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Creating circular pathways for nutrients in aquaculture using biochar

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ABSTRACT

Global food production drives planetary-boundary transgressions, including nitrogen and phosphorus cycle disruption, land use change, and climate change. Increasing nutrient circularity can improve sustainability. This study explores an integrated approach that combines a recirculating aquaculture system (RAS) with biochar from forestry-residue pyrolysis to improve process-level nutrient retention while producing carbon-rich biochar with potential for soil-carbon storage upon land application. In RAS, biochar acts as a filter, capturing nutrients and transforming waste into nutrient-enriched biochar for agriculture. Substance Flow Analysis shows that integration increases nitrogen retention from 30.6 % to 44.6 % and phosphorus retention from 25.5 % to 99.6 % versus separate RAS and pyrolysis. This demonstrates the potential of linking aquaculture, forestry, and agriculture with biochar to support more circular and sustainable food production. This early-stage study examines how and to what extent the approach influences nutrient flows under different assumptions and evaluates a simple recovery-efficiency indicator for assessing circularity in integrated systems.

1. Introduction and problem statement

Aquaculture has emerged as one of the fastest-growing food sectors and, as a result, there is growing interest in understanding its environmental impacts and its potential to contribute to establishing sustainable food systems (Cao et al., 2021; Crona et al., 2023; Edwards et al., 2019; Farmery et al., 2017; Ha, 2024; Hua et al., 2019; Morales-Nin et al., 2024; Reid et al., 2019; Stentiford et al., 2020; Troell et al., 2019). Recirculating aquaculture systems (RAS) are land-based fish-farming systems in which water is continuously treated and reused to minimise intake and discharge. Solid wastes are mechanically removed (e.g., drum/microscreen filters), dissolved wastes are biologically transformed (nitrification/denitrification) or otherwise managed, and CO_2 is controlled via degassing and pH/alkalinity management. RAS benefits include reduced water use, improved waste management, enhanced biosecurity, and the potential for lower environmental impacts – although aspects such as energy efficiency and economic viability are still maturing (Ahmed and Turchini, 2021; Badiola et al., 2018; Bergman et al., 2020; Kucuk et al., 2010; Li et al., 2023; Qiu et al., 2022; Stentiford et al., 2020).

Biochar, a stable form of carbon produced through biomass pyrolysis under low-oxygen conditions, is increasingly recognised for its potential in carbon sequestration, soil amendment, water purification, and as a tool in integrated agricultural and aquacultural systems (Allohverdi et al., 2021; Azzi et al., 2021; Taslakyan et al., 2023; Xiang et al., 2022; Yuan et al., 2022). By storing carbon for hundreds to thousands of years, biochar can help mitigate climate change (Jung et al., 2019). Biochar properties depend on various factors, including feedstock type and pyrolysis conditions (Kwapinski et al., 2010).

Regarding water purification, biochar has received attention as a multifunctional material within aquaculture systems, primarily for its ability to improve water quality through adsorption of pollutants, nutrients, and organic matter (Bare et al., 2023; Paul and Hall, 2021; Yadav et al., 2023). Previous studies have demonstrated biochar's efficacy as a filtration medium for nitrogenous wastes (ammonia, nitrite, nitrate) and phosphorus (Bare et al., 2023; Paul and Hall, 2021), and heavy metals and organic contaminants (Bare et al., 2023; Yadav et al., 2023), as well as its role as a dietary additive to enhance fish health and growth performance (Wong et al., 2024). Biochar has also been integrated into aquaponic systems, effectively linking aquaculture with agriculture to

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improve nutrient cycling and sustainability (Emily et al., 2023; Khiari et al., 2020). Despite this progress, system-level quantitative analyses of integrated nutrient flows and recovery efficiencies remain limited.

In this study, we explore the use of biochar to enhance nutrient circularity and manage carbon, nitrogen, and phosphorus flows in a combined aquaculture–agriculture system. By capturing dissolved and particulate nutrients in RAS using biochar derived from forestry residues, and directing the nutrient-enriched biochar into agriculture, we seek to reduce dependence on synthetic fertilisers. The primary idea is to capture reactive nitrogen on a carrier that can function as a growth substrate for plants or a soil conditioner before it is transformed into nitrogen gas and released to the environment – which is typically the case in conventional RAS.

Circularity indicators have historically emphasized product-level circularity (reuse, recycling rates, end-of-life), often through material reuse, recycling rates, and end-of-life management (Lavallais and Dunn, 2023; Linder et al., 2017; Moraga et al., 2019; Saidani et al., 2019). More recently, process-level indicators have been proposed to quantify circularity within production or operational stages (Harder et al., 2021a, 2021b; Loon et al., 2023). Here, we adopt a process-oriented perspective, as our primary focus is on nutrient fate and recovery within the system rather than on the technologies or solutions, such as nutrient-enriched biochar, as (potential) products. Our approach aligns with the goal of exploring how biochar functions in capturing and retaining aquaculture nutrients, emphasizing process-level nutrient retention rather than the end-use applications of biochar (Tanzer and Rechberger, 2020).

Apart from exploring the technological concept, we also seek to contribute to methodological aspects of assessing resource circularity in multi-sector systems at low Technology Readiness Levels (TRLs), where data are limited. We assess nitrogen, phosphorus, and carbon flows under different assumptions, reflected in scenario analysis, using Substance Flow Analysis (SFA) on a conceptual design of the system that is informed by laboratory and limited pilot-scale trials, literature, and databases. Our objective is to quantify process-level nutrient circularity in a biochar-enhanced RAS using SFA and a simple recovery-efficiency indicator. The goal is to support the development of more sustainable waste-management and food-production strategies, facilitating a more circular economy for an integrated aquaculture-agriculture system in Sweden and beyond.

2. Materials and methods

We explored the integration of RAS with biochar produced from pyrolysis of forestry biomass, targeting the creation of nutrient-enriched biochar for agricultural applications. After making some basic assumptions about the technologies considered and their context, we built a first-order conceptual design of the technical system using laboratory data, limited pilot trials, literature, and databases and used Substance Flow Analysis (SFA) (Tanzer and Rechberger, 2020) to quantify nutrient retention and reuse.

2.1. Description of the technologies studied

2.1.1. Pyrolysis

Information and data on the pyrolysis process was gathered via personal communication with Hjelmsäter farm, near Lidköping, Sweden. The farm has a pyrolysis plant of the brand Biomacon, one of the major actors in this sector in Sweden. In their process, chipped forestry residues from spruce – a dominant tree species constituting around 40 % of Swedish forests (Fridman et al., 2014) – are subjected to pyrolysis at temperatures between 700 °C and 750 °C, yielding biochar, gas, and ash. Apart from its relative abundance in Sweden, initial laboratory tests indicated that spruce-derived biochar offers sufficient sorption capacity for NH_3/NH_4^+. Under these high-temperature conditions, a mass yield of 17 wt % biochar (dry content) was considered; 81 % of the dry content forms gas, and 2 % becomes ash.

Data on the properties of the resulting biochar and ash were obtained from the Eurofins laboratories. All calculations in this study use dry-basis values provided by Eurofins. Based on the measured nitrogen (N), phosphorus (P) and carbon (C) contents in biochar and ash, we calculated the gas-phase content, using mass balance relationships. The shares of spruce N, P, and C across biochar, ash, and gas flows after pyrolysis are summarised in Table 1.

2.1.2. Recirculating aquaculture system (RAS)

The RAS modelled in this study is based on a RAS that was owned and operated by Pond Fish and Greens in Floda near Göteborg, Sweden, and produced African catfish (*Clarias gariepinus*). This species needs warm water, approximately 27 °C. In this RAS a drum filter and a moving bed biofilm reactor (MBBR) were employed to treat the fish wastewater.

Nutrient input from fish feed is characterised by specific N, P, and C contents. The nutrients are distributed within the system in i) fish biomass, ii) dissolved nutrients – primarily ammonia and phosphate, iii) particulate nutrients that are incorporated into sludge and, iv) gas emissions of CO_2 released from fish respiration, see Table 2.

2.2. System integration approach - basic assumptions and design rationale

Biochar was integrated into the RAS as a filtration medium. Before the integration of biochar into aquaculture, the useful outputs from the separate systems are fish from RAS and biochar from pyrolysis. In the combined RAS with biochar system, the useful outputs are fish and nutrient-enriched biochar. To explore the different levels of recovery that can be achieved, we explore scenarios where nutrient-enriched biochar is mixed with RAS sludge and/or ash from the pyrolysis.

Based on early results from the Swedish research project Nutribatt that has designed and tested biochar filters in RAS producing the omnivorous fish species *Clarias* and the use of the resulting enriched biochar in pot trials, we made the following assumptions and considerations:

- **Biochar filter.** We treat 100 % NH_4^+–N capture as an upper bound case over $a \le 7$-day media service life, with a 1.5 sizing safety factor to limit breakthrough. We distinguish capacity (c), a material property measured under laboratory conditions (g NH_4^+ kg^{-1} biochar), from retention efficiency (η), a system-level performance metric defined as the cycle-average fraction of dissolved NH_4–N actually retained in operation (accounting for bypass, breakthrough, biofilm-mediated transformation, and desorption). Prior work on assessing the environmental performance of this biochar–RAS system explored system sensitivity to c (Behjat et al., 2025). Here, we complement this analysis by employing a simple relationship for the sensitivity for η, quantifying its influence on process-level nutrient retention of dissolved NH_4–N (see Section 3.2).
- **Drum filter & sludge.** The drum filter operates as usual (in conventional RAS) and generates sludge before the water reaches the biochar. This sludge is either released to the sewage treatment

Table 1
Yield of pyrolysis and share of nitrogen (N), phosphorus (P) and carbon (C) in the different input and output flows. Source: Biomacon. Values are on dry basis; rounded to two significant figures.

	Pyrolysis yield (wt% of dry biomass)	N content (wt% of flow)	P content (wt% of flow)	C content (wt% of flow)
Dry biomass feedstock	-	0.25	0.050	51
Biochar	17	0.49	0.060	92
Gas	81	0.21	0.00	44
Ash	2.0	0.00	1.8	0.00

Table 2
Share (% by mass) of nitrogen (N), phosphorus (P) and carbon (C) in the RAS inputs and outputs (Timmons and Vinci, 2022).

Parameter	N	P	C	Units
Fish feed content	7 %	1 %	43 %	% of feed
Fish biomass build-up (ingested and assimilated)	18 %	50 %	22 %	% in feed
Dissolved emissions (excreted metabolites and organics)	73 %	30 %	1 %	% in feed
Particulate emissions (feces, uneaten feed, fines)	10 %	20 %	25 %	% in feed
Respiratory emissions (CO_2)			52 %	% in feed

system (current practice at the small fish farm) or considered to be mixed with the enriched biochar to test its effect on recovery. We are aware that mixing might be problematic because of the smell of the fish sludge but still want to understand the effect on the nutrient circularity if this becomes integrated into a product.

- **Biochar source.** Biochar is produced from spruce wood chips from forestry residues. Lab tests in the project indicated superior nutrient-capturing properties in fish water for spruce-derived biochar compared to biochar from agricultural residues.
- **Accounting conventions.** We assume all dissolved N and P, and particulate N, P and C from the RAS are either captured on the biochar or mechanically separated in the drum filter and, in some configurations, later mixed with the biochar. CO_2 from fish respiration and other dissolved inorganic carbon are controlled by standard RAS operations (degassing/aeration and alkalinity-pH management) and are treated as losses. Without these controls, dissolved CO_2 would build up, lower pH, and cause hypercarbia, impairing gas exchange and risking fish stress or mortality. We distinguish between i) nutrients sorbed from water onto the biochar filter during the service cycle as "removed from water" from ii) the total N, P, and C in solid outputs leaving the aquaculture unit for reuse (biochar and ash, with or without mixed-in sludge) as "retained on solids".

In brief, the design rationale followed a sequential approach:

a) **Production target:** We dimensioned the system to produce 10 tonnes of fish biomass annually. This target sets the baseline for subsequent calculations, including daily biomass gain and nutrient flows within the system.
b) **Fish production and feed input:** Daily biomass gain by the fish is approximately 27.4 kg, requiring 47 kg of feed per day, based on a Feed Conversion Ratio (FCR) of 1.2 and a 70 % feed assimilation (personal communication with Pond Fish and Greens AB). Average concentrations of N, P, and C in fish feed are provided in Table 2.
c) **Biochar requirements:** We determined daily biochar needs based on ammonium (NH_3/NH_4^+) sorption capacity and desired nutrient removal efficiency. For our calculations, we used a literature-derived sorption capacity for ammonium (NH_4^+) of 0.42 % per biochar weight (Weldon et al., 2022). Various factors, including feedstock type and pyrolysis temperature, affect the sorption capacity of ammonia. However, due to the exploratory nature of this study, selecting a representative value from literature was considered adequate, and the implications of this choice are later discussed. We estimated the daily required amount of biochar to maintain water quality at 1094 kg biochar/day, including a 1.5 factor to account for potential inefficiencies in nutrient removal since fish health must not be jeopardised.
d) **Substance Flow Analysis (SFA):** We modelled nutrient distribution and capture in the pyrolysis process and the RAS, comparing integrated system configurations (RAS + biochar) against separate RAS and pyrolysis configurations.

Given the explorative nature of the study aims, we did not optimise engineering aspects such as system scaling or configuration for either the RAS or the pyrolysis units (separate or integrated).

Figs. 1 and 2 illustrate the separate and integrated systems, respectively. Fig. 1 presents RAS and pyrolysis as standalone processes. Based on personal communication with Swedish practitioners involved in the project, we know that RAS sludge from smaller facilities is treated in the municipal sewerage system with only a minor share potentially coming to use in cultivation and that forest ash from pyrolysis is typically returned to the forest, but at unspecified times and locations. Thus, in the separated-systems case, we treated sludge and ash as dissipative losses: flows to sinks or to stocks that are not accessible to future users due to various constraints (Beylot et al., 2020). N removal from conventional RAS, typically performed via a bioreactor, is also a dissipative loss because N_2 gas escapes to the atmosphere. Note that the system is "separated" in the sense that pyrolysis and aquaculture are not yet connected, but that there may exist other connections between different parts of the system on a higher system level, which are shown as potential synergies in Fig. 1. Note that the larger system in Fig. 1 is not complete in the sense that only the core processes of interest in this study are shown; for example, there may be other processes providing parts of the feed for the fish farm.

Fig. 2 shows a general overview of the integrated scenario, which potentially prevents major nutrient losses, ensuring accessibility of nutrients to future users. Furthermore, enriched biochar functions as a replacement for synthetic fertilisers and forms a pathway that connects forestry, aquaculture, and agriculture (and any other system involved in feed production). Note that in the integrated scenario, ash and sludge may either follow the same pathways as in the separated scenario (Fig. 1) or be combined with nutrient-enriched biochar to enhance nutrient content for agricultural use; different configurations are explored in this study. In both scenarios, fish respiration remains a loss pathway.

2.3. *Substance flow analysis (SFA) for N, P and C in separated and integrated systems*

We employed SFA to assess the flows of N, P, and C in the separated system as well as in the integrated system. The separated system was evaluated to establish a baseline for comparison. The SFA model quantified the movement of these elements from forestry to agriculture through fish farming, thereby facilitating a comprehensive assessment of nutrient recycling or circularity.

2.3.1. *Assessing circularity*

To assess the potential for nutrient circularity, we adopted a straightforward Recovery Efficiency (RE) approach, defined here as the ratio of nutrients retained within the system to the total nutrient inputs. Specifically, we track N, P, and C flows, calculating RE_N, RE_P, and RE_C. In addition, we estimate a combined $N + P$ recovery efficiency (RE_{N+P}), inspired by prior frameworks that assess nutrient fluxes in aggregate (Preisner et al., 2022), to explore whether the RE_{N+P} metric offers a simplified overview of how effectively these two key nutrients are possible to circulate in our system.

The concept of RE is rooted in classical thermodynamics, drawing parallels with Carnot's efficiency, which describes the theoretical limits of energy conversion within a system (Carnot, 1872). Just as Carnot's efficiency sets an upper bound for the conversion of heat into work, RE provides a simple measure of how effectively nutrient inputs are retained and utilised within a given system, rather than being discarded/dissipated as waste. This efficiency-based perspective has been widely applied in agriculture and environmental sciences to assess nutrient utilization, such as studies on nitrogen use efficiency and recovery efficiency in crop production (Conant et al., 2013; Zhang et al., 2015).

The scope of the process-level RE indicator is to quantify flows within

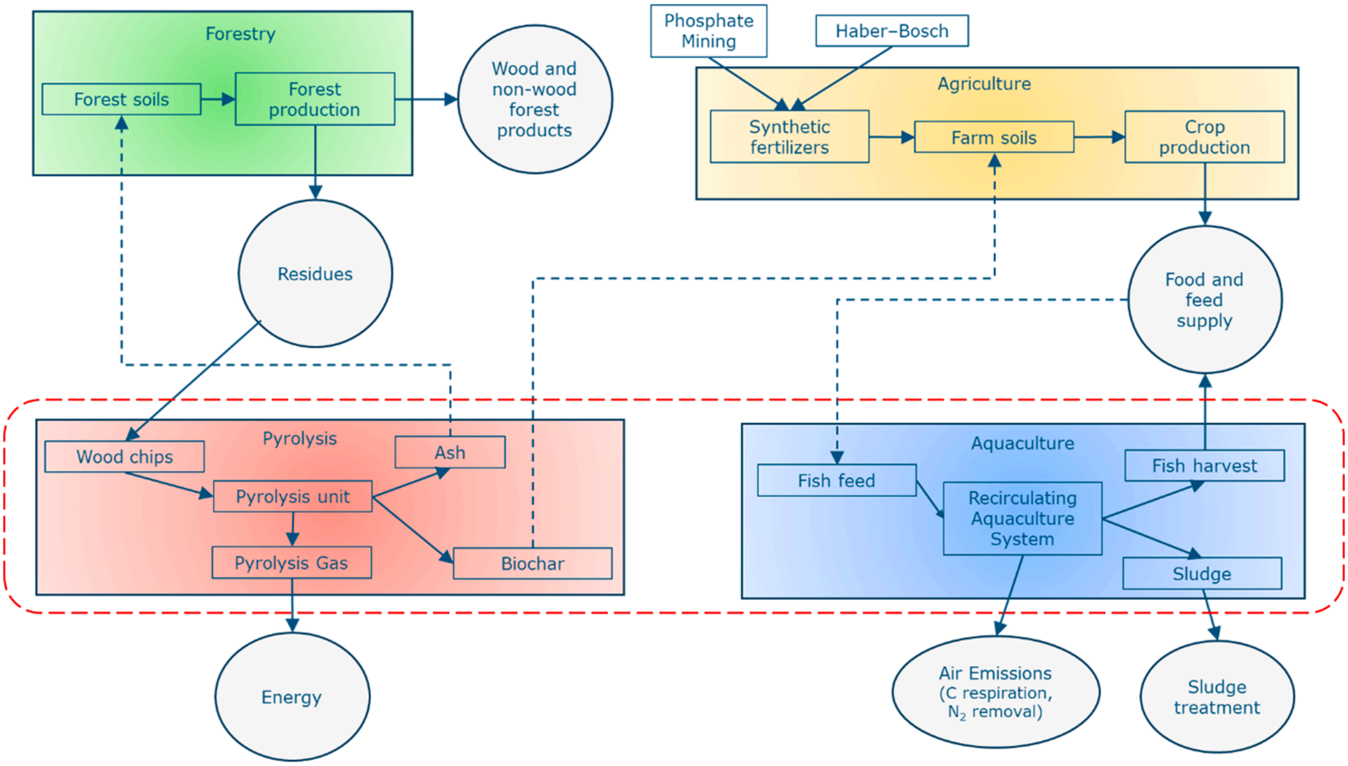

Fig. 1. Processes within the separated system and the synergies among them. Solid arrows indicate established flows, while dashed arrows depict potential synergies. The red dashed line denotes the boundary of our SFA model.

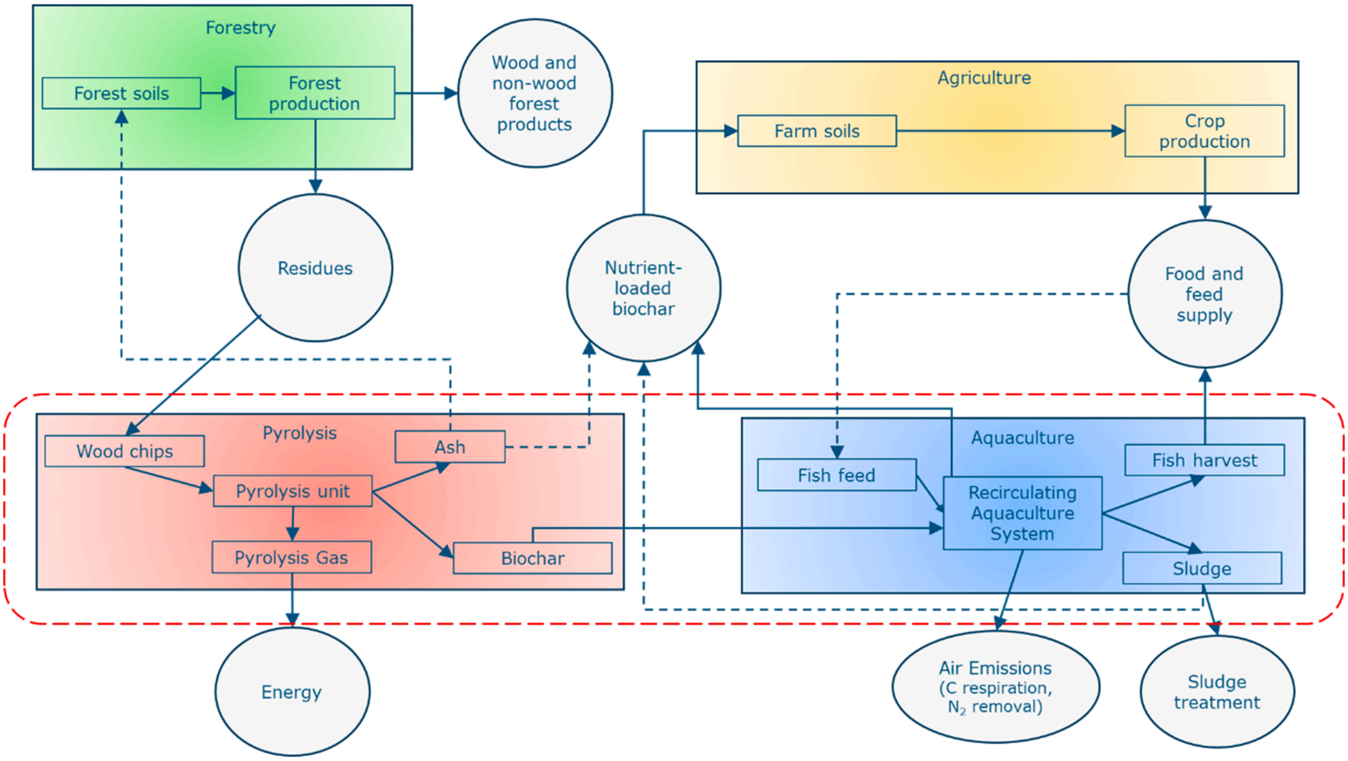

Fig. 2. Processes and synergies in the integrated system. Solid arrows represent established flows, whereas dashed arrows indicate potential synergies. The red dashed line denotes the boundary of our SFA model.

the aquaculture unit (dissolved nutrients retained on biochar and nutrients present in solids). Product-/crop-level nutrient use efficiency is not assessed, and sector-level reuse in agriculture is treated qualitatively to avoid scale conflation.

2.3.2. System boundary

The definition of system boundaries significantly influences circularity assessments, as what is included or excluded affects the interpretation of results (Tillman et al., 1994). The process investigated in this study is the circulation and potential reuse of N, P, and C within an integrated pyrolysis-RAS system. To maintain a process-oriented perspective, we focus on nutrient movement within the system to understand the extent to which nutrients are retained or lost through different output streams. Upstream inputs, such as fish feed production, and potential downstream applications of nutrient-enriched biochar as a marketable product, are excluded from our system boundaries as they fall beyond the scope of this study.

By adopting this process-based indicator, we highlight the potential recycling pathways within our system where forestry residues and fish feed enter and residual streams can either be reused or discarded (and consequently allowed to be dissipated), yielding a practical measure of how much of the total nutrient input is captured under the integrated biochar and RAS configuration (more details about the calculation of the RE are reported in the SM).

3. Results

3.1. Substance flows in RAS and in integrated system configurations

Table 3 summarises the nutrient flows related to pyrolysis and RAS processes. The values reported in the table refer to one day of activity when 27 kg of fish biomass is generated per day.

Daily, the RAS receives 3.29 kg N, 0.47 kg P, and 19.96 kg C in feed. These partition into fish biomass (0.58 kg N, 0.23 kg P, 4.39 kg C), dissolved excrement (2.38 kg N, 0.14 kg P, 0.20 kg C), particulate excrement (0.33 kg N, 0.09 kg P, 4.99 kg C), and respiratory CO_2 (10.38 kg C). For the daily pyrolysis flows, pyrolyzing the spruce residues that supply the filter media yields biochar containing 5.36 kg N, 0.65 kg P, 1007 kg C, gas containing 10.74 kg N and 2277 kg C, and ash containing 2.36 kg P. In the full integration (biochar + ash + sludge), the N retained on solids equals $N_{biochar}$ (5.36) + $N_{dissolved,captured}$ (2.38) + $N_{particulate}$ (0.33) ≈ 8.07 kg N d^{-1} (≈2.95 t N y^{-1}). For P, $P_{biochar}$ (0.65) + $P_{dissolved, captured}$ (0.14) + $P_{particulate}$ (0.09) + P_{ash} (2.36) ≈ 3.24 kg P d^{-1} (≈1.18 t P y^{-1}).

In the integrated configuration, nutrients retained on solids of agronomic interest (biochar/sludge/ash) are about 8.07 kg of N and 3.24 kg of P per day, or 2.95 tonnes of N and 1.18 tonnes of P per year. Of these, the portion removed from water on the biochar filter is up to 2.38 kg N and 0.14 kg P per day. The remainder comes from the inherent contents of the biochar/ash feedstock and, where applicable, mixed-in sludge. For agronomic realism, we note that only a fraction of P in ash and N in biochar is directly available to plants, and we accordingly interpret RE as process-level retention. For C, the agronomic solids carry 1012 kg C d^{-1} (1007 kg d^{-1} is inherent in biochar and 4.99 kg d^{-1} from sludge). Dissolved C is not captured by biochar. Fish biomass (4.39 kg C d^{-1}) is counted in RE but is not an agronomic carrier. In the full integration case, 66 % of the N retained on solids of agronomic interest is inherent in biochar (5.36/8.07 kg d^{-1}), 29 % is dissolved N captured on biochar (2.38/8.07 kg d^{-1}), and 4 % is particulate N in sludge (0.33/8.07 kg d^{-1}). For P, 73 % of the mass retained comes via the ash (2.36/3.24 kg d^{-1}), 20 % is inherent in biochar (0.65/3.24 kg d^{-1}), 4 % is dissolved P captured on the biochar (0.14/3.24 kg d^{-1}), and 3 % is particulate P in sludge (0.09/3.24 kg d^{-1}). For C, 99.5 % is inherent in biochar (1007/1012 kg d^{-1}) and 0.5 % is in sludge (4.99/1012 kg d^{-1}).

Table 3
Daily dry-basis flows of nitrogen (N), phosphorus (P), and carbon (C) in pyrolysis and RAS inputs/outputs for the separated system. N and P are rounded to two decimals and C is rounded to nearest kg Displayed sums may differ slightly due to rounding. Mass-balance closure is verified on unrounded values (see SI).

RAS		N	P	C	Units
Input	Fish feed	3.29	0.47	19.96	kg/day
Output	Fish biomass	0.58	0.23	4.39	kg/day
	Dissolved excretion	2.38	0.14	0.20	kg/day
	Particulate excretion	0.33	0.09	4.99	kg/day
	Respiratory excretion			10.38	kg/day
Pyrolysis		**N**	**P**	**C**	**Units**
Input	Forestry biomass	16.10	3.01	3283	kg/day
Output	Biochar	5.36	0.65	1007	kg/day
	Gas	10.74		2277	kg/day
	Ash		2.36		kg/day

These splits clarify the drivers seen in Figs. 3a–c. N recovery is dominated by biochar (with a small sludge contribution), whereas P recovery hinges on ash reuse. Fish biomass gets 0.58 kg N d^{-1}, 0.23 kg P d^{-1}, and 4.39 kg C d^{-1}, which is included in RE accounting but is not part of the carriers of agronomic interest. Figs. 3a–c compare nutrient distributions across integrated configurations of the RAS-biochar system (biochar alone and biochar combined with fish sludge and/or pyrolysis ash). Each panel reports the corresponding RE in the lower-left corner. More details regarding the RE results are presented in Section 3.2 below. Fig. 3a demonstrates that the N flows in fish farming are small compared to what is inherent in the biochar, but the amount redirected to agriculture through integration represents a major portion of the N in fish feed. Adding fish sludge slightly enhances this opportunity (compare the left and right panels). For P (Fig. 3b), much of the biomass P partitions to ash during pyrolysis, which we count as dissipated in configurations without agronomic ash reuse. Less than half of the fish feed P is retained in the fish, while dissolved P is captured by the biochar. Adding fish sludge further improves P retention slightly. For C (Fig. 3c), as with N, a large portion of biomass C goes to air during pyrolysis, while the remaining fraction is retained in the biochar. In fish farming, about half of fish feed C is lost to air through fish respiration and the rest is evenly distributed between fish and sludge. Additionally, dissolved carbon in fish water (effluent) is not retained in the biochar and returns to the RAS, where it is removed through processes such as water exchange, pH control, and CO_2 stripping.

We benchmarked the integrated RAS-biochar system against separate RAS and pyrolysis operations to evaluate gains from system integration. Table 4 reports REs for N, P and C across configurations, highlighting the circularity benefits of integration and how individual side-stream reuse affects the RE.

To make the efficiency assumption transparent, we separate N-recovery into two parts: i) the portion that depends on the biochar filtration, $\eta \times L$, where L is the daily dissolved NH_4^+ load that reaches the biochar filter, and ii) other N that does not depend on η (denoted as B), such as N already present in the biochar from pyrolysis feedstock and any particulate N retained in sludge. With D the total daily N input to the integrated system, the RE is:

$$REN(\eta) = \frac{B + \eta \cdot L}{D}$$

Thus, RE_N varies linearly with η with slope L/D. Moving from η_1 to η_2 shifts RE_N by:

$$\Delta RE_N = (\eta_2 - \eta_1) \cdot \left(\frac{L}{D}\right)$$

Using our loads ($L = 2.4$ kg N d^{-1} and $D = 19.4$ kg N d^{-1}), increasing η from 0.60 to 1.00 raises RE_N by 0.40 × (2.4/19.4) ≈ 0.05, i.e., about five percentage points (from ~38 % for η=0.60 to 42.9 % for η=1.00). This scales the magnitude of RE_N but does not change which streams drive nutrient recovery.

For the integrated RAS and biochar system, dissolved and particulate

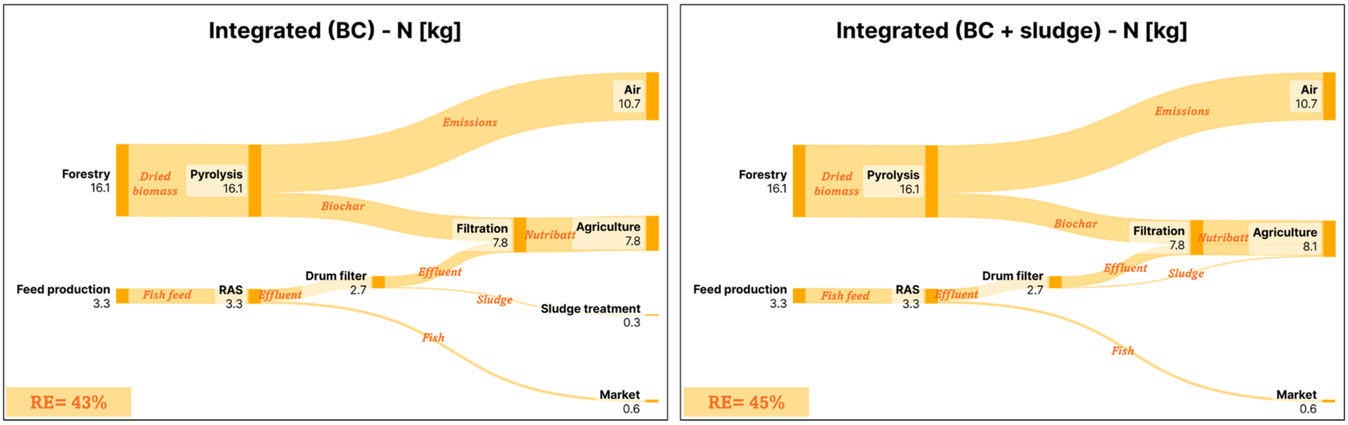

Fig. 3a. Nitrogen flow analysis results for the integrated systems when only biochar (in the left) and when both biochar and sludge (in the right) are used as supplements for soil in agriculture.

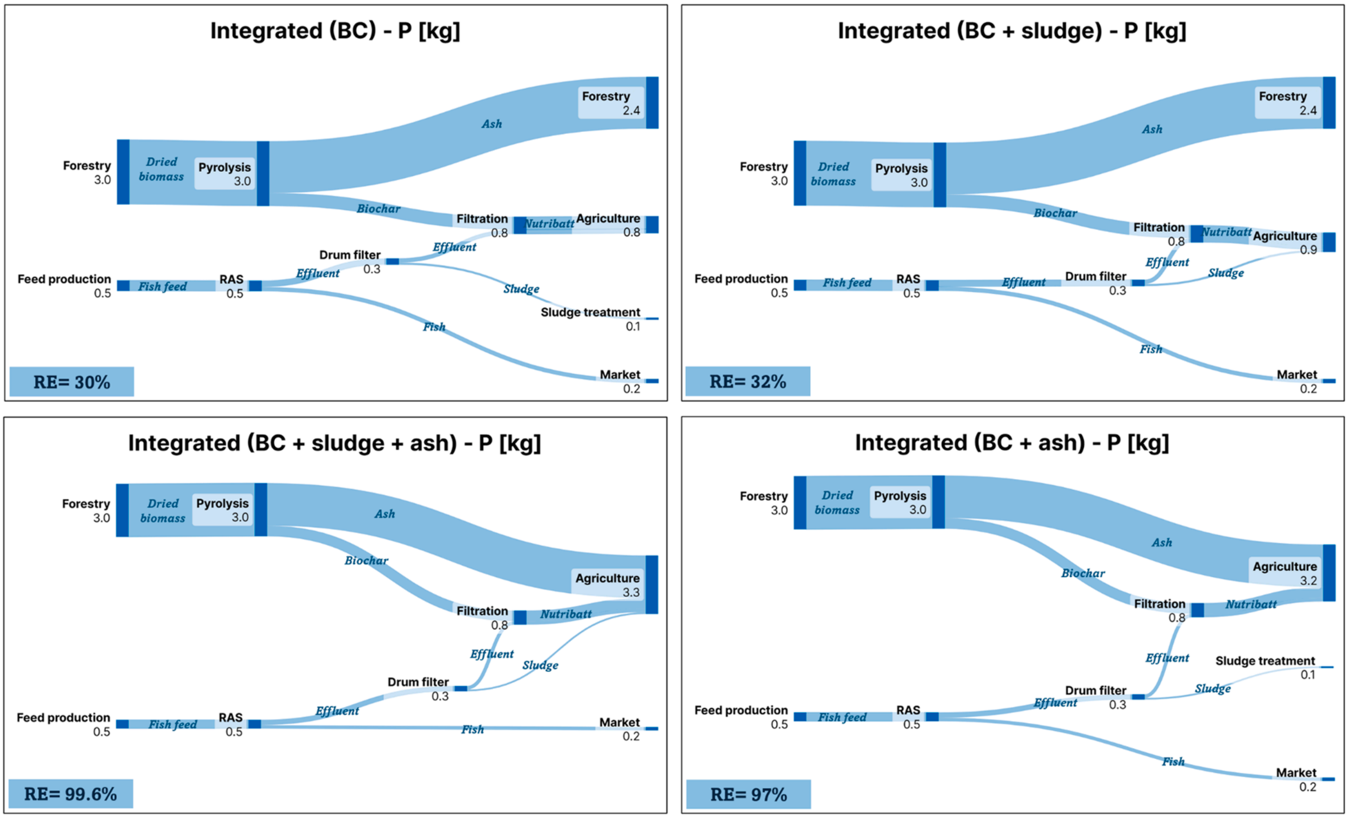

Fig. 3b. Phosphorus flow analysis results for the four configurations of the integrated system: only biochar (BC); biochar and sludge (BC+sludge); biochar, sludge, and ash (BC+sludge+ash); and biochar and ash (BC+ash) ending up in agriculture. In the two integrated systems, BC+sludge and BC+sludge+ash, the ash not used in agriculture is considered dissipated in forestry.

nutrients from the RAS and the ash from pyrolysis are captured and retained, increasing RE compared to separate setups. More specifically, integration raises RE_N from 30.6 % (separate) to 42.9 % with biochar only (Scenario 2) and to 44.6 % when sludge is also reused (Scenarios 4–5). RE_P increases from 25.5 % (separate) to 96.9 % with ash reuse (Scenario 3) and to 99.6 % in the full-reuse case (Scenario 5). This stepwise change clarifies drivers: the main recovery pathway for N is biochar sorption, while for P the main pathway is via mixing in the pyrolysis ash. In the separated system, dissolved N in the RAS is removed from the system via a biofilter, such as a moving bed bioreactor, and is ultimately emitted to the air as N_2 gas. Consequently, all integrated scenarios retain more N.

RE_C remains practically constant (~30.6–30.8 %) throughout all the scenarios. In the RE accounting, C in the pyrolysis gas is treated as “lost” in the sense that it does not remain sequestered in biochar. However, this gas is not simply discarded. Most pyrolysis processes use it as a fuel to generate heat or power, thereby offsetting external energy inputs. In practice, this gas is typically combusted for heat/power in all systems and configurations, but this energy use is not credited in the RE metric. By convention, CO_2 from biogenic gas is often treated as carbon neutral. However, biogenic “carbon-neutrality” is contingent on regrowth and timing: combustion adds CO_2 immediately, while uptake occurs over years to decades; any credit allocated would therefore depend on explicit time horizons and verified regrowth.

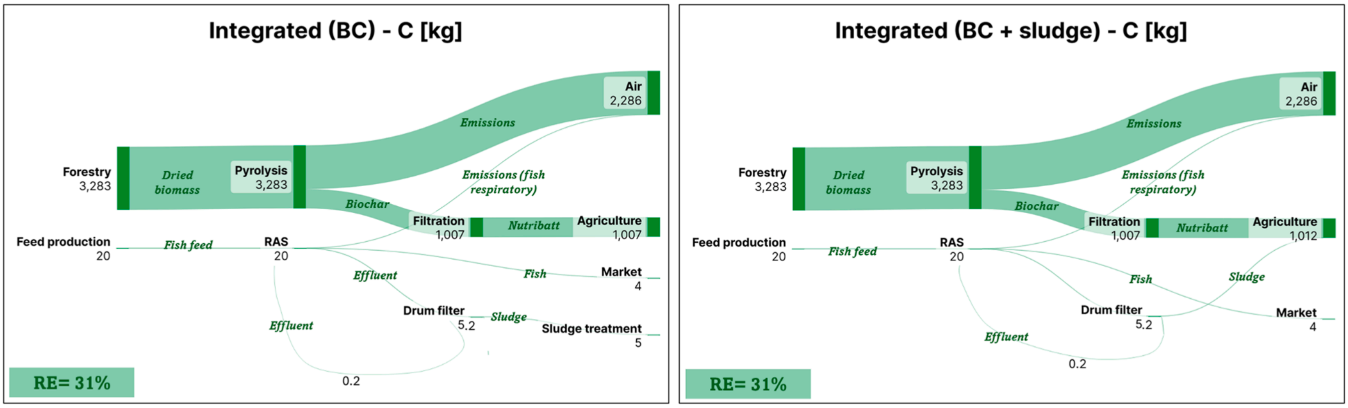

Fig. 3c. Carbon flow analysis results for the integrated system when only biochar (left) and when both biochar and sludge (right) are used as soil supplements in agriculture. The carbon dissolved in the fish water (effluent) is not retained in the biochar and it returns to the RAS. Recovery efficiency (RE) and beyond.

Table 4

Recovery efficiencies for stepwise integration of waste streams, starting from the separated system. For η=0.60→1.00, RE_N increases by 4.95 percentage points, from ∼38 % for η=0.60 to 42.9 % for η=1.00.

Scenario	RE_N	RE_P	RE_C	RE_{N+P}	Explanation
1. Separated System	30.6 %	25.5 %	30.6 %	29.9 %	Sludge and ash are both discarded/dissipative losses.
2. Biochar Only (No Ash / No Sludge)	42.9 %	29.5 %	30.6 %	40.9 %	Biochar in RAS captures dissolved nutrients; sludge and ash remain wasted.
3. Biochar + Ash (No Sludge)	42.9 %	96.9 %	30.6 %	51.2 %	Ash reuse boosts P recovery. N unchanged since sludge is still lost and ash contains no N.
4. Biochar + Sludge (No Ash)	44.6 %	32.2 %	30.8 %	42.7 %	Sludge stream reused with biochar
5. Biochar + Ash + Sludge (Full)	44.6 %	99.6 %	30.8 %	53.0 %	All side-streams reused: Dissolved fraction is captured by biochar and then, the nutrient-enriched biochar is mixed with the ash from the pyrolysis and the RAS sludge.

The aggregated RE_{N+P}, the fraction of the nitrogen and phosphorus in the input that was captured, highlights an overall upward trajectory in nutrient recovery, going from 29.9 % in the separated system to 53.0 % in the fully integrated one, illustrating the cumulative impact of capturing each stream. Consequently, these intermediate steps provide insight into which flows (ash, sludge, or dissolved fraction) dominate N vs. P recovery, and how selectively reusing any subset of those flows can shape the system's circularity.

4. Discussion

Building on the SFA, we first interpret how integrating pyrolysis with RAS diverts N and P from dissipative pathways into recoverable solids within the unit boundary, and we analyze these nutrient gains as the joint effect of a biochar property (uptake capacity, *c*) and a system property (retention efficiency, η). We then assess the use of our simple, process-level indicator at low TRL in avoiding scale conflation while boundaries and data are still forming. Next, we scale the results to place them in context (media turnover, biomass supply, and heat co-products) to identify deployment needs. We then translate these technical aspects into potential implementation pathways, contrasting RAS-led versus biochar-led operations as a function of η, *c*, and market demand for enriched biochar. Next, we discuss how the circularity assessment presented here can be linked to our earlier sustainability assessment of this system, outlining how the proposed RE indicator can be coupled with LCA to answer complementary questions, avoiding double counting. Finally, we outline limitations and the outlook, highlighting data needs on breakthrough behaviour, media ageing, agronomic availability, and regulatory compliance.

4.1. Process-level interpretation

Our study aimed to explore the technical feasibility of the integrated biochar–RAS system at an early development stage. We therefore focused on core nutrient recovery mechanisms in an idealised, isolated system, where nutrient flows are tracked within clearly defined boundaries. We used SFA to build a transparent, first-order mass balance informed by lab data, limited pilot observations, literature, and databases. Within the boundaries of our defined system, forestry residues and fish feed enter, nutrients are either retained on solids (biochar, ash, sludge) or lost, and residual streams are either reused or discarded. This controlled setting enabled us to assess the potential for nutrient retention without conflating it with downstream agronomic performance, the complexities arising from external nutrient exchanges, and broader circularity dynamics.

The SFA quantifies how pyrolysis partitions biomass into a carbon-rich biochar and phosphorus-rich ash, alongside a gas stream typically used on-site for heat/power. When used as a filtration medium in RAS, the biochar becomes nutrient-enriched, reinforcing process-level circularity and creating a recoverable, transportable nutrient stock (a "nutrient battery") for agricultural applications. Nutrient storage on biochar does not guarantee immediate or complete plant availability, which depends on chemical speciation, soil properties, and management. Where quality and compliance allow, nutrient-enriched biochar could be further combined with nutrient-rich sludge from the RAS and pyrolysis ash, particularly for soils requiring additional phosphorus. Because pyrolysis concentrates a large share of biomass phosphorus in the ash (Table 1), the fate of ash largely determines RE_P in the integrated system. Within the RAS, roughly one-fifth of feed-P is routed to sludge. Thus, co-using sludge with enriched biochar adds a smaller, but still useful P contribution. Finding a use for the ash is critical for sustainable P management. Mixing ash into the nutrient-enriched biochar for agriculture can be beneficial where feasible.

Adding fish sludge contributes additional carbon to soil, but this flow is modest relative to biochar-bound C and is probably more labile. Any long-term soil-C storage would materialize only after land application of biochar and depends on biochar properties, site conditions, and management. Because RE is a process-level indicator confined to the aquaculture unit, we do not credit soil-C sequestration. Moreover, doing so would not change the comparison, since both separate and integrated systems can produce and land-apply biochar. Accounting for soil-C is better handled in a separate sustainability assessment (e.g., LCA) with explicit time horizons, permanence criteria, and transparent allocation rules to avoid double counting. In short, biochar enables a potential soil-C stock, but it lies outside the RE boundary and does not alter the N and P retention results.

4.2. Indicator choice and system maturity

Expanding the assessment to explore the potential of this biochar–RAS system within a more specified regional or global context, where cross-boundary nutrient flows – such as feed and food trade – play a significant role, would require more comprehensive assessment approaches and indicators (Harder et al., 2021a). Metrics such as IC and OC (Harder et al., 2021b) or Cycle Count (CyCt), which measures the average number of full cycles completed by a nutrient input before being lost (Loon et al., 2023), can offer insights into systems characterised by multiple reuse loops and/or diverse, interacting waste streams. However, employing these more sophisticated indicators requires more detailed, context-specific data on specific geographic, sociotechnical, and socioeconomic factors, and such information is often unavailable at early stages of technological development. Introducing complex assumptions about a wider system too early can obscure the actionable information technology developers need.

Indicator selection should match system maturity and specificity. At low TRL, a simple, interpretable metric is preferable, and RE fits this role by quantifying nutrient retention at the unit-process level. At higher TRL, as boundaries, data, and market or regulatory conditions solidify, more context-rich and product-level indicators (e.g., for nutrient-enriched biochar as a commercial good) become more appropriate. Accordingly, we use process-level RE to quantify N, P, and C retention within the aquaculture unit. As systems scale and boundaries solidify (see 4.3. below), RE remains useful for internal tracking, while more comprehensive indicators can support site-specific deployment decisions.

4.3. Scale context and energy co-products

Regarding scalability, replicability, and technological maturity, the technical system under study here shows promise but requires further development. Key technical needs include real-time monitoring of water quality, biochar performance, and nutrient levels, as well as optimization of biochar contact time within the system. Real-world biochar performance will be verified in pilot columns, testing breakthrough curves under defined contact time, pH, temperature, and media ageing. Here, we treat 100 % capture as an upper bound case for a modest literature-derived sorption capacity and include a simple closed-form sensitivity check on η to demonstrate robustness (see 4.6.1. below for more details). Given the ongoing growth of the aquaculture sector, integrated nutrient retention pathways like the one explored here could scale via replication and adaptation tailored to local water chemistry, energy, and biomass conditions. Potential barriers to adoption – including economic feasibility, regulatory compliance, public acceptance, and logistical integration across aquaculture, forestry, and agriculture – also need evaluation.

To put scale in perspective, the modelled RAS produces ~10 tonnes of fish biomass per year from 17 tonnes of feed (daily, 27 kg biomass gain from ~47 kg of feed, based on our design parameters in Section 2.2. a–b). This is comparable to a small commercial fish farm supplying two fish-protein portions per week to 640 people. Improvements in FCR or fish feed assimilation that would bring the fish-feed:biomass-gain ratio closer to 1:1, would reduce absolute biochar requirements and ash production roughly proportionally, leaving RE percentages largely unchanged under constant c and η (see Section 4.6.2). Meeting the daily media requirement (1094 kg biochar per day) implies pyrolyzing ~6438 kg of dry spruce residues per day, equivalent to >2300 tonnes of dry biomass per year. For context, Sweden's total annual forest growth is conservatively estimated at 100 million m^3, which is equivalent to 50 million tonnes of forestry biomass (Roberge et al., 2020), assuming a conservative conversion factor of 2 $m^3 = 1$ tonne. This means that the modelled fish farm would require 0.005 % of Sweden's annual forest growth. This pyrolysis activity may occur irrespective of fish production, considering the growing interest in pyrolysis for heat and biochar for agriculture. At the vendor-reported rating (~160–200 kW_{th} at ~127 kg/h dry feed), the pyrolysis unit yields about 4.5–5.7 MJ/kg of usable heat (Biomacon GmbH, 2021). Scaling linearly to the ~268 kg/h feed implied by our media sizing yields approximately 0.34–0.42 MW_{th}. SFA results are independent of heat-recovery assumptions, and we therefore report heat potential qualitatively.

Prioritizing process-level nutrient retention in RAS directly targets the N and P boundaries, which are among the most stressed Earth-system processes in the Planetary Boundaries framework, and a key sustainability pressure (Richardson et al., 2023). Our results show how internal retention can reduce pressure on those boundaries; realizing sector-level benefits depends on compliant agricultural reuse and product quality.

4.4. Implementation pathways

Considering the potential benefits of this approach, adaptation can be directed to a RAS-led operation with biochar enrichment as a side activity or a biochar-led operation with fish farming as a bonus. Beyond the technical results, the business center of gravity depends on the market for enriched biochar. The daily media requirement is proportional to the nutrient load and inversely proportional to η and c, i.e., higher η or c means fewer tonnes of enriched biochar. If nutrient-enriched biochar sells at a reliably higher price than standard biochar with steady demand, revenue can shift away from fish. If that premium is weak or uncertain, the operation remains RAS-led. Conversely, if the premium and demand are strong, even modest η or c can support a biochar-led case.

4.5. Coupling circularity (RE) to sustainability assessment (LCA)

Several studies emphasize coupling circularity metrics with LCA to obtain a holistic view of system performance and move towards standardised practice (Brändström and Saidani, 2022; Harris et al., 2021; Luthin et al., 2023; Niero and Kalbar, 2019; Rigamonti and Mancini, 2021; Samani, 2023; Vadoudi et al., 2022). Process-level recovery efficiency (RE) and life-cycle assessment (LCA) answer complementary questions: RE quantifies how much N, P, and C are retained within the unit process, while LCA evaluates the environmental burdens and credits associated with achieving that retention. To integrate them, boundaries and functional units should be aligned (e.g., per kg fish and per kg nutrient-enriched biochar), attribution should be made explicit (RAS-led vs biochar-led framings), and double counting of credits (heat, fertiliser substitution, soil-C) should be avoided. In SFA, η and c govern media turnover. In LCA these parameters drive scaling of biomass supply, energy use, and potential substitution credits. Conversely, LCA clarifies when higher RE actually improves system sustainability versus shifting burdens upstream.

The companion early-stage LCA for this case (Behjat et al., 2025) quantifies feed and pyrolysis hotspots, treats avoided heat and fertiliser substitution transparently, and explores soil-C assumptions. Read alongside our RE results, it helps identify robust operating ranges and priorities for pilot validation (e.g., breakthrough behaviour, N_2O avoidance relative to biofiltration, agronomic availability and compliance). Together, RE and LCA form a decision framework: improve internal retention when RE is limiting, and otherwise prioritise the external factors driving LCA results (energy integration, substitution efficacy, and product quality/compliance).

4.6. Limitations and outlook

4.6.1. NH_4^+ sorption capacity

We used a literature-derived ammonium sorption capacity $c = 4.2$ g NH_4^+ kg^{-1} biochar (0.42 % by mass), equivalent to 3.27 g N kg^{-1} (using 14/18 to convert NH_4^+ to N), to size the daily media requirement (Weldon et al. 2022). This is a core assumption because it scales the media turnover and, by extension, the magnitude of integrated flows. Reported capacities vary widely across feedstocks and process conditions, e.g., ~0.7–17.6 g kg^{-1} (Maleki Shahraki and Mao, 2022; Weldon et al., 2022) and outcomes will therefore vary with biochar properties (feedstock, temperature, residence time). We treat 100 % capture as an upper bound and provide a closed-form sensitivity check on η. Under our modelled loads, increasing η from 0.60 to 1.00 increases RE_N by ~5 percentage points. Pilot-scale testing will quantify cycle-average η under relevant operating conditions. In reality, sorption is probably not the only mechanism by which nitrogen species will interact with the biochar and other mechanisms, such as biofilm formation, and their temporal dynamics will need to be evaluated before implementation.

4.6.2. Fish feed composition

Feed is a major driver of N, P and C flows in RAS, directly affecting excretion rates, sludge composition, and ultimately the system's overall circularity (Bueno et al., 2016). Fish feed formulations vary widely across species and regions, impacting nutrient content, feed efficiency, and environmental footprint (Bosma et al., 2011). Our aim was to test the integrated concept, and we thus used general but representative values. Without more detailed feed data, our SFA must rely on broad assumptions, which may lead to underestimating or overestimating both nutrient retention and waste outputs, restricting the generality of our findings to the specifics of the assumed feed composition, and the associated FCR and assimilation. For a fixed fish biomass output, daily fish feed requirements scale with the FCR/assimilation ratio, which in turn determines all feed-derived nutrient inflows, including the dissolved NH_4^+ load that reaches the biochar stage. In our integrated design, the required biochar and, consequently, the associated pyrolysis flows, are sized to the dissolved nutrient load in the RAS. This means that absolute masses of enriched biochar, ash managed, and nutrients captured scale proportionally to the fish feed input. RE_N, RE_P, and RE_C are mass percentages expressing the nutrients retained on solids, including fish biomass, compared to the total nutrient inputs from fish feed and biochar supply, and are therefore largely scale-invariant under constant c and η.

Improving feed assimilation would shift some retention from dissolved/particulate pathways towards fish biomass, slightly reducing dissolved loads and the biochar required. In separated RAS, that shift would raise RE_N (less N lost as N_2). In the integrated case, such an improvement would mainly reallocate the N retained from biochar/sludge to fish, with little effect on the RE values. RE_P behaves similarly, with changes driven by how much pyrolysis is needed to meet the biochar demand, and, consequently, how much ash is produced. RE_C remains close to constant because carbon accounting is dominated by the pyrolysis gas fraction, which our RE metric treats as non-retained.

Optimization of feed formulations tailored to local conditions and specific fish species can enhance nutrient recovery in fish, reduce waste outputs, and improve overall system sustainability (Timmons and Vinci, 2022). The omnivorous species *Clarias* can probably thrive on much more sustainable feed formulas than those commercially available today and can potentially also handle significant variations in feed composition, potentially with consequences for the flow distribution in the system.

4.6.3. Forestry feedstock and supply context

Our study models using spruce residues as pyrolysis feedstock. Feedstock properties and supply are subject to the dynamics of forest growth and can introduce additional uncertainties that will influence the long-term sustainability of such an approach. For instance, older trees differ substantially in structure and density compared to younger stands, with variations in wood density, carbon content, and potential yields of biochar feedstock (Skytt et al., 2021). In particular, short-term versus long-term trade-offs are critical: harvesting mature, carbon-rich stands can yield biomass for pyrolysis and negative-emission strategies but simultaneously forgo the ongoing carbon storage that would occur if older forests were left unharvested (Moomaw et al., 2020). Conversely, younger, faster-growing forests may offer more frequent harvest cycles but store less carbon per unit area at any given moment. Such complexities underscore the importance of temporal scales in evaluating mitigation pathways: a policy focusing on near-term gains may support higher harvest rates, while a longer-term perspective might favor lower harvest intensities or extended rotations to maximise carbon storage in situ (Skytt et al., 2021). Ultimately, feedstock supply for biochar hinges on several factors, such as forest productivity, stand age, management regimes, and substitution dynamics, that can shift the overall climate balance of pyrolysis-based systems. Future work should therefore incorporate regional forestry modelling and site-specific data to refine these estimates and align biomass management practices with both short- and long-term climate targets.

4.6.4. Ash and sludge application routes and quality constraints

Returning ash to forest soils (scenarios 2 and 4 – when ash is not mixed with the nutrient-enriched biochar to be used in agriculture) can also be considered a “circular” practice. From an ecosystem perspective, recycling nutrients back to forests maintains or enhances soil fertility, retaining P and other minerals within the landscape. Under an alternative accounting in which ash recirculated to forest land is counted as retained rather than treated as a loss, the separated system's RE_P would rise from 25.5 % to around 94 %, nearly matching the integrated system's RE_P of 99.6 %. However, the practical details of returning ash to forest soils are often more loosely defined compared to agricultural reuse. Forest application may happen at varying, undocumented spatiotemporal intervals and under differing conditions. Such variability can alter how quickly and uniformly the ash's nutrients become available to forest ecosystems. Ash may contain heavy metals and other contaminants in high concentrations and thus its composition should be compared against fertiliser limit values prior to application. Further, agronomic availability remains uncertain as only a fraction of P in ash and N in biochar is directly available to crops, and mixing ash with sludge also introduces handling/quality constraints. For Sweden, a national-scale phosphorus MFA identified wood ashes and sewage sludge as major domestic P stocks, while clarifying that the agricultural usefulness of such streams is governed by plant availability, contaminant limits, and geospatial fit between sources and demand (Lorick et al., 2021). We treat enriched biochar as a transferable, storable carrier and interpret RE as process-level retention. Sectoral deployment depends more on plant availability, planning, and regulatory compliance rather than on co-location with demand. Assessing such deployment constraints is left for future work.

4.6.5. Biophysical and operational timescales – design implications

Our integrated system highlights the critical role of timing and natural cycles in achieving nutrient circularity. A spruce tree takes decades – often 50 years or more – to grow and sequester carbon, yet it is reduced to biochar within hours through pyrolysis, rapidly transforming a long-term carbon sink into a nutrient filtration medium. Similarly, fish in the

RAS grow over several months, while nutrient excretion and biochar adsorption occur almost instantaneously within the system. This disparity in timescales underscores a key challenge: natural processes that accumulate biomass and nutrients over extended periods are juxtaposed against human-engineered processes that operate on much shorter timescales. Designing systems that respect the slow pace of natural regeneration while efficiently managing waste in real-time is essential for resilience and sustainability. Future studies should explore how to balance these timescales to better synchronise resource use, regeneration, and waste valorization.

5. Conclusions

Integrating a biochar filter with RAS increased process-level nutrient retention compared with separated operations. RE_N rose from 30.6 % to 44.6 % and RE_P from 25.5 % to 99.6 % in the full reuse configuration (nutrient-enriched biochar + RAS sludge + pyrolysis ash). Nitrogen retention is driven primarily by biochar sorption of dissolved N, with a small boost when sludge is co-used, while phosphorus gains hinge on ash reuse. Carbon retained in biochar is a potential soil-C stock upon land application, but RE is a unit-process indicator bounded at the aquaculture system, so we do not credit soil-C here. Because the plant-available fractions of P in ash and N in biochar are variable and ash quality must meet regulatory limits, we interpret RE as process-level retention and flag agronomic availability and compliance as next steps.

We treat 100 % dissolved NH_4^+ capture in the biochar filter as an upper-bound case and report a linear relationship for the sensitivity of RE_N to the filter's cycle-average retention efficiency, η. Under the modeled loads, raising η from 0.60 to 1.00 increases RE_N by ~5 percentage points, leaving the qualitative patterns unchanged. The SFA modelling and our simple RE indicator proved effective in evaluating nutrient retention and reuse potential within this integrated biochar–RAS system at an early stage of technological development, providing actionable early-stage insight and a basis for targeted pilot tests and site-specific integration. Further laboratory data and pilot-scale experiments are needed to validate assumptions about nutrient recovery performance, soil-carbon storage upon land application, and overall sustainability. As these systems mature and become more context-specific, more comprehensive indicators beyond RE may be required to capture spatial and temporal complexities in nutrient cycling.

CRediT authorship contribution statement

Efstathios Reppas-Chrysovitsinos: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marta Behjat:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Niklas Wennberg:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization. **Gregory Peters:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Magdalena Svanström:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Supplementary materials

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Data availability

Data and calculation sheets are available as online supporting material.

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