Schematic of an open cage system illustrating linear nutrient flows. (*Source*: Conceptual framework developed by the authors. Visualization supported by AI-assisted graphic tools).

3.2. Semi-closed Systems

Semi-closed aquaculture systems occupy an intermediate position between open and fully closed-loop configurations (Figure 2). They incorporate partial water reuse and limited treatment processes while still allowing periodic exchange with the surrounding environment. Common examples include raceway systems, ponds with internal circulation zones, and partially recirculating systems that incorporate mechanical or biological treatment components (Tidwell, 2012). In semi-closed systems, solids and organic matter are partially removed through sedimentation, filtration, or biological processes before water is reused or released. This enables improved control of water quality and reduces nutrient loading.

Semi-closed systems also offer greater operational flexibility than fully closed systems. They require lower capital investment and technical complexity while providing improved environmental performance relative to open systems. Integration with complementary production systems, such as aquaponics, integrated multi-trophic aquaculture (IMTA), biofloc technology (BFT), or constructed wetlands, can enhance circularity (Liu et al., 2021; Tom et al., 2021; Campanati et al., 2022; Checa et al., 2024). The extent of treatment and reuse varies widely depending on effectiveness; however, it is strongly influenced by system design, hydraulic retention time, and management practices, which affect treatment efficiency and overall system stability. Nonetheless, their relative simplicity, flexibility, and lower investment requirements make semi-closed systems particularly relevant for small- to medium-scale producers and LMIC contexts, where incremental transitions toward circularity are more feasible than fully closed-loop designs.

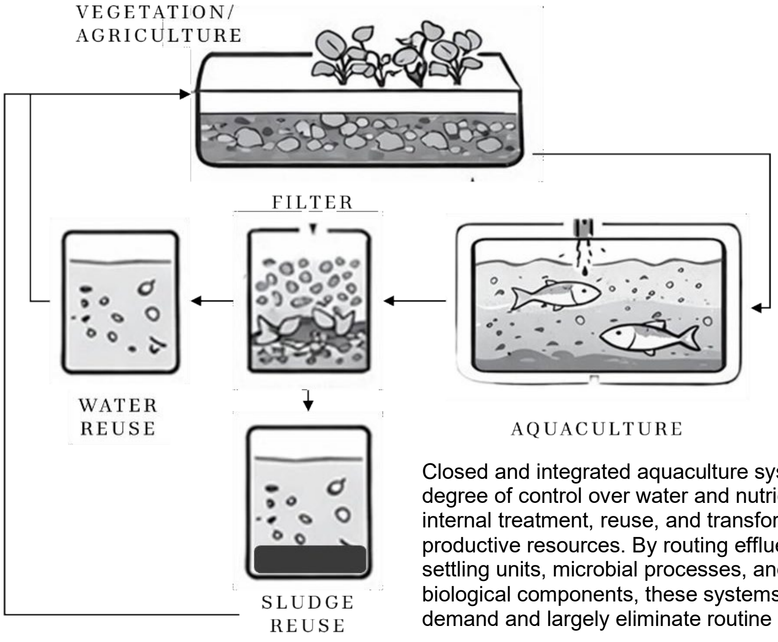


Semi-closed systems offer greater control over water exchange and waste retention, creating opportunities for basic treatment, sediment management, and limited nutrient recovery, but still rely on external water use for diluting effluents; when effluents are poorly managed, nutrient-rich discharges can contribute to localized (point-source) pollution.

Figure 2. Schematic of a semi-closed pond or tank-based aquaculture system. (*Source:* Conceptual framework developed by the authors. Visualization supported by AI-assisted graphic tools).

3.3. Closed Systems

Closed aquaculture systems are designed to operate with minimal or near-zero water exchange, relying on internal treatment and recirculation to maintain water quality and system stability (Figure 3). These systems include RAS, biofloc-based systems, and integrated multi-trophic configurations that integrate mechanical, biological, and chemical treatment units directly into the production cycle. Water reuse rates in such systems can exceed 90–99%, significantly reducing freshwater abstraction and effluent discharge (Tidwell, 2012). Closed-loop systems offer the highest potential for circular resource management, as water, nutrients, and biomass are continuously retained, treated, and repurposed within the system. For example, BFT and IMTA integrate biological nutrient conversion and recycling through symbiotic interactions among microbial and cultured species (McCusker et al., 2023; Checa et al., 2024; Campanati et al., 2022), thereby maintaining system stability and productivity. RAS is a highly intensive and technologically advanced system that maximizes internal water reuse while significantly reducing freshwater abstraction and effluent discharge (Liu et al., 2021; Chopin & Tacon, 2021; Chary et al., 2025). In these systems, solid waste and nutrient-rich effluents can be captured and directed toward valorization pathways, including composting, anaerobic digestion or integrated with aquaponics and algal cultivation (Zhang et al., 2023; Kurniawan et al., 2025). However, these benefits come at the cost of substantial capital investment, increased energy demand, and greater operational complexity (Verdegem et al., 2023; Osei et al., 2025). Continuous pumping, aeration, filtration, and disinfection increase energy requirements, whereas system failure can rapidly compromise stock health due to high stocking densities. As a result, closed-loop systems require skilled management, a reliable energy supply, and robust monitoring frameworks. While they offer strong circular potential, their scalability and applicability are context-dependent, particularly in low-resource settings where cost and technical capacity remain limiting factors. Nevertheless, where these are available, closed-loop systems represent the most advanced pathway to circular production.



Closed and integrated aquaculture systems provide a high degree of control over water and nutrient flows, enabling internal treatment, reuse, and transformation of wastes into productive resources. By routing effluents through biofilters, settling units, microbial processes, and complementary biological components, these systems minimize freshwater demand and largely eliminate routine external discharges.

Figure 3. Schematic of a closed or hybrid circular aquaculture configuration illustrating internal water reuse and nutrient recovery pathways. (*Source:* Conceptual framework developed by the authors. Visualization supported by AI-assisted graphic tools.

3.4. Hybrid Systems

Hybrid aquaculture systems combine elements of open, semi-closed, and closed-loop configurations to balance productivity, environmental performance, and operational feasibility (Tidwell, 2012). Rather than relying on a single treatment or production pathway, hybrid systems integrate multiple subsystems, such as flow-through units, recirculation loops, biofiltration modules, and natural treatment components, within a single operational framework. This modular design enables producers to optimize resource efficiency while reducing capital and energy requirements compared to fully closed systems.

Common hybrid configurations include recirculating aquaculture systems coupled with constructed wetlands, raceways linked to settling basins and biofilters, and IMTA arrangements that combine fed species with extractive organisms such as algae, bivalves, or aquatic plants. These systems allow waste streams from one production unit to serve as nutrient inputs for another, thereby improving overall resource-use efficiency and reducing external pollution loads (Tidwell, 2012). Empirical evidence indicates that hybrid and integrated systems, particularly multi-trophic configurations, can substantially reduce nutrient losses while maintaining high production levels (FAO, 2007; Chary et al., 2024). For example, IMTA and biofloc-based hybrid systems have demonstrated improved feed conversion ratios and enhanced nitrogen retention by converting dissolved nutrients into microbial biomass that can be reused as feed ingredients (McCusker et al., 2023; Checa et al., 2024).

From a circular perspective, hybrid systems represent a pragmatic solution between conventional and fully closed systems. They enable partial closure of nutrient and water loops, reduce dependence on external inputs, and increase opportunities for resource valorization. Importantly, hybrid systems are often more adaptable to variable environmental and infrastructural conditions, making them particularly suitable for low- and middle-income contexts where energy costs, technical capacity, and capital availability constrain full recirculation. However, hybrid systems also present management challenges. Their performance depends on effective integration across system components, coordinated hydraulic control, and careful balancing of biological processes. They may underperform or revert to the limitations of open systems.

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4. Key Parameters Influencing Operational Performance

A range of operational parameters shapes the performance, environmental footprint, and sustainability of aquaculture systems. These parameters determine water quality, nutrient dynamics, system efficiency, and the extent of environmental externalities. Tables A.1-A.3 (*Appendix A*) summarize system-level characteristics, wastewater composition, and farm-level circularity indicators for measuring system performance, while Tables A.4–A.6 (*Appendix A*) synthesize key treatment technologies and valorization pathways.

4.1. Stocking Density

Stocking density is a primary driver of nutrient loading and waste generation across all aquaculture systems. In cage-based systems, stocking densities vary widely by species, cage design, and hydrodynamic conditions. Low-density systems, typically 5–20 fish per cubic meter (m^3), are common in marine cages, whereas freshwater cage systems may operate at much higher densities of up to 450 fish per m^3 (Masser, 2012; Karnatak et al., 2021). Higher stocking densities increase biomass yield but also intensify organic loading, oxygen consumption, and nutrient release, particularly nitrogenous wastes (Berntsson et al., 2025). Excessive stocking can therefore exacerbate eutrophication and stress aquatic organisms, whereas moderate densities improve oxygen availability, growth performance, feed conversion efficiency, and environmental stability (Karnatak et al., 2021).

In pond systems, optimal stocking density is also strongly species-dependent, with studies showing that moderate densities support higher productivity while limiting oxygen depletion and sediment nutrient accumulation (Tucker & Hargreaves, 2012; Mulugeta et al., 2024). Empirical examples illustrate this variability: African catfish juveniles (*Clarias gariepinus*) perform best at around 500 fish m^{-3} (≈13.5 kg m^{-3}) (Khumaidi et al., 2025), whereas male Nile tilapia fingerlings (Oreochromis niloticus) show optimal growth at approximately 7 fish m^{-3} (≈1.84 kg m^{-3}) (Mulugeta et al., 2024). In flow-through systems, continuous water passage reduces internal waste retention but increases the risk of nutrient export to receiving waters. High stocking densities in such systems increase feed inputs, oxygen competition, and organic waste loads, thereby intensifying downstream eutrophication, whereas lower densities reduce nutrient outputs but may compromise economic efficiency. A medium density of around 78 fish m^{-3} (≈2.32 kg m^{-3}) has been identified as optimal for tilapia fingerlings, balancing productivity and environmental performance (Komal et al., 2024; Berntsson et al., 2025). In integrated and recirculating systems, stocking density is constrained by the capacity of biofilters and aeration systems, with intensive systems typically operating at 10–40 kg m^{-3} (Taufik et al., 2024). Excessive fish biomass can overwhelm the assimilative capacity of plants or secondary components, increasing ammonia, nitrite, and suspended solids and undermining nutrient recycling efficiency (Ani et al., 2022). Moderate densities promote balanced nutrient flows, enabling effective recovery and reuse while reducing freshwater demand and waste discharge (Ani et al., 2022; Chary et al., 2025). RASs are therefore specifically designed to sustain much higher biomass densities through multi-stage treatment and tight process control. Commercial RAS commonly operate at 60–120 kg m^{-3}, with highly optimized grow-out systems reaching average final densities of around 85 kg m^{-3} for Atlantic salmon (Brown et al., 2025). Short-term or holding systems may exceed 150 kg m^{-3} for robust species. These reported values are not a fixed “safe” value but a function of treatment and oxygenation capacity: excessive biomass rapidly elevates CO_2, ammonia, and suspended solids, increasing system instability and failure risk (Tom et al., 2021; Shitu et al., 2022; Mnyoro et al., 2022; Liu et al., 2024; Mutegoa, 2024). Aligning stocking density with hydraulic design and treatment performance is therefore central to sustainable RAS operation, ensuring that productivity gains from high biomass loading do not compromise water quality, fish welfare, or system stability.

4.2. Feeding Regimes

Feeding rate is another critical determinant of system performance because it directly governs nutrient loading and waste generation across aquaculture systems. It is influenced by species type, size, age, feed composition, and environmental conditions (Huang et al., 2025). Overfeeding results in uneaten feed and fecal matter, increasing biochemica l oxygen demand (BOD), ammonia, and suspended solids in the culture environment (Rust et al., 2014; Azizpour et al., 2025). In cage and pen systems, excessive feeding exacerbates nutrient discharge into surrounding waters, while protein-rich diets further increase total nitrogen and ammonia, accelerating nutrient enrichment (Mes et al., 2023; Azizpour et al., 2025). In open and flow-through systems, these feed-derived wastes are not retained or treated within the farm boundary but are discharged directly with effluent, transferring organic matter, nitrogen, and phosphorus loads downstream and promoting sedimentation and eutrophication (Rust et al., 2014; Yuniarti et al., 2023; Azizpour et al., 2025). In pond and recirculating systems, overfeeding can lead to the accumulation of suspended solids and organic matter, resulting in oxygen depletion and sediment formation. In RAS in particular, excess feeding can overload mechanical and biofilters, reducing treatment efficiency and destabilizing water quality (Azizpour et al., 2025). Operational benchmarks are therefore important; for example, Tucker and Hargreaves (2012) recommend limiting daily feed inputs for channel catfish ponds in the southeastern United States to 35 kg ha^{-1} day^{-1} to prevent oxygen depletion and excessive accumulation of sediment-borne nutrients.

To address these impacts, feeding regimes must shift from input-based to performance-optimized management, matching feed inputs to species requirements, biomass, growth stage, and the hydraulic and biological capacity of the production system. This reframes feeding from a purely production-oriented decision into a core environmental control lever, linking feed management directly to water quality, treatment demand, and nutrient recovery potential. Optimal feeding strategies, often expressed as a percentage of body weight, are therefore essential for balancing growth and environmental performance. For example, feeding rates of 1.4–1.8% body weight per day has been shown to optimize growth and minimize nitrogen loading in intensive salmonid systems (Nilsen et al., 2020; Sun et al., 2016). In integrated systems, feed management must align with the assimilative capacity of plants or the extractive capacity of organisms to prevent nutrient overload (Ani et al., 2022).


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4.3. Hydraulic Retention Time and Water Exchange

Hydraulic retention time (HRT) and water exchange rate govern water quality, nutrient dynamics, and treatment performance across aquaculture systems. Together, they determine the degree of dilution, oxygen renewal, pollutant dispersal, and the contact time between wastewater and physical, biological, or nature-based treatment processes. Short retention and high exchange favor rapid flushing and dilution, while longer retention enhances sedimentation, microbial activity and nutrient uptake.

In open cage-and-pen systems or other flow-through systems, water exchange is largely governed by ambient hydrodynamics. High flows provide rapid dilution and oxygen renewal, but they also quickly export nutrients and organic matter to receiving waters due to short retention times (Xiong et al., 2025; Tidwell, 2012). Weak flows extend retention, increasing internal processing but also elevating the risk of waste accumulation and physiological stress in fish if oxygen supply becomes limiting (Berntsson et al., 2025). Optimal current velocities typically range from 0–20 cm s^{-1}, with occasional peaks up to 60 cm s^{-1} considered acceptable for cage culture (Masser, 2012; Berntsson et al., 2025). Cage design and biofouling can impede flow, effectively increasing local retention time and reducing exchange efficiency.

In pond systems, water exchange is deliberately managed to balance nutrient dilution and water conservation. Higher exchange rates reduce pollutant concentrations but increase water demand, whereas low exchange rates promote nutrient retention and internal recycling (Niu et al., 2023). Conversely, low or zero exchange promotes nutrient retention and internal recycling but can lead to the accumulation of organic matter and oxygen depletion if not supported by aeration or internal treatment (Baluyut, 1989; Niu et al., 2023). In integrated systems, including IMTA, moderate exchange and longer retention times are advantageous, enabling nutrient transport to extractive components such as shellfish, plants, or macroalgae and providing sufficient contact time for assimilation and microbial transformation. This enhances nutrient circularity and reduces net nutrient export (Ani et al., 2022; Chary et al., 2025). RAS specifically operates with minimal water replacement, relying on mechanical and biological treatment to maintain water quality. These systems achieve high water-use efficiency and low effluent discharge but are highly sensitive to treatment performance. Retention time within treatment units is carefully controlled to optimize nitrification and, where present, denitrification processes (Taufik et al., 2024). Biofloc-based RAS can operate with near-zero daily water exchange (Soliman et al., 2025), illustrating the extreme end of closed-loop operation. Optimizing HRT and water exchange is therefore central to balancing production intensity, treatment efficiency and environmental performance. Insufficient retention limits biological processing, whereas excessive retention, without adequate aeration or treatment, promotes oxygen depletion and the accumulation of harmful metabolites.

4.4. Water Quality Management and Monitoring

Water quality parameters, including dissolved oxygen, temperature, pH, ammonia, nitrite, nitrate, suspended solids, and pathogen load, directly influence nutrient transformation processes and biological stability in aquaculture systems. Temperature influences metabolic rate, feed conversion efficiency, and microbial activity, while dissolved oxygen directly affects fish health and waste assimilation (Abd El-Hack et al., 2022; Godoy et al., 2021). Deviations from optimal ranges can rapidly compromise system stability. Similarly, pH affects nutrient solubility and microbial processes, influencing both water quality and organism health (Edwards et al., 2024). Effective management of these parameters through aeration, system design, and monitoring is therefore fundamental to achieving sustainable and resilient aquaculture operations. For example, systems with limited water exchange, such as BFT, RAS, and aquaponics, require continuous monitoring and rapid corrective responses to prevent system collapse, whereas open and semi-closed systems rely more on dilution and periodic water exchange. Effective water quality management is therefore a prerequisite for maintaining closed or semi-closed loops and enabling safe water reuse. This includes solid waste management, e.g., accumulated sludge from ponds, biofilters, and mechanical filters, which contains concentrated nutrients and organic matter that can be recovered and valorized through composting, anaerobic digestion, biochar production, or use as soil amendments. Systems that enable effective solids capture (e.g., RAS) offer greater opportunities for resource recovery than open systems where solids are dispersed.

4.5. System Design and Operational Management

System design, including pond geometry, tank configuration, hydraulic layout, and integration of treatment units, fundamentally affects water circulation patterns, solids accumulation, and treatment performance (Oca & Masaló, 2013; Khater et al., 2022). Experimental and modelling studies in circular tanks demonstrate that flow rate, inlet geometry, and nozzle configuration determine rotational velocity, mixing efficiency, and self-cleaning capacity, thereby directly influencing waste retention, oxygen distribution, and fish welfare. In open and semi-closed systems, site selection (e.g., hydrodynamics, soil permeability and proximity to receiving water bodies) plays a critical role in dilution capacity and environmental risk (FAO, 2007; Verdegem et al., 2023). In closed-loop systems such as RAS and aquaponics, design decisions determine internal loading rates, treatment capacity, and system resilience; poorly sized hydraulic circuits or treatment units can rapidly lead to solids accumulation, oxygen depletion, and cascading system failure (Verdegem et al., 2023; Chary et al., 2024).

Operational data in Table 1 demonstrate that aquaculture systems differ in hydraulic scale, intensity, and production structure. RAS operates with very low water exchange but high internal loading, producing small volumes of highly concentrated effluents and requiring tight hydraulic control. Raceway systems are characterized by extremely high throughputs, generating large daily flows and high nutrient loads per unit time. Pond-based systems span a wide range of intensities and account for a large share of global production, combining moderate stocking densities with large areal footprints and substantial aggregate water use. Cage systems exhibit the largest absolute water fluxes, relying on natural dilution in open waters and exposing receiving ecosystems to continuous nutrient loading.

Poorly matched design and site conditions can therefore undermine circular outcomes regardless of system type. In addition, the level of technical expertise, labour availability, and institutional capacity significantly influences system performance. While biologically driven systems reduce reliance on advanced infrastructure, they require ecological understanding and adaptive management. Technologically intensive systems demand skilled operators, a reliable energy supply, and robust monitoring frameworks (Verdegem et al., 2023; FAO, 2007). Thus, careful management of operational parameters and optimization are needed to enable the transition from linear production models to circular, resource-efficient aquaculture systems that minimize waste, enhance nutrient recovery, and support long-term sustainability.

Table 1. System-level operational characteristics for key aquaculture types (*Source:* Campanati et al. 2022)

Parameter	RAS	Raceways	Ponds	Cages
Daily water flow (m^3 day^{-1})	116 ± 17 (0.007 – 3,216; n = 266)	81,038 ± 26,010 (0.01 – 1,843,200; n = 173)	11,500 ± 3,626 (0.006 – 591,780; n = 299)	227,108 ± 40,882 (25.9 – 820,000; n = 67)
Water use (m^3 t^{-1} production)	-	16,000 – 42,000	Fishponds: 1,200 – 10,000; shrimp ponds: 20,000 – 100,000	~0.75
Stocking density (kg m^{-3})	31.7 ± 2.2 (0.6 – 100; n = 248)	48.6 ± 1.6 (17.5 – 85; n = 153)	26.0 ± 2.1 (0.15 – 113; n = 277)	31.4 ± 2.7 (2 – 50; n = 66)
Feed conversion ratio (kg feed/kg gained)	1.77 ± 0.11 (0.70 – 3.0; n = 67)	1.97 ± 0.03 (0.24 – 2.15; n = 299)	1.28 ± 0.04 (1.12 – 2.74; n = 173)	1.48 ± 0.04 (0.5 – 3.71; n = 173)
Farm production (t yr^{-1})	12.1 ± 1.3 (0.000005 – 131; n = 266)	472.9 ± 88.7 (0.03 – 4,021; n = 173)	5,096.7 ± 718 (0.04 – 6,000; n = 299)	1,847.6 ± 441 (0.07 – 9,400; n = 67)

Note: Values are reported as mean ± SE (minimum, maximum; number of observations/sample size.

4.6. Composition and Pollutants in Aquaculture Wastewater

Aquaculture effluents constitute a complex mixture of dissolved nutrients, suspended and settleable solids, and associated microbial and chemical contaminants derived primarily from uneaten feed and faecal matter. Its composition is strongly system-dependent, shaped by species, feed formulation, stocking density, water exchange, and hydraulic/system design (Ojewole et al., 2024). Across systems, solid fractions typically retain 10–30% of total nitrogen and 30–80% of total phosphorus, while the majority of nitrogen released from aquaculture (60–90%) occurs in dissolved form, predominantly as ammonia (NH_3/NH_4^+), with subsequent transformation to nitrite (NO_2^-) and nitrate (NO_3^-) through biological processes (Campanati et al., 2022; Kurniawan et al., 2025). Kashem et al. (2023) report that intensive land-based systems can generate high-strength effluents, with chemical oxygen demand (COD) reaching 1,201 mg L^{-1}, total ammonia nitrogen (TAN) reaching 101 mg L^{-1}, and total nitrogen (TN) reaching 359 mg L^{-1}. These dissolved nitrogenous compounds are central drivers of toxicity and eutrophication risk, with non-ionized ammonia and nitrite exerting acute physiological stress on cultured organisms even at low concentrations.

Empirical evidence further demonstrates pronounced differences in effluent characteristics among system types. RAS and raceways generate low-volume but highly concentrated wastes, with mean total suspended solids exceeding 2,700 mg/L in RAS and elevated TN and TP loads, whereas ponds and cage systems discharge much larger volumes of dilute effluents (Campanati et al., 2022; Table 2). Suspended solids, comprising fine organic particles, biofilm fragments, and sediments, are a major pollutant class that promotes pathogen proliferation and reduces system performance. In contrast, particulate phosphorus is largely bound within fecal material, whereas dissolved nitrogen predominates in the aqueous phase (Kashem et al., 2023), creating distinct recovery challenges across systems.

These contrasts have direct implications for circular-economy design. Closed and intensive systems concentrate recoverable nutrients within manageable volumes, enhancing circular recovery potential but increasing treatment complexity and risk. Such systems create discrete, high-strength streams that are amenable to engineered recovery pathways (Kashem et al., 2023), provided that both particulate and dissolved fractions are addressed. Open and semi-closed systems, on the other hand, distribute nutrients diffusely across landscapes and water bodies, heightening environmental risk while constraining interception opportunities. These findings suggest that aquaculture wastewater varies in composition. Recognizing these differences is essential for selecting appropriate CE approaches.

Table 2. Average concentrations of dissolved nutrients and solids in wastewater effluents from different aquaculture systems (*Source:* Campanati et al. 2022)

Compound	**RAS**	**Raceways**	**Ponds**	**Cages**
NO_2^- (mg/L)*	1.61 ± 0.38 (0.02 – 9.40; 39)	48.99 ± 20.76 (0.006 – 260; 19)	0.22 ± 0.05 (0.004 – 1.30; 33	0.02 ± 0.02 (0.002 – 0.06; 3)
NO_3^- (mg/L)*	41.77 ± 9.03 (0.17 – 239; 41)	33.42 ± 11.93 (0.05 – 243.5; 29)	1.38 ± 0.34 (0.04 – 9.80; 38)	0.55 ± 0.48 (0.06 – 1.99; 4)
NH_3/NH_4^+ (mg/L)*	2.24 ± 0.56 (0.05 –14.65; 41)	32.75 ± 19.83 (0.08 – 411; 25)	0.86 ± 0.13 (0.01 – 4.2; 38)	0.08 ± 0.07 (0.002 – 0.22; 3)
PO_4^{3-} (mg/L)*	7.75 ± 2.59 (0.06 – 46; 20)	29.01 ± 20.19 (0.01 – 306; 16)	0.82 ± 0.32 (0.002 – 7.4; 31)	0.09 ± 0.03 (0.002 – 0.59; 17
Total Suspended Solids (mg/L)	2747.31 ± 861.80 (1.3 – 21,390; 42)	317.79 ± 158.22 (0.92 – 3635; 23)	91.06 ± 13.72 (2.6–444.5; 38)	35.38 ± 18.90 (0.007 – 290; 15)
Organic Solids (mg/L)	296.95 ± 89 (68.5 – 500; 5)	548.00 ± 522.51 (19 – 1593; 3)	49.69 ± 14.93 (5.44 – 122.5; 10)	2.79 ± 0.80 (0.16 – 5.2; 5)
Total Nitrogen (TN) (mg/L)	229.08 ± 126.58 (0.56 – 3000; 24)	188.75 ± 125.53 (0.11–2080; 17)	4.72 ± 0.87 (0.03 – 26.5; 39)	8.14 ± 6.31 (0.12 – 57.3; 9)
Total Phosphorus (TP) (mg/L)	12.29 ± 2.83 (0.065 – 88.5; 43)	138.32 ± 88.02 (0.008 – 2405; 32)	0.71 ± 0.15 (0.002 – 7.4; 69)	3.15 ± 2.76 (0.002 – 63.7; 23)

*nitrite (NO_2^-), nitrate (NO_3^-), ammonia/ammonium (NH_3/NH_4^+), and orthophosphate (PO_4^{3-}). Values are reported as mean ± SE (minimum, maximum; number of observations/sample size.

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5. Circular Aquaculture Systems: Overview and Performance

Circular aquaculture systems represent a transformative approach to aquatic food production, efficiently converting waste streams into valuable resources while minimizing reliance on external inputs (Figure 4). Unlike conventional linear aquaculture systems, which consume large volumes of water, feed, and energy and discharge waste, circular systems intentionally integrate production, treatment, and recovery processes to minimize external inputs, reduce waste discharge, and retain water, nutrients, and biomass within system boundaries (Pawar et al., 2020; Outa et al., 2024). This holistic approach is most effectively achieved when processes, system design, and operational management are jointly optimized rather than applied as end-of-pipe or add-on treatments (Liu et al., 2021). From this perspective, four primary system typologies emerge as fundamental to circular aquaculture: IMTA, BFT, aquaponics, and RAS. While these systems vary in scale, technological complexity, and management intensity, they share a unified focus on internalizing nutrient flows, reducing environmental emissions, and facilitating the recovery of valuable resources.

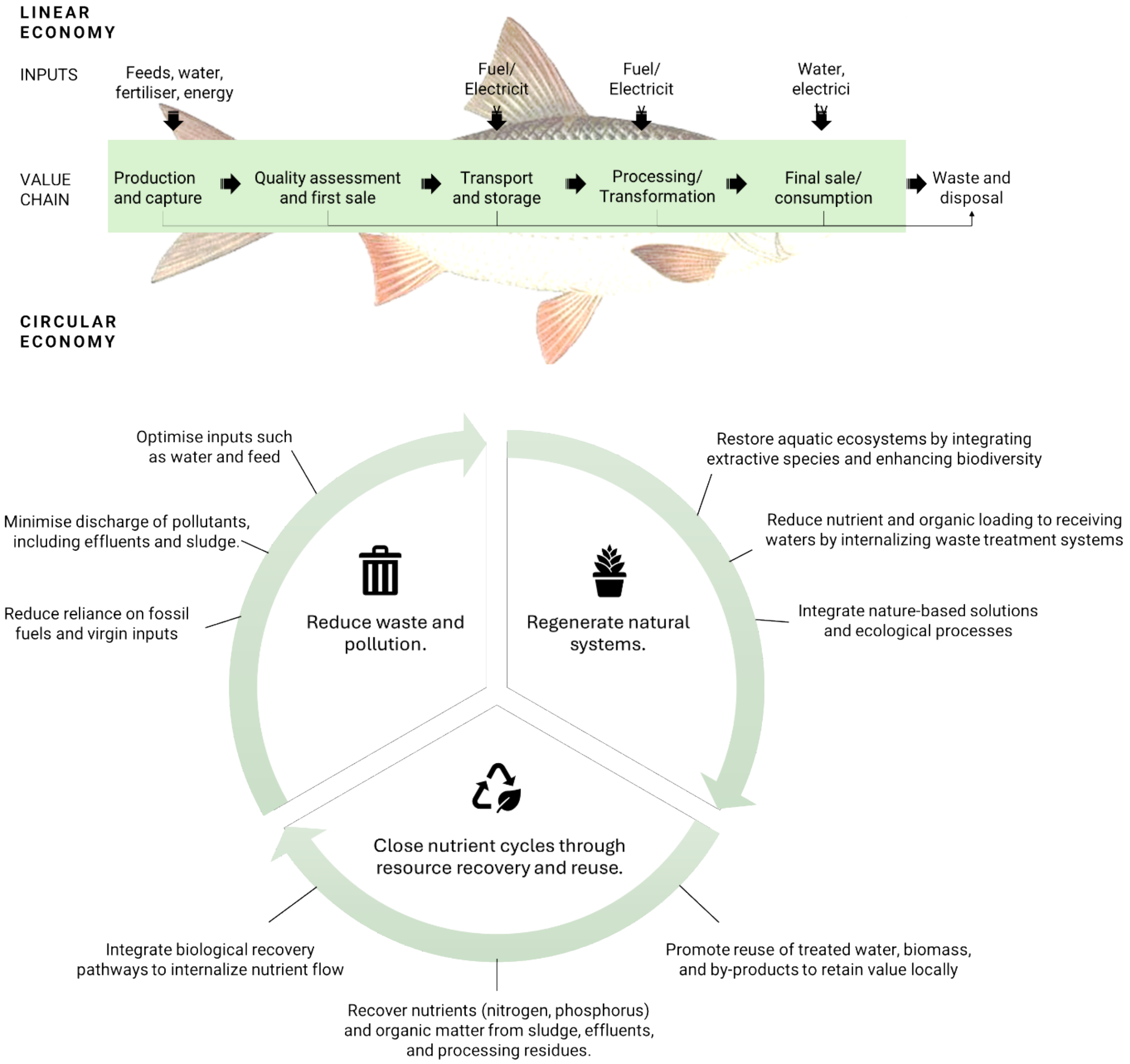

***Figure 4**. Circular economy framework applied to the fish value chain (Source: Authors' creation)*

5.1. Circular Configurations

5.1.1. Integrated multi-trophic aquaculture

IMTA systems effectively mimic natural ecosystem processes in which energy and nutrients are continuously recycled across trophic levels. Their fundamental principle is the biological recycling of nutrients, whereby the metabolic by-products of fed species (e.g., finfish or shrimp) serve as inputs for extractive organisms, such as filter-feeding invertebrates and photosynthetic organisms (e.g., seaweeds) — Figures 5 and 6. This deliberate trophic coupling (co-cultivating species from distinct trophic levels within a hydraulically connected system) transforms nutrient-rich effluents into harvestable biomass. For example, particulate organic matter, such as uneaten feed and faeces, is assimilated by suspension feeders (e.g., bivalves), whereas dissolved inorganic nutrients, particularly nitrogen and phosphorus, are taken up by macroalgae or aquatic plants. Through this trophic complementarity, IMTA reduces waste discharge, improves nutrient-use efficiency, reduces the eutrophication risk, and stabilizes water quality across the production cycle (Pawar et al., 2020). Empirical evidence from a marine IMTA trial integrating steelhead trout, mussels, and sugar kelp showed that fish released an estimated 25.1 kg N, while mussels and kelp together extracted 41.5 kg N, resulting in a net reduction of ~16.4 kg N from the surroundings and no detectable deterioration in local water quality (Chambers et al., 2024).

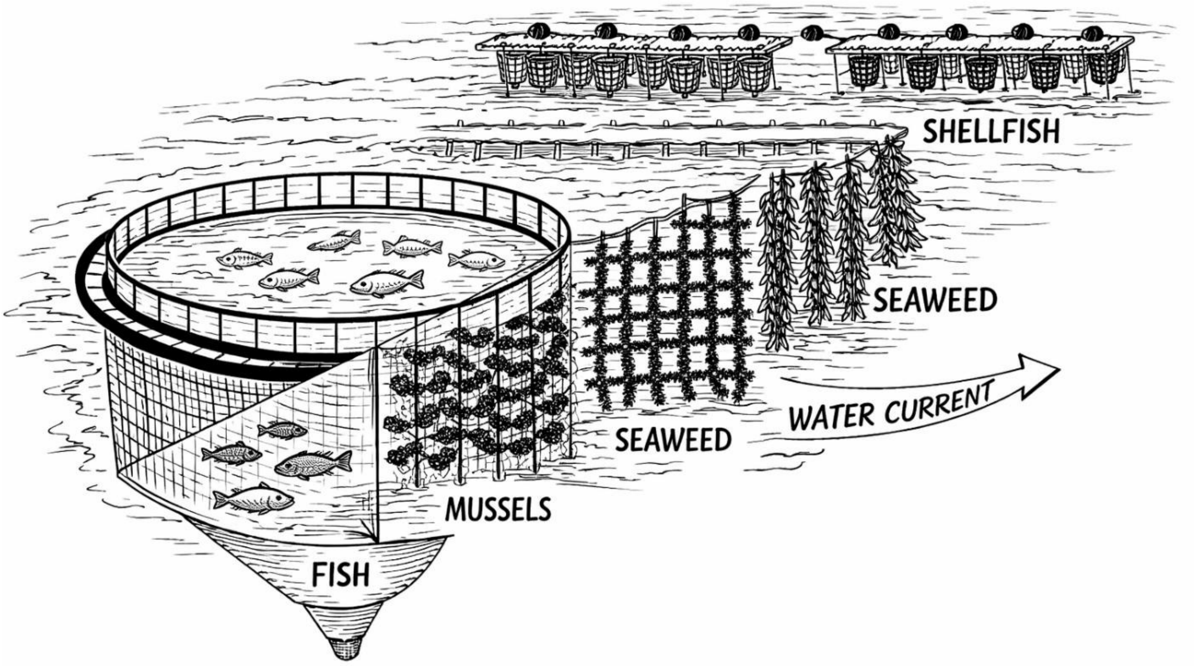

Figure 5. Schematic of an IMTA, illustrating the spatial coupling of fed species with extractive organisms along the direction of water flow (*Source:* Holdt & Edwards, 2014 modified).

The configuration of IMTA systems varies depending on environmental conditions, species selection, and production objectives. In coastal and marine environments, IMTA often integrates finfish cages with shellfish and seaweeds, while in freshwater or land-based systems, combinations may include fish, aquatic plants, and filter-feeding invertebrates. These designs enable both horizontal (across co-cultured species) and vertical integration (across trophic levels), enhancing system resilience and overall system productivity (Chambers et al., 2024). The inherent flexibility of IMTA to diverse climates, spatial constraints, and market structures supports deployment across smallholder, semi-intensive, and intensive production contexts.

Beyond nutrient recovery, IMTA improves environmental performance by intercepting solids and assimilating dissolved nutrients, thereby reducing organic loading, dampening diel fluctuations in dissolved oxygen, and limiting the accumulation of organic matter beneath culture units. Several studies have shown that IMTA systems can significantly reduce nitrogenous waste and suspended solids concentrations compared with monoculture systems, thereby reducing the risk of localized eutrophication and benthic degradation (Pawar et al., 2020). In a semi-commercial freshwater IMTA system using duckweed as an extractive component, annual nitrogen and phosphorus removal ranged from 0.77–1.7 t N yr^{-1} and 0.22–0.40 t P yr^{-1}, while maintaining good effluent water quality (Paolacci et al., 2022). These attributes are particularly salient in regions subject to tightening nutrient-emission standards and environmental compliance requirements, where IMTA offers a biologically mediated alternative to end-of-pipe treatment.

IMTA can operate in both open-water and land-based configurations and can be adapted for semi-intensive or intensive production. Its circular performance is strongly governed by balanced species ratios, appropriate hydrodynamic conditions that ensure effective waste capture, and timely biomass harvesting to maintain uptake capacity (Paolacci et al., 2022; Chambers et al., 2024; Tang et al., 2024). When well designed, IMTA systems demonstrate high nutrient recycling efficiency with low energy demand compared to engineered treatment technologies. However, their scalability is influenced by site-specific ecological conditions, regulatory constraints, and market demand for secondary species. These constraints underscore the need for context-sensitive system design and integrated planning that aligns ecological function with economic viability.

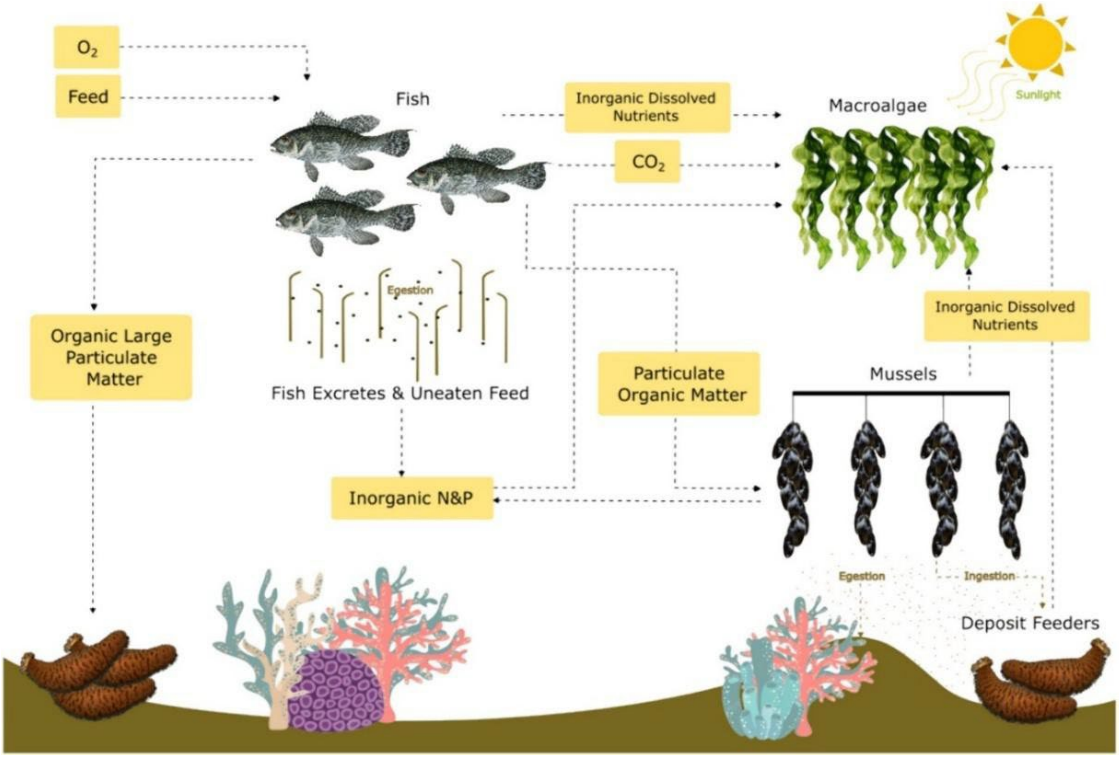

Figure 6. Nutrient exchanges within an IMTA system, consisting of primary producers (seaweeds), bivalves, deposit feeders (sea cucumbers), and fish (*Source*: Hala et al., 2024).

5.1.2. Biofloc technology

Biofloc is a microbial-driven approach in which heterotrophic and autotrophic microorganisms convert dissolved organic waste into microbial biomass within the aquaculture system. The system operates on the principle of maintaining a high carbon-to-nitrogen ratio (>10:1) in the culture water to stimulate the growth of heterotrophic microbial communities that assimilate inorganic nitrogen compounds into microbial flocs (Figure 7). These bioflocs not only improve water quality by reducing ammonia and nitrite concentrations but also serve as a supplemental protein-rich feed source for cultured organisms (Akange et al., 2024; Nisar et al., 2022). Evidence suggests that in zero-water-exchange ponds, sediments exhibited potential nitrification rates of 150–1024 ng N g^{-1} h^{-1} and denitrification rates of 48–145 ng N g^{-1} h^{-1}, demonstrating in situ capacity for microbial nitrogen transformation and removal (Niu et al., 2023). This dual function (waste treatment and biomass generation) substantially reduces water demand while preventing nutrient discharge into surrounding environments.

The operational performance of the BFT system is highly dependent on the regulation of key parameters, including carbon supplementation, dissolved oxygen, and solids concentration. Continuous aeration and mixing are essential to maintain floc suspension, oxygen availability, and microbial activity. The dense microbial aggregates formed under these conditions comprise bacteria, protozoa, algae, and detritus, collectively contributing to nutrient recycling and system stability. Through this internal “microbial loop,” waste nutrients are efficiently converted into harvestable biomass, enhancing feed conversion efficiency and reducing reliance on external feed inputs. However, imbalances in the system can lead to excessive floc accumulation, oxygen depletion, or deterioration of water quality. Despite these management challenges, BFT offers substantial environmental advantages, including reduced effluent discharge, lower water demand, and improved nitrogen retention within the system. It exemplifies closed-loop nutrient cycling by transforming waste into productive biomass and minimizing external resource inputs. Their integration into broader aquaculture systems therefore supports resource efficiency, environmental resilience, and sustainable intensification, particularly in land- and water-constrained contexts.

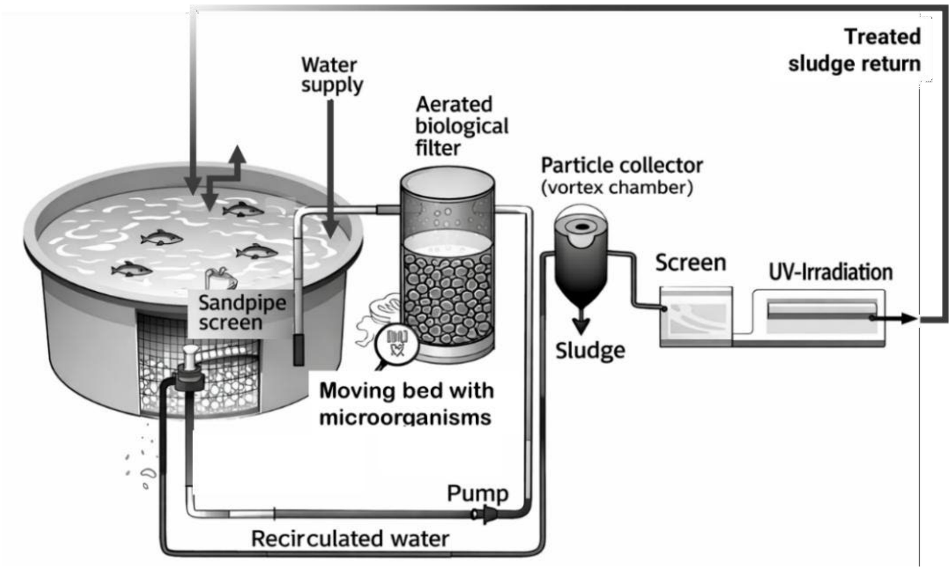

Figure 7. Schematic of a BFT system illustrating internal water recirculation, biological treatment, and solids management (*Source:* adapted from Eikebrokk & Ulgenes, 2000).

5.1.3. Aquaponics

Aquaponics integrates aquaculture and hydroponic plant production in a closed or semi-closed-loop system, in which nutrient-rich effluent from fish tanks is biologically treated and absorbed by plants (Figure 8). This system exemplifies CE by linking animal and crop production within a single water cycle. This closed-loop interaction reduces nutrient discharge, conserves water, and enhances overall system productivity (Krastanova et al., 2022; Kashem et al., 2023). Life-cycle assessments demonstrate that aquaponic systems internalize a large share of nitrogen and phosphorus that would otherwise be discharged, with nutrient releases contributing only a minor fraction of total eutrophication potential compared with conventional aquaculture–horticulture chains (Bordignon et al., 2022; Ravani et al., 2024).

The effectiveness of aquaponic systems depends on maintaining a dynamic balance between fish biomass, plant uptake capacity, and microbial activity. Nitrifying bacteria play a central role by converting ammonia excreted by fish into nitrate, which plants readily assimilate. Proper regulation of hydraulic loading rates, pH, and nutrient availability, however, is essential to sustain both aquatic life and plants. For example, empirical studies show that mismatches between fish stocking density and plant biomass lead to nutrient accumulation and water-quality deterioration. This underscores the need for proportional system sizing and operational control (Maucieri et al., 2020; Paudel, 2020). When optimally managed, aquaponic systems can achieve high water-use efficiency, often using up to 90% less water than conventional soil-based agriculture. Aquaponics also offers flexibility in system design, ranging from small-scale household units to commercial-scale installations. The integration of hydroponic crop production enhances economic viability by diversifying outputs, while reducing reliance on synthetic fertilisers. Environmental assessments further indicate that system performance is strongly shaped by the energy source, with renewable-powered aquaponics reducing greenhouse gas emissions and eutrophication impacts by 50 –86% compared with grid-powered systems (Bordignon et al., 2022; Ravani et al., 2024).

Furthermore, aquaponic systems are well-suited to urban and peri-urban settings with limited land and water resources, thereby supporting local food production and circular resource flows. Aquaponics thus embodies the principles of CE by closing nutrient loops, minimizing waste, and maximizing productivity per unit of input. However, successful implementation requires careful system balancing, technical expertise, and continuous monitoring to maintain stable biological interactions and avoid system imbalances.

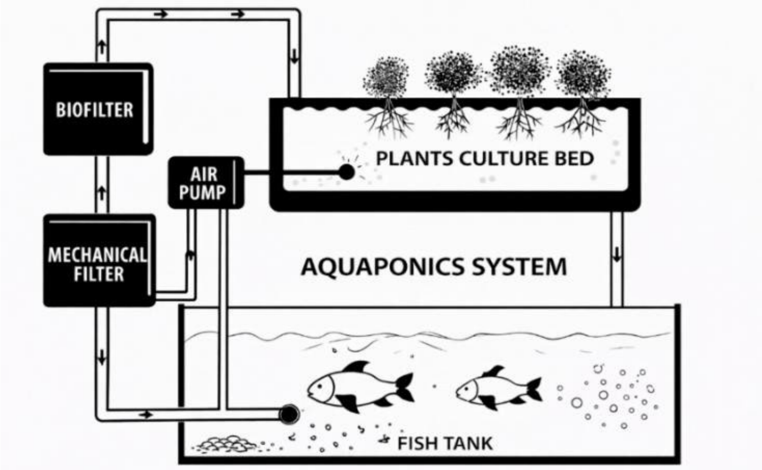

Figure 8. Schematic of an aquaponics system integrating fish production with hydroponic plant cultivation (*Source:* adapted from Oliveira et al., 2025).

5.1.4. Recirculating aquaculture systems

RASs are highly controlled, closed-loop systems that rely on a sequence of mechanical, biological, and chemical treatment processes to enable continuous water reuse (Figure 9). They represent one of the most technologically advanced forms of circular aquaculture, designed to minimize water use while maintaining high levels of environmental control. This is facilitated by a series of treatment units, including mechanical filters, biofilters, degassing units, and disinfection systems. Through these processes, waste metabolites are removed or transformed, allowing water to be recirculated with minimal replacement (Taufik et al., 2024; Shitu et al., 2022). RAS enables precise control of key environmental parameters, including temperature, dissolved oxygen, pH, and nutrient concentrations, making it suitable for high-density, high-value aquaculture operations. Biological filtration plays a central role, converting toxic ammonia excreted by fish into less harmful nitrate through nitrification. In advanced systems, denitrification units further reduce nitrate accumulation, enhancing water reuse efficiency and environmental performance (Liu et al., 2024). From a CE perspective, RAS exemplifies closed-loop resource management by decoupling production from natural water bodies and enabling nutrient recovery through integrated treatment pathways. Solid waste and nutrient-rich effluents can be separated and valorized through composting, anaerobic digestion, integration with aquaponics, or algae cultivation. Its scalability and compatibility with waste valorization technologies further strengthen its role as a cornerstone of sustainable aquaculture development. Despite its advantages, RAS is energy-intensive and capital-demanding, requiring significant investment in infrastructure, monitoring, and skilled management. Continuous pumping, aeration, and filtration make RAS highly sensitive to system failure, necessitating a reliable energy supply and skilled management. Operational complexity and system sensitivity to failures, such as biofilter disruptions or power outages, pose significant risks. As a result, their applicability in low- and middle-income settings depends on context-specific adaptations and hybridization with lower-cost treatment approaches. Nevertheless, when appropriately designed and managed, RAS offers substantial benefits, including minimal water consumption, reduced effluent discharge, enhanced biosecurity, and year-round production capability.

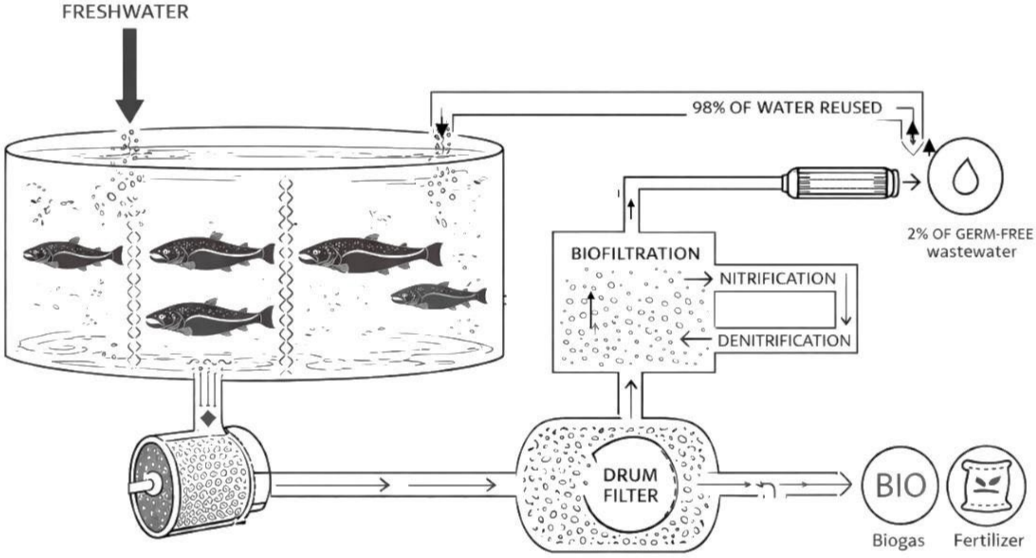

Figure 9. Schematic representation of an intensive recirculating aquaculture system (*Source:* adapted from Hoffman et al., 2021)

5.2. Measuring Circularity in Aquaculture Systems

Circularity in aquaculture cannot be captured by a single indicator; it is instead a multi-dimensional concept rooted in how effectively production systems retain, transform, and reuse resources. Conventional CE metrics, such as the Material Circularity Indicator, are poorly suited to these systems because “waste” in aquaculture is primarily expressed as nutrient loss rather than as discarded material. As a result, recent frameworks argue for farm-level, nutrient-centered indicators that track how effectively nitrogen, phosphorus, carbon, water, energy, and biomass are retained, recycled, or valorized within and across production units (Chary et al., 2024; Checa et al., 2024; Osei et al., 2023; Oca et al., 2022**)**.

One such approach, the “Integrated Aquaculture Circularity” framework, operationalizes circularity through five interlinked pillars: productivity, efficiency, recycling, self-sufficiency, and ecosystem regeneration (Checa et al., 2024; Table 3). *Productivity* is measured not only as biomass yield, but also as nutritional output per unit input. *Efficiency* indicators focus on losses, including nutrient emissions, feed conversion ratios, and mortality. *Recycling* is captured through indicators such as bioremediation efficiency, which quantify the proportion of waste nutrients captured by extractive components in integrated systems. *Self-sufficiency* is assessed via dependence on external feed, fertiliser, forage fish, and water inputs. Finally, *ecosystem regeneration* is framed as the capacity of a system to operate within ecological limits, reflected in whether nutrient imports exceed exports or local carrying capacity.

Circularity, in farm-level scale, is therefore assessed through two core pillars: (i) nutrient management, quantified using mass-balance approaches that compare nutrients excreted by cultured organisms with those retained or recovered within the system, and (ii) resource-use efficiency, captured through indicators of water reuse, feed circularity, energy intensity, and material demand. Empirical evidence shows that integrated systems like IMTA can achieve very high internal recycling, with water reuse approaching 90–100% and nutrient retention improving by 80–90% relative to linear monoculture baselines (Checa et al., 2024; Azhar and Memiş, 2023). Life Cycle Assessment complements these farm-level metrics by capturing upstream and downstream burden, particularly feed production and energy supply, translating circular practices into changes in eutrophication potential, water use, and carbon footprint (Ravani et al., 2024; Osei et al., 2023). Together, these approaches reposition circularity as a measurable farm attribute grounded in nutrient flows and resource intensity, enabling aquaculture systems to be benchmarked and compared with other production systems.

Table 3. Farm-level circularity indicators for aquaculture systems

Pillar	Criterion	Indicator	What it Measures
Productivity	Overall production	Food yield (kg m^{-3})	Biomass produced per unit volume of production containment
		Food productivity (kg m^{-3})	Biomass gain (in fresh matter) per unit volume of production containment and unit time
Efficiency	Input use efficiency	Nutrient use efficiency (%)	Mass of nutrient recovered in the targeted product per mass of nutrient supplied
		Feed Conversion Ratio (FCR)	Mass of external feed used per mass unit of food produced
	Losses	Nutrient losses (N, P) (kg kg^{-1})	Nitrogen and phosphorus emissions per unit product harvested
Recycling	Input or output recycling	Bioremediation index (%)	Fraction of C, N, P released by fed species captured by extractive components
		Share of valorized feed inputs	Proportion of feed ingredients from by-products or waste streams
Self-sufficiency	Dependence on external inputs	Nutrient self-sufficiency (%)	Percentage of nutrients (N or P) in the feed used for the fed species.
		Synthetic/fossil fertiliser dependence (%)	Mass of N or P fertiliser from fossil or synthetic sources per total mass of P or N in the inputs
		Water recirculation rate (%)	Share of water reused within the system
Resource intensity	Resource intensity	Energy per kg biomass (kWh kg^{-1})	Energy demand per unit production
		Water per kg biomass (kWh kg^{-1})	Water mass per unit biomass produced
Ecosystem regeneration	Net nutrient balance	Import/export balance (kg ha^{-1})	Whether nutrient imports exceed exports or ecological carrying capacity
	Complementarity	Extractive: fed biomass	Biomass of extractive species harvested per kg of fed species harvested

Source: Checa et al., 2024; Chary et al., 2024

6. Treatment Options in Circular Aquaculture Systems

A wide range of physical, physicochemical, biological, and hybrid wastewater treatment technologies is used across aquaculture systems to remove organic matter, nutrients, and suspended solids, enabling water reuse and resource recovery. Selection is largely determined by system scale, water-quality requirements, and resource availability.

6.1. Primary Treatment: Solids Removal and Load Reduction

Primary treatment focuses on removing suspended solids and particulate organic matter, which together constitute a major fraction of nutrient and pollutant loads in aquaculture wastewater. This reduction is necessary to protect downstream biological processes, improve water clarity, and concentrate nutrients into manageable sludge streams, particularly in open cages or poorly managed flow-through systems. The comparative roles, strengths, and limitations of these primary and secondary treatment technologies are synthesized in Table 4.

6.1.1. Physical treatment technologies

Physical treatment methods constitute the first line of intervention in aquaculture wastewater management, primarily for removing suspended solids and particulate organic matter. Common approaches include sedimentation, screening, filtration, and flotation. Sedimentation relies on gravity to remove settleable solids and is widely applied in ponds, raceways, and pre-treatment units due to its simplicity and low energy requirements (Dauda et al., 2019; Liu et al., 2024). The efficiency of sedimentation depends on particle size, density, hydraulic retention time, and water temperature, with longer retention (Lasaki et al., 2024).

Screening is also often used as a preliminary treatment to prevent clogging of downstream systems by removing large particles such as uneaten feed and faecal matter. Its performance depends on screen aperture size, flow velocity, and maintenance frequency (Akhtar et al., 2024). Filtration, using sand, gravel, or synthetic media, provides finer solids removal and improves effluent clarity. Although effective, filtration systems require periodic backwashing and energy input, which can increase operational costs (Kashem et al., 2023). Flotation techniques, including dissolved air flotation, enhance the removal of fine suspended solids by attaching air bubbles to particles, which then rise to the surface. These systems are particularly effective for high-strength effluents, such as those from RAS, although their application is constrained by higher capital and operational requirements (Jokela et al., 2001).

6.1.2. Physicochemical treatment technologies

Physicochemical treatment processes are used to improve effluent quality by removing dissolved and colloidal pollutants that cannot be eliminated through physical means alone. Coagulation–flocculation is one of the most widely applied methods, involving the addition of chemical coagulants (e.g., aluminum or iron salts) to destabilize colloids and facilitate aggregation into settleable flocs (Liu et al., 2024). While effective in reducing turbidity, phosphorus, and organic matter, this approach generates chemical sludge that requires appropriate handling and disposal. Adsorption processes using natural or waste-derived materials such as locally sourced activated carbon, biochar, sand, gravel, or modified clays have been increasingly explored for the removal of nutrients and contaminants, particularly nitrogenous compounds and trace pollutants (Foo & Hameed, 2010). These materials can be regenerated or repurposed. They can enhance microbial colonization and provide additional pathways for pollutant removal with minimal energy input. In aquaculture systems, they serve dual functions: improving water quality while generating spent materials that can be repurposed as soil amendments or as inputs for further processing. Such approaches are particularly relevant where access to conventional chemicals and advanced infrastructure is limited. Advanced oxidation processes, although less commonly used in aquaculture, are also employed to degrade refractory organic compounds and improve effluent quality when stringent treatment standards are required (Tomasi et al., 2025).

6.2. Biological Treatment and Nutrient Transformation

Biological treatment is central to most sustainable wastewater management strategies in aquaculture. These systems rely on microbial communities to transform organic matter and nutrients into less harmful or reusable forms. In biologically driven systems such as IMTA and BFT, treatment is embedded within the production system. Extractive microbial communities assimilate nutrients directly, converting waste into secondary biomass. In engineered systems, biological filters and treatment units perform similar functions under controlled conditions. The effectiveness of biological treatment depends strongly on operational parameters, including hydraulic retention time, oxygen availability, temperature, and microbial stability.

Biofiltration is central to RAS, in which nitrifying bacteria convert toxic ammonia to nitrate via nitrification (Taufik et al., 2024). Denitrification units may further reduce nitrate concentrations by converting them to nitrogen gas under anoxic conditions. Constructed wetlands are a nature-based biological treatment approach that combines physical filtration, microbial transformation, and plant uptake to remove nutrients and suspended solids. These systems are particularly effective for polishing effluents from ponds and RAS, offering low-energy treatment, enabling water reuse for aquaculture and irrigation, or safe discharge, and providing additional ecosystem services (Tom et al., 2021; Ojewole et al., 2024). While their treatment efficiency is generally lower than that of highly engineered systems, their robustness, low operating costs, and use of locally available materials make them attractive components of circular aquaculture landscapes. BFT represents an integrated biological approach in which heterotrophic microbial communities assimilate dissolved nitrogen into microbial biomass. This biomass can then serve as a supplementary protein source for cultured species, closing nutrient loops and reducing water exchange requirements (Akange et al., 2024; Nisar et al., 2022). BFT systems require precise control of carbon-to-nitrogen ratios, aeration, and mixing to maintain system stability.

6.3. Integrated and Hybrid Valorization Pathways

Modern aquaculture increasingly adopts integrated treatment systems that combine multiple physical, biological, and chemical processes to enhance treatment efficiency and resource recovery. IMTA exemplifies a hybrid approach by combining fed species with extractive organisms such as filter feeders and macroalgae, which assimilate dissolved and particulate nutrients, thereby reducing waste outputs (Chambers et al., 2024; Pawar et al., 2020).

Similarly, aquaponic systems integrate aquaculture with hydroponic plant production, enabling the direct reuse of nutrient-rich effluents for crop cultivation. Through this symbiotic relationship, fish waste is biologically transformed into plant-available nutrients, thereby improving nutrient-use efficiency, reducing effluent discharge, and enhancing overall system sustainability (Krastanova et al., 2022; Kashem et al., 2023). These closed-loop configurations exemplify circular production principles by linking waste management with food production.

Beyond biological integration, hybrid systems increasingly combine mechanical, physicochemical, and biological treatment processes to optimize performance across varying operational contexts. Mechanical filtration and sedimentation remove suspended solids, while biofiltration, constructed wetlands, and microbial processes facilitate nutrient transformation and removal. Solid residues captured through these processes can be valorized via composting, anaerobic digestion, or biochar production, while nutrient-rich effluents may be redirected to aquaponics, algal cultivation, or fertigation systems, extending circularity beyond the aquaculture unit itself. The effectiveness of integrated and hybrid treatment pathways depends on system scale, species composition, waste characteristics, and local resource availability. Closed and semi-closed systems, particularly RAS, offer high levels of control and efficiency but require greater technical capacity and capital investment. In contrast, hybrid configurations that combine conventional aquaculture with nature-based treatment units offer flexible, lower-cost solutions suitable for diverse socio-environmental contexts. Collectively, these integrated approaches demonstrate strong potential to transform aquaculture from a linear, waste-generating activity into a circular production system that enhances resource efficiency and long-term sustainability. Table 5 summarizes key circular aquaculture systems as functional treatment units, highlighting their targeted contaminants, typical applications, and key advantages and constraints.

photo: Tom Fisk/Pexels

7. Conclusions and Future Work

A comparative analysis of aquaculture systems reveals that each model differs in circular performance, reflecting distinct strategies for resource use and efficiency. Results indicate that biological systems such as IMTA and BFT perform best at nutrient recycling and with low external inputs but are sensitive to ecological imbalances. Technologically intensive systems such as RAS offer high control and scalability within a controlled environment, albeit at higher energy and capital costs. Aquaponics performs moderately across all criteria, with strengths in integrated food production and water reuse, but with limitations in system balance and large-scale economic viability. Hybrid configurations and modular integration of treatment and valorization options, therefore, represent a critical direction for advancing scalable and inclusive circular aquaculture solutions. Additionally, the review of low-cost treatment strategies and technologies indicates their practical viability for adoption. No single treatment option optimizes all dimensions of circularity. Highly engineered systems offer high treatment efficiency and reuse potential but are constrained by cost, energy demand, and operational complexity. Low-cost, nature-based systems are more accessible and resilient but require larger land areas and longer treatment times. Circular aquaculture, therefore, benefits from context-specific treatment trains that combine technologies to balance performance, affordability, and scalability. Despite growing interest in circular and sustainable aquaculture, the review identified several critical gaps that constrain the sector's prompt transition from linear to circular production models. Existing studies have largely focused on system performance and pollutant removal, with limited integration of resource recovery efficiency, energy optimization, and life-cycle assessment, including the cost implications of the locally available materials and nature-based treatment mechanisms. Further operational optimization studies are needed to clarify how key parameters, including hydraulic retention time, loading rates, microbial dynamics, and sludge characteristics, influence nutrient recovery and system stability across different aquaculture configurations. Continued innovation in low-cost and hybrid treatment approaches, including the use of locally available substrates, biochar-based filters, and nature-based systems, remains critical, alongside the evaluation of their long-term performance and maintenance requirements. Furthermore, the scalability and techno-economic feasibility of circular strategies such as biofloc integration, sludge valorization, and nutrient recycling remain underexplored.

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Appendix A.

Table A.1. Typical Wastewater Composition across Different Aquaculture Systems

Aquaculture System	Type	Concentration Range	References
Cage & pen-based	Intensive cage, rainbow trout (during culture)	Temp: 13.0–14.0 °C; DO: 8.62–9.52 mg L^{-1}; TSS: 3.0–4.5 mg L^{-1}; COD: 4.1–6.0 mg L^{-1}; TP: 0.007–0.014 mg L^{-1}; TN: 0.48–1.02 mg L^{-1}; NH_4–N: 0.029–0.045 mg L^{-1}; NO_3–N: 0.133–0.185 mg L^{-1}; CHL-a: 3.02–6.22 µg L^{-1}; trace metals (As, Co, Cu, Fe, Mg, Pb, Zn)	Varol, 2019
	Intensive cage, rainbow trout (post-harvest)	Temp: 28.4–29.4 °C; DO: 7.68–8.15 mg L^{-1}; TSS: 0.1–0.7 mg L^{-1}; COD: 4.3–5.0 mg L^{-1}; TP: 0.010–0.022 mg L^{-1}; TN: 0.47–0.62 mg L^{-1}; NH_4–N: 0.015–0.023 mg L^{-1}; NO_3–N: 0.019–0.028 mg L^{-1}; CHL-a: 1.04-2.00 µg L^{-1}; trace metals (As, Co, Cu, Fe, Mg, Pb, Zn)	Varol, 2019
	Cone-shaped marine cage, salmon fry	Inorganic P: 22 ppb; TN: 69.5 ppb; NH_3: 103.7 ppb; NO_2: 26.9 ppb; NO_3: 6 ppb; BOD: 679 mg L^{-1}; silica: 1,424 ppb; phytoplankton: 3.5×10^{7}–1.1×10^{8} ind. m^{-3}; zooplankton: 4.4×103–17.1×104 ind. m^{-3}	Azizpour et al., 2025
Pond	(zero-exchange, polyculture) e.g. grass carp, crucian carp, bighead carp	pH: 8.08-8.88; Temp: 23.41–31.31 °C; NH_4^+: 0.33–0.79 mg L^{-1}; TN: 4.99–5.45 mg L^{-1}; TP: 0.07–0.42 mg L^{-1}; PO_4^{3-}: 0.01–0.05 mg L^{-1}; NO_3–N: 1.32–3.89 mg L^{-1}; NO_2–N: 0.22–0.48 mg L^{-1}; DO: 2.61–4.44 mg L^{-1}; pH: 8.08–8.88; TSS: 228–6,329 mg L^{-1}; COD: 56–60 mg L^{-1}; TDS: 593–680 mg L^{-1}; CHL-a: 0.14-0.19 µg L^{-1}	Niu et al., 2023
Pond (intensive)	Nile tilapia	pH: 6.79–6.96; Temp: 23.7–25.5 °C; NH_3–N: 0.55–2.00 mg L^{-1}; TN: 2.08–5.10 mg L^{-1}; TP: 0.26–0.59 mg L^{-1}; COD: 19–54 mg L^{-1}; BOD: 7–24 mg L^{-1}; DO: 6.36–7.38 mg L^{-1}; TDS: 22.5–40.0 mg L^{-1}; EC (µ.s/cm): 8.25-82.50	Coldebella et al., 2018
Pond (intensive)	Yellow catfish	pH: 8.08; Temp: 28.28 °C; Turbidity: 136.6 NTU; COD: 507 mg L^{-1}; TN: 87.1 mg L^{-1}; NH_3–N: 4.54 mg L^{-1}; NO_3–N: 0.76 mg L^{-1}; NO_2–N: 1.30 mg L^{-1}; TP: 0.24 mg L^{-1}; Dissolved inorganic P: 0.013 mg L^{-1}; K: 0.52mg L^{-1}; Phytoplankton: 5.13–37.25 mg L^{-1}	Li et al., 2019
Pond (intensive)	Freshwater shrimps	pH: 8.50; Temp: 28.61 °C; Turbidity: 39.9 NTU; COD: 345.5 mg L^{-1}; TN: 54.5 mg L^{-1}; NH_3–N: 2.70 mg L^{-1}; NO_3–N: 0.34 mg L^{-1}; NO_2–N: 0.84 mg L^{-1}; TP: 0.04 mg L^{-1}; Dissolved inorganic P: 0.007 mg L^{-1}; K: 0.22 mg L^{-1}; Phytoplankton: 4.25–6.32 mg L^{-1}	Li et al., 2019
Flow-through / Raceway	Rainbow trout	pH: 5.9–9.4; DO: 5.4–14.3 mg L^{-1}; TSS: 1–97 mg L^{-1}; TOC: 0.1–4.0 mg L^{-1}; TAN: 0.02–1.52 mg L^{-1}; NO_3–N: 0.1–2.5 mg L^{-1}; TP: 0.01–1.09 mg L^{-1}	Stewart et al., 2006
Integrated (aquaponics)	Nile tilapia + lettuce (56 days at 150 fish m^{-3})	Temp: 23.6 °C; DO: 5.35 mg L^{-1}; pH: 7.60; NO_3–N: 1.11 mg L^{-1}; TAN: 5.24 mg L^{-1}; hardness: 185 mg L^{-1}	Ani et al., 2022
Integrated (rice–fishpond)	Yellow catfish /shrimp + rice	Temp: ~28 °C; COD: 340–418 mg L^{-1}; TN: 48–51 mg L^{-1}; NH_3–N: 0.84–2.26 mg L^{-1}; NO_3–N: 0.22–0.31 mg L^{-1}; TP: 0.04–0.30 mg L^{-1}; pH: 7.7–8.1; Turbidity (mg/L): 29–42	Li et al., 2019
Recirculating (RAS)	Rainbow trout	Temp: 7–21 °C; pH: 5.9–9.2; TAN: 0.1–0.63 mg L^{-1}; NO_3^-: 2–135 mg L^{-1}; DO: 1.82–7.5 mg L^{-1}; NH_4^+–N: 0.1–0.63 mg L^{-1}; alkalinity: 35–43 mg $CaCO_3$ L^{-1}; TDS: 250–410 mg L^{-1}; salinity: 0.20–0.3 PSU; conductivity: 412–632 µS cm^{-1}; TP: <0.1 mg L^{-1}	Pepe-Victoriano et al., 2025

Units and parameters: pH (–); dissolved inorganic nitrogen species (nitrate–N (NO_3^-–N), nitrite–N (NO_2^-–N), and ammonia/ammonium–N (NH_3/NH_4^+–N), phosphate (PO_4^{3-}–P), total nitrogen (TN), total phosphorus (TP), dissolved oxygen (DO), and chemical oxygen demand (COD) in mg L^{-1}; turbidity in nephelometric turbidity units (NTU); and salinity in parts per thousand (PPT).

Table A.2. Characteristics and composition of aquaculture wastewater across species and culture types (Kashem et al., 2023)

Fish type	pH	NO3−–N (mg/L)	NO2−–N (mg/L)	NH4+–N (mg/L)	PO43−–P (mg/L)	TN (mg/L)	TP (mg/L)	DO (mg/L)	COD (mg/L)	Turbidity (NTU)	Salinity (PPT)
Tilapia	6.5–8.27	0.389–40.67	5.52	1.06–5.3	8.82	10.8–51.51	0.909–8.82	4.17	65–96	8.7	0.26–6
Southern flounder	7.7–8.1	–	0.03–0.04	0.2–0.4	–	–	–	6.5–8.2	2.1–4.1	1.2–1.6	–
Pike perch	7.05–7.5	–	–	7.4–9.6	3.3–5.0	24.1–34.1	3.5–6.1	–	153–273	–	–
Catfish	6.68–7.5	2.5–11.9	–	0.08–24.5	0.07–4.8	23.7–29.2	3.6–5.7	4.17–6.3	12.6–256	307	–
Salmon	7.98–8.54	–	–	–	–	31.83	1.1	–	–	–	10
Shrimp	7–8.2	0.499	0.108	0.14–0.28	–	210	85–176.4	5.3	18.3–1730	29.4	22–23
Eel	6.3–7.8	17	0.05–0.21	1.6–4.62	3.6–5.4	12.4	3.64–5.4	–	48–155	0.41–44.5	–
Crucian carp	–	–	–	72	–	47.6	–	–	368	–	–
Rainbow trout	7–7.6	0.38–14	0.3	0.27–2.06	0.54–5.45	1.18	0.19–7.6	–	17.6–74	–	–
Yellow catfish	–	0.51	0.134	2.35	–	3.6	0.23	2.45	66.6	–	–
Mixed culture	6.72–8.04	0.38–30.17	0.17–30	0.63–9.7	0.93–34	1.09	0.07–32.5	3.82–3.84	204–206	67.2–76.2	44
Whitefish	7.39–7.49	96.87–97.03	0.03–0.05	0.03–0.05	3.76–3.83	–	–	–	–	1.33–5.27	–

Table A.3. Commonly used technologies for aquaculture wastewater treatment, with operational conditions and performance metrics (Kurniawan et al. 2025)

Type of treatment	Treatment unit	Operational conditions	Removal performance
Physical	Filter (*Crassostrea rhizophorae; C. gigas*)	HRT: 6 h; Volume: 50 L	Turbidity 62.1%; TSS 70.6%; TVS 36.1%; BOD 17.5%
Physical	Filter (sand & anthracite)	HRT: 80 min; Filtration rate: 12 m^3 h^{-1}	Turbidity 92%
Physical	Filter (*Saccostrea commercialis*)	HRT: 24 h; Volume: 10 L	TSS 12%; TN 28%; TP 14%; NH_4^+ 76%; NO_3^- 30%; PO_4^{3-} 35%
Physical	Membrane filter	Length 60 mm; Diameter 10 mm; Area 0.11 m^2; Pressure 0.4 MPa	Turbidity 99.2%
Physical	Sedimentation tank	HRT: 6 h; Volume: 90 L	Turbidity 18%; TSS 5.6%; TVS 27.5%; BOD 23.2%
Physical	Sedimentation tank	Flow rate: 2.49 m^3 h^{-1}	Turbidity 27%
Biological	Anaerobic sequencing batch reactor	HRT: 20 d; Volume: 4 L	COD 97%; TSS 96%; TVS 91%
Biological	Column photobioreactor	HRT: 7 d	TN 90%; TP 90%
Biological	Tubular photobioreactor (*Tetraselmis suecica*)	HRT: 15 d; Volume: 4 L	TN 49%; TP 99%
Biological	Upflow anaerobic sludge blanket	Volume: 12 m^3; Rate: 45 m^3 h^{-1}	Solids 80%
Biological	Constructed wetland (multiple macrophytes)	HRT: 14 d; Volume: 15 L	NH_3–N ≤98%; TSS ≤90%; PO_4^{3-} ≤64%
Biological	Constructed wetland (*Ipomoea asarifolia*)	HRT: 28 d	NH_3–N 85%; TSS 73%; PO_4^{3-} 53%
Biological	Constructed wetland (*Azolla pinnata*)	HRT: 14 d; Volume: 10 L	NH_3–N 78%; PO_4^{3-} 79%
Physicochemical	Adsorption	Dosage 3.5 g; HRT 45 min; Mixing 150 rpm	Turbidity 91.4%; TSS 89.1%
Physicochemical	Advanced oxidation (Fenton)	–	Antibiotics 89%

Units and measures: hydraulic retention time (HRT; hour (h) or day (d)), volume (L or m^3), flow/filtration rate (m^3 h^{-1}), membrane dimensions (mm, m^2), pressure (MPa), adsorbent dose (g), and mixing speed (rpm). Removal performance is reported as percentage (%) reduction of turbidity, solids (TSS, TVS), organic load (BOD, COD), nutrients (TN, TP, NH_3–N, NO_3^-, PO_4^{3-}), and antibiotics.

Table A.4. Overview of key treatment technologies, targeted contaminants and applications in aquaculture wastewater treatment.

S/N	Treatment method	Contaminants targeted	Typical applications	Pros	Cons	References
1	Sedimentation/ Settling ponds	Suspended solids, sludge particles	Primary treatment; pond effluent; pre-treatment in RAS	Simple to operate; low-cost; effective at removing large particles	Inability to remove fine particles; cannot remove dissolved organic matter; requires frequent sludge removal	Dauda et al., 2019; Nájera et al., 2021; Liu et al., 2024
2	Biofiltration (nitrification/ denitrification)	Nitrogen (ammonia, nitrite, nitrate)	RAS biofilters; polishing units; wetlands	Effective for nitrogen removal; supports biological stability in closed systems	Requires careful DO/carbon balance; risk of nitrite accumulation; sensitive to hydraulic and temperature shocks	Nájera et al., 2021; Pepe-Victoriano et al., 2025
3	Constructed wetlands	Nitrogen (ammonia, nitrite, nitrate)	Effluent polishing (flow-through systems or pond discharge)	Nature-based; cost-effective; facilitates nutrient recovery and ecosystem services	Large land requirement; seasonal variation in treatment efficiency	Kurzbaum, 2022; Biswal & Balasubramanian, 2022; Karungamye, 2024
4	Ion exchange / Adsorption (e.g., biochar)	Nitrogen (ammonia, nitrite, nitrate)	Ammonia/nitrate removal in closed-loop systems	Fast and selective removal; media reusable; spent biochar applicable for soil conditioning	Media exhaustion; requires regeneration or replacement	Mutegoa, 2024
5	Biofloc technology (BFT)	BOD, COD, dissolved nitrogen	Pond and tank systems	Converts waste nutrients into microbial protein; improves feed efficiency; reduces water exchange	Requires continuous aeration and monitoring; risk of system instability	Liu et al., 2021
6	Chemical coagulation / Electrocoagulation	Phosphorus, suspended solids	RAS side-stream polishing; pond discharge	Effective phosphorus removal; simultaneous solid capture	Secondary waste generation; requires energy or chemicals for post-sludge handling	Laktuka et al., 2023; Soliman et al., 2025; Yu et al., 2023; Khanjani et al., 2023; Tomasi et al., 2025; Shah et al., 2024
7	UV disinfection / Ozonation	Pathogens (bacteria, viruses, parasites)	RAS effluent disinfection; reuse systems	Effective microbial inactivation; rapid treatment	High energy demand; residual toxicity risk (ozone); no nutrient removal	Zhang et al., 2023

Table A.5. Circular aquaculture systems as treatment units with targeted contaminants, applications, key advantages and limitations

S/N	Treatment Method	Contaminants Targeted	Typical Applications	Pros	Cons	References
1	Recirculating Aquaculture Systems (RAS) – Mechanical filtration, Biofiltration, UV/Ozonation	Suspended solids; organic matter; ammonia, nitrite, nitrate; pathogens	Intensive fish production with internal water reuse in tanks and raceways	High water-use efficiency; stable and controllable water quality; reduces waste discharge; enables high stocking densities; supports integration with advanced treatment units	High capital and operational costs; energy-intensive (aeration, pumping, UV); requires skilled management; critical sludge handling; system failure risk under power or biofilter shocks	Outa et al., 2024; Liu et al., 2024; Nájera et al., 2021; Zhang et al., 2023
2	Aquaponics	Dissolved nitrogen (ammonium, nitrate); dissolved phosphorus; organic matter	Coupled fish tanks and plant beds for integrated fish–vegetable production	Mimics ecological cycles; converts nitrogen and phosphorus into plant biomass; >90% water reuse; reduces effluent discharge; dual outputs (fish and vegetables); nutrient recycling into food and fertiliser	Sensitive to water-quality imbalance; requires constant pH and nutrient monitoring; dependent on plant uptake capacity; limited scalability for large effluent loads	Tom et al., 2021; Ani et al., 2022; Krastanova et al., 2022
3	Integrated Multi-Trophic Aquaculture (IMTA)	Organic matter (particulates for detritivores/bivalves); dissolved inorganic nitrogen (macroalgae/seaweeds); phosphorus (algal uptake)	Coastal and pond-based polyculture (fish/shrimp with shellfish and seaweed)	Ecosystem-based nutrient recycling; valorises waste into additional crops (shellfish, seaweed); improves environmental sustainability; high social acceptance as a “green” system	Best suited for coastal or large pond settings; space-demanding; limited control over environmental factors (salinity, temperature); complex species management; low applicability in closed RAS facilities	Checa et al., 2024; Chambers et al., 2024; Chary et al., 2024

Table A.6. Comparative Assessment of Circular Aquaculture Systems

S/N	Criteria	Indicators	Aquaculture systems			
			IMTA	**RAS**	**BFT**	**Aquaponics**
1.	**Resource Efficiency**	Water reuse	**Moderate:** Shared water column sustains multiple species; minimal replacement; self-cleaning, no dilution flushing.	**High:** 90–99% water reuse via continuous recirculation	**High:** Near-zero exchange; minor additions for evaporation.	**Moderate:** Effluent reused for plants; losses via evaporation/transpiration (~90%).
		Water recirculation	**75-100% (for a short period)**	**90–99%**	**90–99%**	**90%.**
		Energy-friendly design	**High:** ~0.25 kWh/kg; ecological processes reduce aeration/mixing.	**Low:** ~9.6 kWh/kg; ~664 MWh/15 weeks; pumping, aeration, filtration.	**Moderate** ~114.6 MJ/kg (≈31.8 kWh/kg); aeration for biofloc.	**Low- Moderate** 44.7–454 kWh/kg; pumping & automation-driven.
		References	Chary *et al*., 2025; Hala et al., 2024; Loayza-Aguilar et al., 2023; Checa et al., 2024	Ayuso-virgili et al., 2023	Ogello *et al*., 2021; Checa et al., 2024	Ibrahim *et al*., 2023; Bordignon et al., 2022b; Arbour et al.,2024; Ravani et al 2024
		Scoring Matrix	**7**	**6**	**7**	**6**
2.	Nutrient and Waste Management	Nutrient recycling efficiency	**High** Multi-trophic uptake enables nutrient recycling	**Moderate** Limited biomass conversion without add-on treatment.	**High** Waste converted to biofloc feed.	**Moderate – High** Design and crop dependent.
		Pollution reduction	**High** Extractive species reduce discharge.	**High** Near-zero exchange with treatment units.	**High** Minimal/zero exchange; in-system reuse.	**High** Plant uptake; sensitive to imbalance.
		By-product utilization	**High** Sediments/sludge valorised.	**High** Solids & effluent for AD, compost, algae, biochar.	**High** Biofloc feed; sludge is processable.	**High** Marketable plant biomass is produced from the system

		References	Checa *et al*., 2024; Paolacci et al., 2022	Yogev *et al*., 2020; Soliman et al., 2025	Akange *et al*., 2024; Soliman et al., 2025; Raza et al., 2024	Krastanova *et al*., 2023; Kurniawan et al., 2025; Ani et al., 2022
		Scoring Matrix	**8**	**7**	**8**	**7**
3.	System Resilience	Sensitivity to system failure	**Moderate-High**.	**High**	**High**	**Moderate -High**
			Design/operation-sensitive; requires monitoring.	Strong control; high risk if unstable.	Microbial dependence; rapid collapse on disturbance.	Deviation in water quality destabilises the system
		Disease management capacity	**Moderate**	**High**	**Moderate-High**	**Moderate**
			Inter-species coupling can introduce operational complexity when failures occur.	Effective if only well managed.	High Instability raises risk.	Different optimal conditions for fish and the plants could complicate disease control.
		Scalability	**Moderate**	**High**	**Moderate**	**Low-Moderate**
			Site-specific, regulatory and complexity limits.	Modular, compact, high-density; capital/energy constraints.	Compact; energy and skill-intensive.	Compact; energy and skill-intensive.
		References	Tang *et al*., 2024; Alam et al., 2024	Brown *et al*., 2024	Yu *et al*., 2023; Raza *et al*., 2024; Khanjani et al.,2024	Ibrahim *et al*., 2023; Chandramenon et al., 2024; Raulier et al., 2023
		Scoring Matrix	6	8	7	6

Scoring Matrix: Very Low =1, Low =2, Moderately good = 3, High =4. CED- cumulative energy demand

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Contact
Susanne Bodach, Research Group Leader - Integrated Circular Economy Transformations, IWMI, Colombo, Sri Lanka
(S.Bodach@cgiar.org)

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