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Citation for the original published paper (version of record):
Behjat, M., Svanström, M., Peters, G. et al (2025). Life cycle assessment of recirculating aquaculture systems with innovative biochar filter for
enhanced nutrient recirculation. Resources, Environment and Sustainability, 21.
http://dx.doi.org/10.1016/j.resenv.2025.100233

Resources, Environment and Sustainability 21 (2025) 100233

Contents lists available at ScienceDirect

Resources, Environment and Sustainability

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

Research article

Life cycle assessment of recirculating aquaculture systems with innovative biochar filter for enhanced nutrient recirculation

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ARTICLE INFO

Keywords:
LCA
Environmental impact
Nutrients recovery
RAS
Biochar
Carbon
Water treatment

ABSTRACT

Reducing pollution caused by losses of carbon (C), nitrogen (N), and phosphorus (P) from the technosphere and turning these flows into resources is a focus of current research towards a circular economy. Producing biochar from biomass pyrolysis and using it in agriculture is a promising way to mitigate climate change and improve soil quality. In this study, we explore the environmental performance of using biochar for nutrient recovery in recirculating aquaculture systems (RAS) and generating a nutrient-enriched biochar for agricultural use. Through prospective life cycle assessment (LCA), the study looks into two different RAS configurations, one with a conventional biofilter and one with the innovative biochar filter. The latter is also explored using two different system perspectives: in the first, the biochar production is considered an activity that happens solely for the purpose of the fish farming but with the added function that it captures and transports nutrients along with stable C to agricultural soil; in the second, biochar is considered already produced and destined for agriculture but it takes a detour to a fish farm to collect some nutrients *en route*. The main environmental hotspots for the conventional system are related to fish feed production and electricity usage. When the biofilter is replaced by a biochar filter and biochar is generated for the main purpose of being a filter, additional large impacts from forestry biomass production and construction of a pyrolysis plant are associated with the RAS. This is only partially counteracted by recovered heat and nutrients, but for climate impact, the gains related to C sequestration are considerable. A sensitivity analysis revealed considerable variability in the performance of the first RAS biochar configuration due to variations in NH_4^+ adsorption capacity. When biochar is considered a "sunk cost" - a resource generated for other purposes - the weight of impacts shifts back to fish feed production and to biochar container construction. With regard to overall performance, RAS with biochar shows promising results compared to conventional RAS, but there are variations between impact categories. The innovative technology is promising also when compared with benchmarks in the literature. The technology still needs proof of concept, both concerning the action as a filter and the behaviour as a fertiliser product, but performing an LCA at early stages provided useful insights into further development. It is clear that fish feed is underexplored in LCA contexts. Further work could also look into how the fish sludge could be valorised and what the best system integration is for the innovative technology.

1. Introduction

Population pressure is increasing the demand for food products (Fukase and Martin, 2020). At the same time, the urgency of some environmental problems has become increasingly evident. Additionally, the recent pandemic and increasing geopolitical tensions make countries look into how to secure food production in times of crisis. Agricultural industries are pursuing new and potentially more sustainable production practices to cover this increasing demand while minimising environmental impact and resource consumption. Also, local production and local nutrient cycles are advocated.

The 2030 Agenda for Sustainable Development is the main overall strategy for the transformation of the global food system, promoting sustainable agriculture (United Nations, 2015). To fulfil the Agenda, the European Union (EU) has established a set of strategies associated with sustainable food systems (European Commission, 2018). The importance of sustainability was especially underlined by the Farm2Fork strategy, aiming to make sure that everyone has access to sufficient,

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https://doi.org/10.1016/j.resenv.2025.100233
Received 11 January 2025; Received in revised form 6 March 2025; Accepted 21 April 2025
Available online 30 April 2025

safe, nutritious, and sustainable food (European Commission, 2018). These strategies are further supported by the Circular Economy Action Plan (2015), which sets the basis for the development of the 2019 EU fertilising products regulation (2019/1009) (European Union, 2019). This EU regulation aims to facilitate access to organic and waste-based fertilisers for food production in the EU market (EPA, 2019), while establishing common rules on safety, quality and labelling requirements (European Union, 2019). Furthermore, minimising waste generation and enhancing the efficiency of waste usage are essential for protecting both human health and the environment. Directive 2008/98/EC outlines measures aimed at using waste more efficiently, which is crucial for transitioning to a circular economy (European Union, 2008). Overall, such strategies and regulations state the ambition of more sustainable food production by implementing technologies that transform waste into resources, and by incentivising the fertiliser industry in the use of bio-waste fertilisers as renewable nutrient sources.

Since the 1990s, aquaculture has been the fastest growing food producing sector in the world (KSLA, 2009). Increasing the availability of "blue foods" for domestic markets can make them affordable and more accessible to local consumers. "Blue food" is a term used to emphasise the role of water-based (or "blue") ecosystems, and it includes all fish, shellfish, aquatic plants, and other species consumed as food from oceans, rivers, lakes, and other bodies of water, including land-based aquaculture (Crona et al., 2023). The aquaculture sector can play an important role in efforts to eliminate hunger and malnutrition since its products are rich in protein, essential fatty acids, vitamins and minerals (KSLA, 2009). Furthermore, the EU has been actively integrating climate considerations into various policies, including those related to new protein sources. This integration is part of a broader strategy to achieve climate neutrality by 2050, as outlined in the European Green Deal (Caserini, 2017; Ruse and Pubule, 2022). Indeed, aquaculture production can serve as a viable alternative to meat and dairy products.

One kind of aquaculture technology that is receiving increasing attention is the recirculating aquaculture system (RAS). This means a closed, land-based system. Many recently established Swedish RAS sites produce tropical fish and crustacean species in tanks (Bergman et al., 2020). A RAS reuses water by circulating it through a filtration system that removes pathogens, solids or dissolved compounds that can be damaging to fish health (Timmons et al., 2018; Xiao et al., 2019). A RAS filtration system generally incorporates mechanical and biological filters (Xiao et al., 2019). The mechanical filter is used to remove solids, that might contain some pathogens, and organic matter, that would otherwise decompose and consume oxygen. The biological filter utilises bacteria to eliminate ammonia from the water, which can be toxic to fish in high concentrations. Ammonia is eventually turned into nitrogen gas (N_2), which is released into the air. This release is in itself not detrimental to the environment as the air is already made up of mostly nitrogen gas. However, it is a missed opportunity for recovering reactive nitrogen (N) that was once captured by industrial or biological fixation. Some N and also phosphorus (P) are removed from the system with the sludge trapped in the mechanical filter, and the fate of that flow can differ between sites depending on scale and local practices, but frequently it does not go to agriculture. The potential losses in the two filters, underscore the importance of considering the redirection of nutrients, such as P and N, from fish waste water to, for example, agriculture.

Replacing the biofilter with one that can capture and hold the nutrients from the fish wastewater is a potential solution to avoid the transformation of ammonia into N_2 and its release into the air while maintaining healthy living conditions for the fish. In addition, if the nutrient-enriched material can be transferred from fish farming to agriculture, a more circular nutrient cycle can be achieved.

Pyrolysis is a process that can convert lignocellulosic resources into energy. Compared to combustion, this process has been viewed as an attractive alternative due to its flexible ability to generate a combination of solid, liquid and gaseous products with relatively high potential value (da Costa et al., 2023). Biochar is the solid C product obtained from pyrolysis. Currently, biochar is largely used as a soil improver (Murtaza et al., 2023). It is believed that the addition of charcoal to soil was employed to generate fertile soil called *terra preta* several hundred years BC in the Amazon by the native people; high levels of charcoal remain there which suggests this is an effective method for sequestration of C in soil (Criscuoli et al., 2014). In Sweden, farmers and landowners can use biochar on their land and certify themselves to sell C credits, creating new income opportunities and contributing to reaching global climate goals (VIA, 2024). This is claimed to be a "win-win-win" for the climate, soil health and the economy (VIA, 2024). Biochar acts as a highly stable C sink while increasing soil productivity.

The present study explores the use of biochar in RAS. This novel idea has been investigated in the Swedish Nutribatt research project (Nutribatt, 2023). The aim of the project was to explore replacement of the biofilter with an innovative biochar filter in RAS. The analyses conducted within the project show that biochar derived from pyrolysis of forestry waste from conifer residues, specifically the spruce tree (*Picea abies*), sufficiently retains nutrients. Spruce is a coniferous evergreen tree in the family *Pinaceae*. This tree is the most common tree species in Sweden; making up 40% of the total wood volume in the country (The Swedish Forest Industries Federation, 2024). The project also investigated the use of the nutrient-enriched biochar for agricultural use.

The work in the Nutribatt project was of an explorative nature and generated answers to some questions but opened up many others. Although many questions still remain around the biochar as a filter in RAS, the present study assumes that full replacement of the biofilter with a biochar filter can be realised in order to permit assessment of the environmental viability of such applications. This study reflects a Swedish context, with a large interest in investments in cutting-edge technology such as RAS. The Swedish Board of Agriculture and the Swedish Agency for Marine and Water Management have launched an action plan for the development of aquaculture (Nordin and Granit, 2021). Efforts to develop this sector have occurred in broad cooperation with other government agencies, industry organisations, NGOs and researchers, including aquaculture researchers (European Commission, 2022) in order to support EU to achieve the goal of the European Green Deal. This is a driver for research to establish more land-based blue food production reducing pressure on coastal ecosystems, developing better methods for sustainable farming practices, reducing environmental impacts, and improving efficiency.

Although adding the activity of nutrient-enriched biochar production in fish farms seems effective for enhancing circular flows of nutrients, evaluating its sustainability is also essential. A common method for assessing the overall environmental impacts of alternative systems is life cycle assessment (LCA) (Behjat et al., 2022). Conducting an LCA study in the early stages of technology development is challenging due to the difficulty in obtaining performance data and the complexities involved in scaling up processes that are not yet established. However, conducting an LCA on processes and technologies during their early development stages offers the advantage of identifying potential improvement opportunities in process design, before technological lock-in occurs. This allows developers to make more informed decisions and select more advantageous pathways in the development process. In order to evaluate the environmental performance and guide technical development towards environmental sustainability for the novel RAS system, three research questions (RQs) were formulated:

RQ1: How different is the environmental performance of the different RAS configurations (biofilter versus biochar)?

RQ2: What are the environmental hot spots within the life cycle of each configuration?

RQ3: Can the use of biochar lead to carbon neutrality in RAS fish production?

Although no specific LCA study has yet focused on biochar as a filter in RAS, related research indicates its potential benefits and environmental impacts. One study concluded that the environmental impact of using biochar as a filter material varies based on its production and end-of-life scenarios; renewable energy contexts and specific biochar production methods can reduce overall impacts (Zakrisson et al., 2024). Biochar has demonstrated effectiveness in removing turbidity, suspended particles from water (Khiari et al., 2020), ammonia, sediment properties and P (Chen et al., 2024). Additionally, the use of biochar in aquaculture has been shown to enhance the growth performance of aquatic species, other than contributing positively to water quality (Jateen et al., 2023). These outcomes indicate that biochar can improve the aquaculture environment by removing certain contaminants and promoting the health of fish.

There is thus a need to conduct an LCA to evaluate the full environmental footprint of using biochar in RAS. Indeed, with this analysis, we contribute to evaluating the environmental performance of fish farming with nutrient-enriched biochar production for agricultural activities, at an early stage, and provide input to further development and upscaling.

2. Materials and methods

2.1. Description of the studied technologies

This study considered a RAS owned and operated by Pond Fish and Greens in Floda near Göteborg, Sweden, which produces African catfish *Clarias gariepinus*. This African catfish is a highly productive species and requires low protein inputs, but needs to be farmed in warm water, approximately 27 °C. At the time of making this study (2024), this fish farm had approximately 3200 catfish, with different weights (average weight = 0.75 kg), and approximately 43 kg of fish feed was used per day. In this RAS, a drum filter and a moving bed biofilm reactor (MBBR) are used to treat the fish wastewater. The sludge separated from the aquacultural water with the drum filter is collected and sent via the sewerage system to sewage treatment in the municipal plant. The MBBR contains carriers, small plastic elements with high surface areas, specifically designed to encourage bacterial colonisation. These move freely within the filter chamber, set in motion by the water currents and bubbles released by the aerator, and they become over time coated with beneficial bacteria that form biofilms on their surfaces (Ecotao, 2021). The bacteria are mainly nitrifying species, such as *Nitrosomonas* and *Nitrobacter*. Their primary function is to remove compounds harmful to the fish from the water. Furthermore, the use of biofilm carriers creates microenvironments suitable for both processes, nitrification and denitrification, leading to efficient N removal from wastewater (Bhattacharya and Mazumder, 2021). Removing ammonia and nitrites from the aquacultural water is essential for the health of the fish. After a series of nitrification and denitrification steps in the MBBR, emissions of N_2 and N_2O occur. The MBBR has a lifespan of 10 to 15 years, requiring the replacement of bio-carriers and biofiltration tanks after this period. The plant operates 24 h a day.

In the conceptual set-up for the innovative RAS solution, the MBBR is completely replaced by a biochar filter. After the drum filter, we assume the aquacultural water is filtered through a carefully designed biochar filter, and that all the remaining nutrients are held in the biochar. There are early indications in the project that this could be feasible and that the pyrolysis of dried spruce residues makes a suitable biochar. After some time, the biochar becomes a nutrient-enriched soil conditioner, which can be used in agriculture to add both nutrients and stable C. Kinetics and appropriate safety margins remain to be fully understood; only limited results were generated in the explorative project. The function as a cultivation substrate was also investigated within the project, but with limited scope.

To collect data for the pyrolysis, we chose to consider a specific plant of the brand Biomacon, located in the Hjelmsäter farm, near Lidköping, Sweden. In this plant, spruce wood residues are chopped, dried and then pyrolysed at high temperatures (720–780 °C) with low oxygen addition, forming biochar, ash and pyrolysis gas. Depending on weather conditions and wood moisture content, the biomass can be dried using a drier, at 50–70 °C, or outdoors if needed. In the pyrolysis process, 20%, 78% and 2% of the dried mass becomes biochar, gases, and ash, respectively. The biochar, which is a versatile material with significant potential in agriculture, environmental management, and waste management, is usually used to improve soil health in agriculture, for carbon sequestration, or in waste or wastewater management to remediate contaminants (Guo et al., 2015; Kumar et al., 2016). The gas, converted into heat via combustion, is used to heat the drier (small share) and the house/farm, depending on heating needs. Ashes are normally used as biofertilisers in forestry. The plant operates 24 h a day, year-round.

For this case study, it was decided to scale the whole system relative to the production of 30 m^3 of biochar because this is the standard volume of a shipping container, making it easy to integrate into existing logistics chains and markets. Containers of this size can be efficiently loaded onto various transportation modes, such as trucks, trains, and ships. The container is filled with biochar from pyrolysis which will be used for filtration/treatment of fish wastewater in RAS and transform into nutrient-enriched biochar. After reaching capacity, the biochar container will be disconnected and drained and then transported to agricultural operations and emptied. Potassium chloride (KOH) is added in the current RAS to maintain the pH of the water in the fish tanks between 6.5 and 7. However, laboratory experiments have shown that when aquacultural water comes into contact with fresh biochar, its pH increases. To control this effect, sulfuric acid (H_2SO_4) is instead used to lower the pH in the RAS set-up with biochar. This actually significantly reduces the cost for pH regulation. More details are provided in the life cycle inventory analysis section.

2.2. Environmental assessment

2.2.1. Goal, scope, and system boundaries of the study

Defining the goal and scope of a study is the first step when conducting an LCA, to clarify the purpose and determine consistent system boundaries and modelling assumptions. The goal of this LCA study is to inform design and optimisation of an innovative RAS solution by benchmarking to current technology and identifying hot-spots. The intended audience of this work is primarily stakeholders involved in RAS, pyrolysis and agriculture, who want information on process design priorities in a RAS context, and on biochar uses as alternative fertiliser products.

Specifically, this study evaluated and compared the environmental performance of two alternative RAS configurations, the first representing current technology and the second exploring the novel nutrient recovery concept. Further, two system perspectives (accounting approaches) were explored for the innovative configuration:

- Configuration 1: RAS with conventional biofilter
- Configuration 2a: RAS with innovative biochar filter (accounting approach 1)
- Configuration 2b: RAS with innovative biochar filter (accounting approach 2)

The distinction between accounting approach 1 and 2 lies in the different perspectives on whether biochar has to be produced specifically for the purpose of the use in the fish farm or if it can be seen to be already available and destined for use in agriculture. In the second case, it just takes a detour to the fish farm to enable the recovery and transport of some nutrients on its way to agricultural soil.

Configuration 2a therefore takes into account the construction and operation of a new pyrolysis plant co-located with the RAS, forestry activities to provide the input, and C credits in agriculture. In configuration 2b, biochar production is instead a “sunk cost” and none of these activities are included in the assessment. It can be argued that a fair comparison to the conventional RAS would require something in between these system views, but looking into both of them provides the explorative cornerstone analysis in which we are interested in this study.

The functional unit (FU) in an LCA is the description of the function or service provided by the product or system under study and the basis for comparing alternatives (Peters and Svanström, 2019). This was carefully chosen to represent the function of the RAS scenarios in the most meaningful way. To understand the environmental impacts of the processes involved in the two configurations and alternative system perspectives and to compare the resulting impact, the production of 1 tonne of whole *Clarias gariepinus* fish for the market was selected as FU. The chosen FU is the most common type of unit of measure in the context of aquaculture (Hala et al., 2024). This FU is meaningful and easy for the targeted stakeholders to understand what is being measured and compared for the RAS. If instead, we wanted to discover opportunities for biofertiliser production, an alternative FU based on the amount of nutrient (N or P) in the biochar would also make sense, but this would shift the focus to the fertiliser industry instead of RAS.

Fig. 1 shows the studied scenarios. The pyrolysis process and RAS are the two core processes. Since this study focuses on understanding the fish wastewater treatment activity rather than the overall performance of the fish farm, only the construction of the biofilter and its biocarriers in configuration 1 and the container for biochar in configurations 2a and 2b are included in the model assessment. All other components of the RAS, like fish tanks, piping and pumps, were excluded. However, in evaluating the operational aspects of the RAS, we nevertheless considered the fish feed in addition to energy and chemicals. This inclusion helps us gauge the significance of fish feed in relation to other factors. In configuration 2a, all the aspects related to the production of the biochar are included in the boundaries, including construction and operation of the pyrolysis facilities and the forestry activity. It is assumed that the forestry biomass is always dried using a drier, before partial combustion, regardless of the weather (a worst-case assumption), and that the generated heat is utilised for heating the fish farm and for local heating of buildings, substituting other means of heating. This is a logical choice when the starting point is a RAS set-up based on current technology that does not provide heat but rather is a heat sink. The co-location of both facilities and also the user of heat eliminates the need for transportation, but transport was anyway not considered in any configuration. Establishing new pyrolysis plants will probably increase the use of spruce forestry for biomass production. Configuration 2b, on the other hand, excludes all elements connected to biochar production and agricultural use and only focuses on its use in the fish farm and the nutrients that are recovered. Agricultural activities were not captured in any other way than as nutrients replaced (for any studied system) and C sequestered (but only configuration 2a).

The sludge produced by the drum filter in all systems is considered to be sent to municipal wastewater treatment via the sewerage system. This sludge was assumed equivalent with regard to amounts and content in all systems and was therefore not included in the assessment as it would not add important information to the comparison. In Sweden, a variety of methods are employed to treat wastewater and sludge in municipal wastewater treatment plants. The primary goals of sludge treatment include reducing volume, improving physical properties, and ensuring environmental safety, but it is also increasingly focusing on energy and resource recovery. The combination of anaerobic digestion, incineration, and stringent quality control measures could ensure that the sludge is managed in an environmentally and economically sustainable manner. Under some circumstances, this sludge could be beneficially used for energy recovery or circulating nutrients to agriculture. There might also be ways to collect the sludge and integrate it into a fertiliser product on the RAS site, but this was not explored in this study.

The operation of all core processes (foreground system) are fully included within the system boundaries, as are the production processes of chemicals, bio-carrier, electricity and biomass (background system).

2.2.2. System expansion

This study considered not only the environmental impacts from direct emissions, from the construction of the technologies and from the production and consumption of chemicals and energy, but also the benefits derived from resource recovery, such as energy from the combustion of pyrolysis gas, or replacement of commercial fertiliser with biofertiliser in agriculture. This must be done to ensure that each of the compared systems are functionally equivalent. Additional functions of the systems were therefore handled through a “system expansion by substitution” approach. This is a common approach in similar studies, and it means that the alternative production is added to the LCA model, and the systems are credited for the related impacts in a way that makes them functionally equivalent (Heimersson et al., 2019). The system expansions are shown graphically in Fig. 1 (pink boxes) for configurations 2a and 2b.

The recovered nutrients are assumed to be used in agricultural activities, exploiting their fertiliser potential. Calcium ammonium nitrate (CAN; 27% N) and triple superphosphate (TSP, 25% P) are the fertilisers considered to be avoided in this substitution. CAN and TSP are the most commonly used N- and P-containing fertilisers in Europe. These two fertilisers are favoured for their high nutrient content and bioavailability (Miao and Zeller, 2025; Oldfield et al., 2018). Other content in the recovered biofertiliser that can bring value in agriculture, such as organic content or micronutrients, was not accounted for (other than as carbon sequestration, as explained later). The nutrient availability of the enriched ‘recovered’ biochar was assumed to be equivalent to that of the replaced commercial fertilisers, with a substitution ratio of 1:1, which can be seen as a best-case scenario.

Furthermore, for each cubic meter of biochar produced through the pyrolysis process, 26 kWh of heat is generated (data calculated based on the data shared by Hjelmsäter), which is considered to displace wood chips (1.72 kWh/kg of wood chips) in configuration 2a in our study. The avoided process for this system expansion was the production of heat with wood chips by combustion, for which data were taken from the Ecoinvent database.

More information about the calculations for the system expansions is reported in the supplementary material (SM).

2.2.3. Life cycle inventory

The inventory data used for the foreground system in the LCA was collected from technical data sheets of different equipment (pumps, air blowers and drum filter) and from the operating conditions of the RAS and pyrolysis plants, provided by Pond Fish and Greens, Biomacon and Hjelmsäter farm. Some data and information about the pyrolysis process and the RAS were also collected from experimental laboratory tests conducted within the Nutribatt project. When no experimental data was available, process performance was calculated or estimated using literature data. A summary of the data inventory used for the LCA can be found in Table 1.

Data for the background system and substitutions, i.e., production of energy, forestry biomass and chemicals and avoided production of commercial fertilisers and heat, were retrieved from the Ecoinvent database, for Swedish (SE) conditions. When data specific to Swedish conditions were unavailable, European (RER) or global (GLO) data were utilised.

The specific RAS plant in Floda is equipped with solar panels to generate electricity for running the circulation pumps, air pumps, heat pumps and drum filters. However, since this study aims to assess for a more explorative scope rather than being a site-specific case study, the Swedish electricity mix (dominated by renewable and low C sources, such as hydropower, nuclear power, wind power, bioenergy and solar energy) is considered in the analysis.

Regarding fish feed, previous publications exhibit a wide range of feed recipes and feeding rates for African catfish (*Clarias gariepinus*), but inventory data for the latter is not available. For this reason, we used an ecoinvent dataset for Tilapia fish feed in this case study.

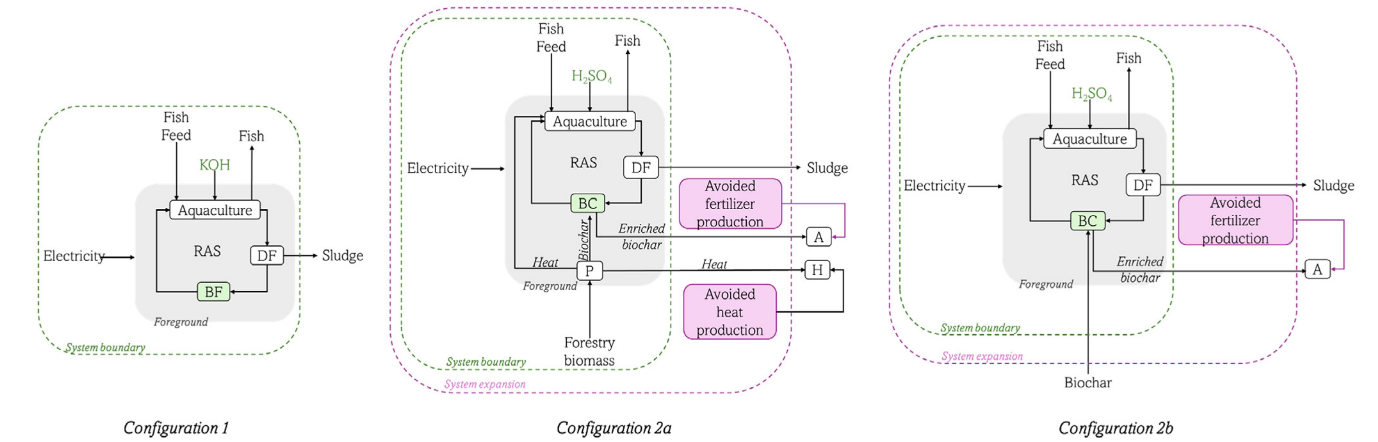

Fig. 1. System boundaries of configuration 1 (RAS with conventional biofilter (BF)); configuration 2a (RAS with conventional biofilter fully replaced by innovative biochar filter (BC) – including all the aspects related to the biochar); and configuration 2b (RAS with conventional biofilter fully replaced by innovative BC filter – excluding all the aspects related to the biochar) considered for the LCA study. The diagram includes components such as drum filter (DF), pyrolysis (P), agriculture (A), and for local heating of building (H).

Table 1
Quantity of input and output flows for one tonne of fish and the corresponding information/data sources, such as Pond Fish and Greens (PFG). The two acronyms, PE and PU, represent polyethene and polyurethane, respectively.

Mass and energy flows [Activity]		Unit	Conf.1	Conf.2a	Conf.2b	Source
	Forestry waste [Pyrolysis]	kg		119199		Biomacon
	Electricity [Pyrolysis]	kWh		3125		Hjelmsäter
	KOH [RAS]	kg	21			PFG
Input	Electricity[1] [RAS]	kWh	73	50	73	PFG
	Heat [RAS]	kWh		3079		Calculated
	Sulfuric Acid (14%) [RAS]	kg		6	6	Calculated
	Fish feed [RAS]	kg	1200	1200	1200	PFG
	Biochar [RAS]	m^3		121	121	Calculated
	Biochar [Pyrolysis]	m^3		121		Calculated
	Ash [Pyrolysis]	kg		1783		Biomacon
	Heat [Pyrolysis]	kWh		150171		Biomacon
Output	Sludge [RAS]	kg	300	300	300	PFG
	N_2O emissions [RAS]	kg	0.67			Literature
	Fish (biomass) [RAS]	kg	1000	1000	1000	Calculated
	Enriched biochar [RAS]	kg		18833	18833	Calculated
	NMVOC [Pyrolysis]	kg		8		
	PM_{10} [Pyrolysis]	kg		45		
	NOx [Pyrolysis]	kg		9		
	CO [Pyrolysis]	kg		83		
	PE for bio-tank	kg	3.5			Calculated
Construction	PU for bio-carrier	kg	0.2			Literature
	Pyrolysis plant	item[2]		0.005		Ecoinvent
	Container	item[3]		0.007	0.007	Ecoinvent

[1] The total electricity consumption includes the energy used by the pumps, drum filter, and heat pump. The heat pump is utilised only in configurations 1 and 2b. In configuration 2a, the RAS is heated using the gas produced in the pyrolysis process.
[2] One unit of the pyrolysis plant includes a floor measuring around 210 m^2 and a wood chips storage silo, both made of concrete (dimensions: 13 m x 7 m x 5 m). The silo is assumed to be built in an external space outside an already existing building.
[3] This dataset represents the production of a 20-foot (30 m^3) ISO standard container.

We assumed that all the dissolved N in the fish wastewater, which is 73% of all the N in the feed, passes the drum filter and is held by the biochar, which, based on literature values, has an ammonia sorption capacity of 4.2 g per kg of biochar (Weldon et al., 2022). The actual sorption capacity of ammonia on biochar is influenced by multiple factors including the type of feedstock and pyrolysis temperature. Higher pyrolysis temperatures can significantly enhance the sorption capacity (Feitosa et al., 2019; Li et al., 2015). Understanding these variables can help optimise biochar for effective ammonia adsorption in various environmental applications. The explorative nature of our study made it sufficient to select a generic value from literature and evaluate the implications of the choice in a sensitivity analysis. The calculated volume of biochar required to treat fish wastewater from the production of 1 tonne of slaughtered fish was 121 m^3.

When calculating the N_2O emissions from the MBBR activity, an emission factor (EF) of 1.1% N_2O-N kg^{-1} TN was used. This value is the average value of different EFs assessed by Song et al. (2024). It is important to note that while the IPCC recommends using an EF of 1.6% for the N_2O emissions (Buendia et al., 2019), the composition of influent wastewater and the type of bioreactor used can significantly influence the EF for N_2O (Mannina et al., 2018; Song et al., 2024).

Forests store a significant amount of C in leaves, branches, trunks and roots. When trees are cut down, some of this C is transferred to the soil unless forestry biomass is collected. Carbon stored in the soil is exposed to aerobic conditions and microbial activities, leading to increased decomposition and the release of carbon dioxide (CO_2) into the atmosphere. However, through the pyrolysis process, the C from the forestry biomass will be stored more stably in biochar instead, preventing or at least delaying some CO_2 emissions into the air. Based on laboratory analysis conducted within the project, it was estimated approximately 1 tonne of biochar carbon per FU. In this study, it was assumed that all C deposited in the soil after biochar application on agricultural land will be stored without degradation (a best-case assumption), meaning that no biogenic carbon will be released into the atmosphere after application. Biogenic carbon is, however, released when pyrolysis gases are combusted, but biogenic carbon emissions are here considered climate neutral.

We estimated that for every tonne of fish slughtered for the market, the use of 121 m^3 of enriched biochar in agriculture could avoid the production of 570 kg of CAN and 105 kg of TSP. This estimate accounts for nutrients captured on the biochar (originally added to the system in the fish feed) and partly from the biochar itself.

More details about data collection, data calculation, data quality, or assumptions around the data are provided in the SM.

2.2.4. Life cycle impact assessment

The life cycle impact assessment (LCIA) stage is fundamental for understanding the potential environmental impacts (Margni and Curran, 2012). Typically, various flows related to the life cycle of a product are aggregated into environmental impact categories (Behjat et al., 2024) by attributing a characterisation factor to each (Klöpffer and Grahl, 2014). The choice of a specific LCA software and method can influence the final LCA results. The impact assessment was carried out using the OpenLCA software, specifically using the Environmental Footprint (EF 3.1) method. The EF 3.1 method is a multi-impact, standardised, and EU-driven LCA approach. This method is recommended by the European Commission as a standard approach for measuring environmental performance and quantifying the environmental impacts of products and organisations in European regions, which makes it suitable for the studied cases.

For a better understanding and representation of the final results, the calculated environmental impacts were also normalised using normalisation factors (NFs). In LCA, normalisation is an optional step of LCIA (International Organisation for Standardization, 2006), used to gain a better understanding of the magnitude of the environmental impacts caused by the system under study. The NFs represent the total impact of a reference region for a certain impact category in a reference year (Baumann and Tillman, 2004; Sala et al., 2017). For EF 3.1, due to the international nature of supply chains, the use of global normalisation factors, calculated by the research centre of the European Commission, is recommended (Sala et al., 2017).

An impact not included in the selected LCIA method is the effect of forestry activities on arboreal habitats and biodiversity. To assess this, it is important to know if the area of spruce forest is constantly used for timber production, or if it has been converted into a forest via tree planting. This was not considered to be an important focus of this study.

3. Results and discussion

3.1. Overall environmental impact results

The findings that directly address the comparative environmental performance of the RAS configurations (RQ1) are reported in this section.

The main purpose of this analysis was not primarily to compare absolute impact estimates but to provide an understanding of orders of magnitude, to identify what influences the environmental impact in the three configurations and what should be considered in further technical development work. The normalised absolute values per tonne of fish produced are shown in Fig. 2. The figure shows the 12 of the 25 impact categories of the EF 3.1 LCIA method that achieved the highest results for any configuration after normalisation: global warming potential (GWP) in kg CO_2 eq.; acidification potential (AP) in mole of H^+ eq.; photochemical ozone formation potential (POFP) in kg NMVOC eq.; freshwater eutrophication potential (FEP) in kg P eq., marine eutrophication potential (MEP) in kg N eq., terrestrial eutrophication potential (TEP) in mole of N eq., human toxicity for cancer (HTP_c) and ecotoxicity in freshwater (ETP) in CTU, particulate matter (PM) in disease incidence, abiotic depletion potential for fossil (ADP_f) in MJ, land use (LU) as a dimensionless number, and water use (WU) in m^3 water eq. deprived. For details about the impact categories not shown here, see the SM. The section of the bars above zero represents the impacts related to the different processes in each configuration. The section below zero represents the avoided impacts related to credits from substitutions or carbon sequestration.

It is important to remember that these results stem from specific modelling choices made to fulfil the purpose of the study. Modelling focused on maximising the visibility of relevant environmental impacts and performance aspects for both RAS configurations. This approach is valid and useful in an initial evaluation prior to potential further development and future implementation. One consequence is that we assume in configuration 2a that a new pyrolysis plant is built to cater for the needs of the fish farm when biochar is needed for the filter. More wood is then taken out of the forest, more biochar will end up on the soil and more heat will replace other heat sources. We assumed in configuration 2b, however, that biochar is a product that is already on the market and destined for agricultural soil that is merely diverted to our fish farm and will land on soil carrying some nutrients in addition to the stable C. Configuration 2a allows us to see if increased use of biochar can help move the fish product system towards carbon neutrality and it also discloses more details about the larger system.

An initial observation is that the impacts related to the forestry activities and pyrolysis facility construction in configuration 2a are large. Forestry activities significantly contribute to LU and FEP. This activity occupies large areas of land for an extended period, which can limit the availability of that land for other uses, potentially leading indirectly also to land transformation. Additionally, forestry practices disturb the soil and increase erosion due to tree harvesting and deforestation. This disruption can result in nutrients, such as P, being washed into nearby freshwater bodies, contributing to eutrophication.

The construction of the pyrolysis plant contributes significantly to ETP and HTPc (carcinogenic). The construction of this sort of plant involves processes like metal smelting, refining, and combustion, which release carcinogenic heavy metals into the environment. These metals can be emitted into the air, water, and soil during the construction of the facility. Once these metals reach freshwater systems, they can accumulate in sediments and bioaccumulate in aquatic organisms, leading to toxic effects across the food chain, and consequently also affect human health. Indeed, long-term exposure to these substances is associated with an increased risk of developing cancer. This impact is related to inhalation or ingestion of toxic emissions or dermal contact with dangerous materials. In this case, the HTPc impact is due to emissions of anthracene, a polycyclic aromatic hydrocarbon (PAH). This substance is released during the production of steel and concrete, materials commonly used in the construction of containers or pyrolysis plants, where exposure might be elevated. The life length and construction of a pyrolysis facility are critical factors influencing ecotoxicity and human toxicity. The management of input materials and waste products, including the treatment of hazardous waste, and construction practices are important elements to take into consideration to mitigate ETP and HTPc, particularly carcinogenic effects. Additional environmental pressure related to ETP in all three configurations is linked to fish feed production. The cultivation of crops for fish feed, like

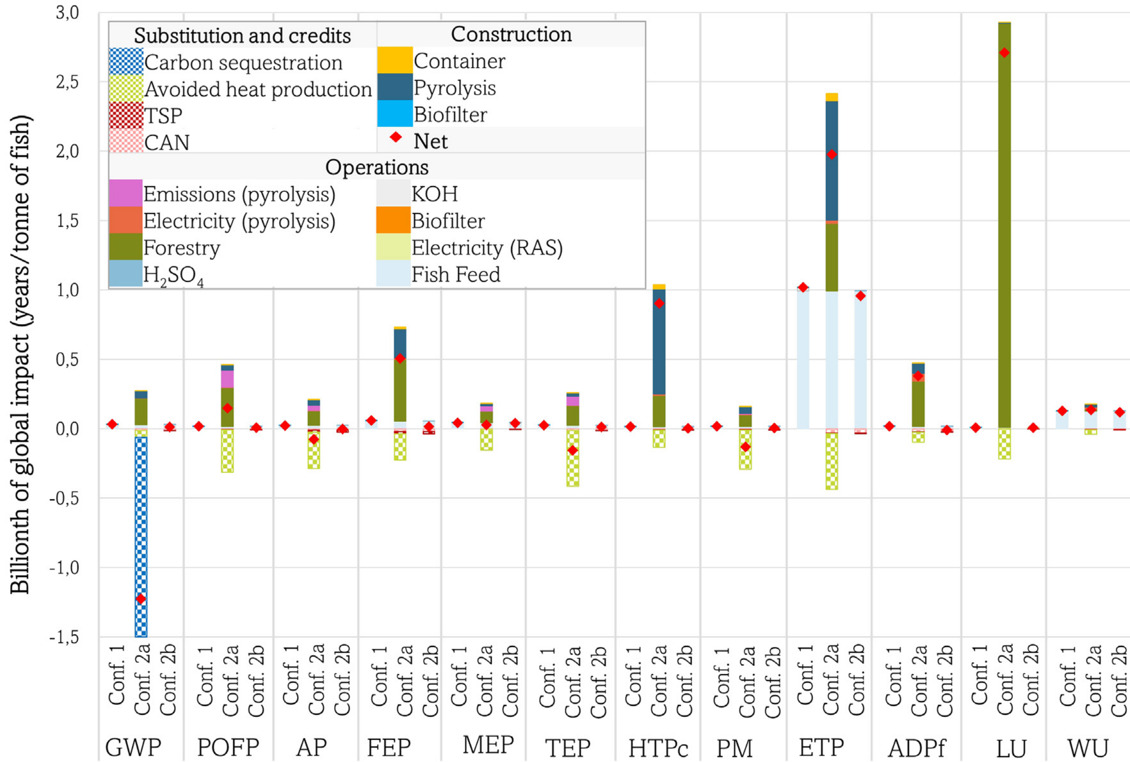

Fig. 2. Normalised environmental impact results for the three configurations for selected impact categories per 1 tonne of Clarias gariepinus fish slaughtered. The analysed impact categories are: global warming potential (GWP), acidification potential (AP), photochemical ozone formation potential (POFP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), terrestrial eutrophication potential (TEP), human toxicity for cancer (HTPc), and ecotoxicity in freshwater (ETP), particulate matter (PM), abiotic depletion potential for fossil (ADPf), land use (LU), and water use (WU).

soy, wheat, and corn, often involves the use of pesticides, herbicides, or fungicides. The use of these chemical products can cause toxic runoff into water bodies or into the soil, contributing to ecotoxicity.

Carbon sequestration contributes strongly to the net benefit for the GWP for configuration 2a. This is due to the biogenic carbon in biochar being stored long-term in soil. The pyrolysis transforms the biomass into a more stable material that resists break-down and thus prevents the transformation of biogenic carbon captured in forestry to be released as CO_2 into the atmosphere. An important assumption is here that all the C in the biochar remains over the full duration of the assessed time period, which is 100 years. This results in overall carbon neutrality and even negative emissions from configuration 2a.

Looking at the net outcomes for the three configurations, for many environmental impacts, the RAS configurations with biochar perform better than the conventional configuration with the biofilter, configuration 1. This is due to benefits derived from resource recovery, such as the heat from gas combustion in pyrolysis and the replacement of commercial fertilisers with the enriched biochar. For configuration 2a, the substitution of heat from combustion of wood chips contributes significantly to the gains for GWP, AP, TEP, and PM. It can be seen, though, that the substitutions do not fully make up for the pyrolysis plant construction and forestry activities in configuration 2a. When it is assumed that the biochar is produced for the market anyway and is only temporarily diverted to the fish farm, avoiding the construction of a new pyrolysis plant and avoiding more wood taken out from the forest (configuration 2b), some of the more prominent impacts related to configuration 2a, are no longer relevant and gains related to heat recovery and C credits are not there.

3.2. Contribution analysis

Here we address the second research question (RQ 2) regarding the environmental hot spots in the life cycle of each configuration. Revealing hotspots is important at this early stage of exploration of this innovative technology and the comparison between configurations focused primarily on comparing hot spots and understanding influencing factors. Identifying hot spots is crucial for prioritising environmental strategies and achieving more sustainable outcomes.

Relative values for the contribution of each process in the three configurations are presented in Fig. 3, enabling a more detailed analysis of hot spots with regard to both impacts and avoided impacts related to substitution (the latter shown with checkerboard pattern).

A clear observation is that fish feed production significantly contributes to all the environmental impacts, especially for configuration 1. This is of course no surprise as this material will be utilised by the fish to make up a large part of the fish biomass. The impacts from fish feed production are more significant than those from chemicals for RAS in all the configurations. The key factors behind these impacts are the composition of feed ingredients, as well as the energy consumption during the production process. Fish feed production includes steps like grinding, mixing, and extrusion, which are energy-intensive processes. When the used energy is derived from non-renewable sources, it contributes to various impacts, for example through greenhouse gas emissions and other pollutants. The expansion of agricultural land for feed crops can affect land use, leading to further ecotoxic impacts as soils are exposed and erosion carries agrochemical residues into waterways (Hossner and Dibb, 2015). Although the fish feed was not put under special scrutiny in this study, it is important to point out its importance to the fish life cycle impacts in general and that addressing this hot spot can help to enable more sustainable food production. More research into this is warranted. Fish feed production has earlier been found to be a critical factor in the environmental performance of RAS. For instance, in a study on Atlantic salmon, feed production accounted for a significant portion of the total GWP (Song et al., 2019). The production of fish feed is also highly energy-intensive. According

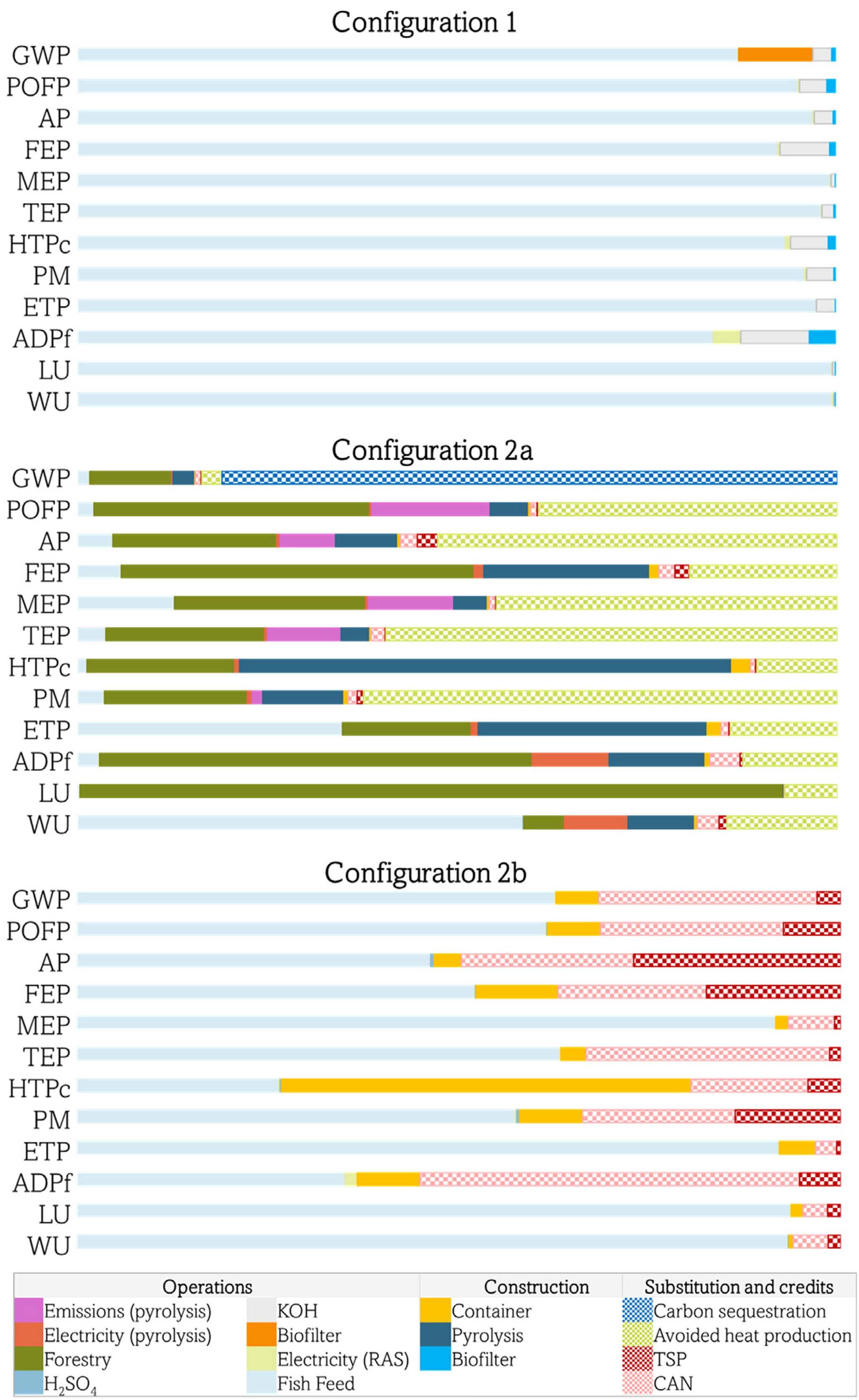

Fig. 3. Contribution analysis for processes involved in the investigated RAS configurations, for selected impact categories: global warming potential (GWP), acidification potential (AP), photochemical ozone formation potential (POFP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), terrestrial eutrophication potential (TEP), human toxicity for cancer (HTPc), and ecotoxicity in freshwater (ETP), particulate matter (PM), abiotic depletion potential for fossil (ADPf), land use (LU), and water use (WU).

to Ramesh et al. (2024), significant energy use was attributed to the production of feed ingredients.

As already mentioned, in configuration 2a, a large part of the impact is attributed to the forestry and the pyrolysis construction, and by excluding these activities in configuration 2b, the impact profile changes, shifting the hot spots to fish feed and container construction. In configuration 1, the operation of the biofilter contributes (by circa 10%) to the GWP and this is because of nitrous oxide (N_2O). It is our assumption that ammonia will not be transformed into nitrogen gas and lost in the biofilter in the innovative set-ups. This also ideally prevents the emission of N_2O produced from the denitrification reaction caused by the bacterial activity during the biofiltration, which was here assumed. It needs to be stated that N_2O emissions have not been measured for the biochar configuration and further studies are warranted.

Fig. 3 also indicates that, overall, chemical production (H_2SO_4), used for configuration 2, does not contribute significantly to the environmental impacts. However, replacing KOH in the pH regulation is a clear advantage to the novel technology. The effect on pH of the biochar is an unexpected positive side-effect that needs further attention in more in-depth studies.

The amounts of N and P captured by the biochar are assumed to be valorised in agriculture. Indeed, the substitution of avoided production of CAN and TSP, contributes in important ways to the gains in configuration 2b for AP, FEP, and ADP_f. Fig. 3 clearly shows that CAN plays a more important role than TSP. CAN substitution notably contributes to positive outcomes, particularly regarding ADP_f. This is because the higher energy consumption associated with the production of CAN through Haber-Bosch technology compared to TSP production. It should be mentioned again that the sludge generated in the drum filter is not considered to be valorised in the current study. It is unclear what the benefits will be when it becomes part of the municipal wastewater management. Future studies could look into the possibility to integrate the sludge into a fertiliser product, possibly even the nutrient-enriched biochar. This could enhance the value of fish sludge by evaluating the most effective system integration for this innovative technology.

Additionally, research should address the economic feasibility of these approaches, considering production costs, market potential, and financial incentives for adoption. From a policy perspective, regulatory frameworks, environmental standards, and incentives for circular economy solutions should be examined to ensure the scalability and practical implementation of these innovative technologies.

3.3. Carbon neutrality

Carbon sequestration plays an important role in the biochar system, allowing configuration 2a to achieve carbon neutrality, as shown in Fig. 3. This addresses the third research question (RQ3), which focuses on understanding whether the RAS with biochar can achive carbon neutrality. For climate change, the carbon sequestration itself counteracts all other impacts relating to the building and use of both pyrolysis plant and biochar filter solution. It is further helped by the opportunity to utilise excess heat. However, avoided heat on its own, will not be enough to counteract the impact related to construction and use of the pyrolysis plant plus the biomass production. Attention needs to be paid to trade-offs with some other environmental impact categories, in particular FEP, HTPc, ETP, ADPf and LU.

A comparison of the three configurations for production of *Clarias gariepinus* and literature data for a benchmark product, salmon fillet, was conducted. Given that the system boundaries and other features of individual studies can be different, comparisons between studies should be made with caution. The contribution to climate change of a salmon fillet is 5.03 kg of CO_2 eq. per kg (Coelho et al., 2023). We assumed that circa 35% of *Clarias gariepinus* can be turned into fillet (Pinheiro et al., 2006). On this basis, the contributions to climate change of biochar configurations 2a and 2b were −203 and +2.70 kg, respectively per kg of fillet. In contrast, for the biofilter RAS configuration, this value is 5.32 kg of CO_2 eq. per kg of fillet. Other authors suggest that the GWP of fish from RAS varies from 3.73 to 28 kg CO_2 eq. per kg (Ahmed and Turchini, 2021). This impact is significantly influenced by energy consumption and feed production (Ahmed and Turchini, 2021; Bergman et al., 2020).

3.4. Sensitivity analysis and potential limitations

Given the early stage of technical development for the RAS configuration with biochar, it is important to consider how specific assumptions influence the impact assessment results. For instance, different biomass feedstock produces biochar with varying properties and yields (Liu et al., 2018; Wang et al., 2019). Additionally, pyrolysis temperature significantly affects biochar yields. Higher temperature decreases biochar yields while increasing gas production (McNamara et al., 2016; Torres et al., 2020). For example, raising the pyrolysis temperature from 300 to 800 °C reduces the biochar yield by 10.5%, and increases the gas yield by 17.2% (Torres et al., 2020). This trend in biochar yield is consistent with other research (Zhang et al., 2020). Lower temperatures require less energy, making the process more energy-efficient and potentially more cost-effective. However, the biochar produced at lower temperatures may have lower C content and stability compared to biochar produced at higher temperatures (McNamara et al., 2016). Yields will affect how much biochar is available for the innovative filter per land area used for biomass production. Another potentially very important assumption is the NH_4^+ adsorption capacity since this sets the dimensions for major parts of the system. In our specific case study, we adopted the NH_4^+ adsorption capacity suggested by Weldon et al. (2022) (4.2g NH_4^+ /kg). However, depending on the type of biochar, NH_4^+ adsorption can range from 0.7 to 17.6 g/kg (Maleki Shahraki and Mao, 2022).

To examine the influence of NH_4^+ adsorption capacity, a sensitivity analysis was performed. Two additional scenarios were considered for this: 1) NH_4^+ adsorption capacity is 0.7 g/kg of biochar; and 2) NH_4^+ adsorption capacity is 17.6 g/kg of biochar. The RAS configuration 2a is the only configuration that is affected by this variation. A comparison of some of the environmental impact results for configuration 2a for these different scenarios is shown in Fig. 4 (more results are reported in the SM).

Using a low NH_4^+ adsorption capacity (0.7 g/kg of biochar) increases the required biochar mass, which consequently raises the benefit related to replaced products (CAN, TSP, and heat). More biochar mass means more forestry biomass, leading to increased environmental impacts, particularly for LU. This scenario shows better performance in terms of GWP, as more biochar is produced, used as a filter and ultimately contributes to carbon sequestration. The opposite happens when a higher NH_4^+ adsorption capacity (17.6 g/kg of biochar) is used. Compared to the base scenario, scenario 2 shows a better performance for all the environmental impacts except GWP.

Furthermore, the relevant replacement ratios for substituting mineral fertilisers such as CAN and TSP may vary depending on the type of biochar and many other parameters. Since this is a new type of fertiliser product, it remains to be explored how the comparison to current mineral fertilisers plays out in reality. This study assumes a 1:1 replacement ratio, meaning that all the N and P content in biochar will replace N in CAN and P in TSP. Some studies suggest that a significant portion of N and P in biochar can stoichiometrically replace N and P in mineral fertilisers (Abdo et al., 2022; Shaltout et al., 2023) but information in literature is scarce. The effectiveness of biochar depends also on its combination with other fertilisers and the specific crop and soil conditions (Abdo et al., 2022; Shaltout et al., 2023; Sun et al., 2024). Heimersson et al. (2016) showed that replacement ratios for sewage sludge in agriculture compared to mineral fertilisers ranged from 0.3 to 1 for N and from 0.5 to 1 for P. However, further research

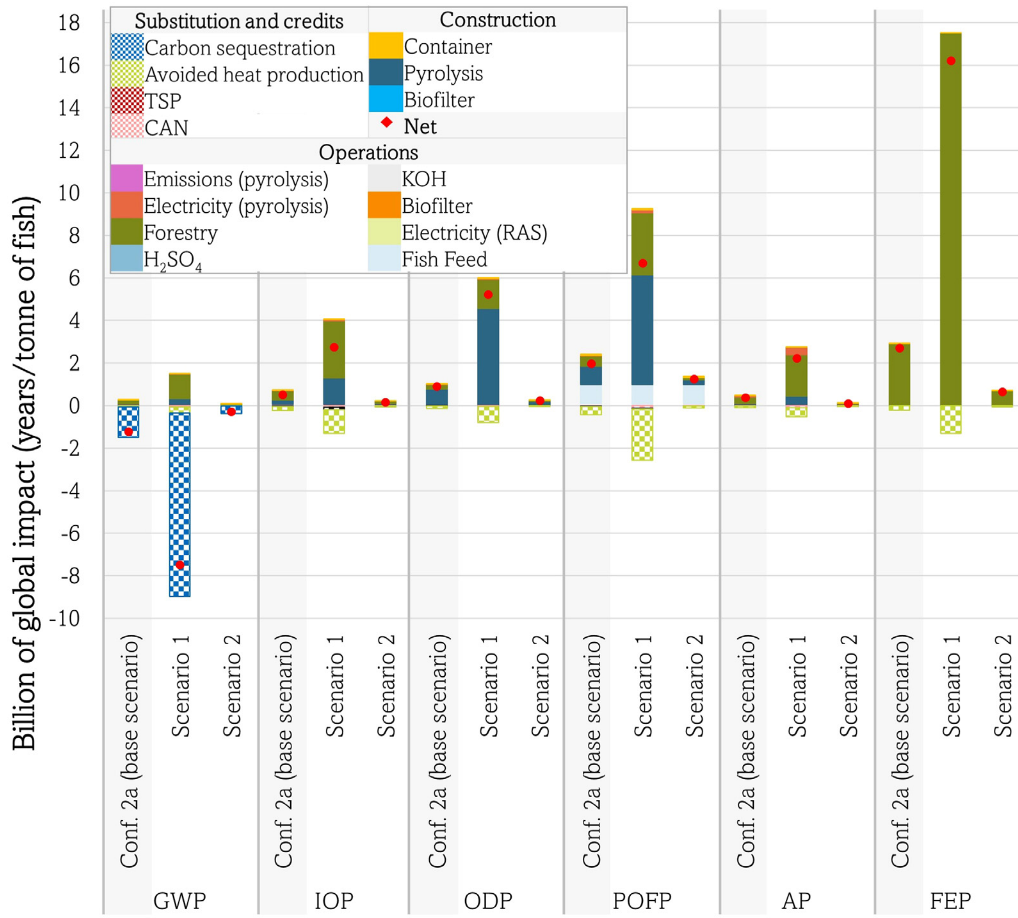

Fig. 4. Sensitivity analysis for RAS configuration 2a, for selected impact categories global warming potential (GWP); freshwater eutrophication potential (FEP); human toxicity for cancer (HTPc) and ecotoxicity in freshwater (ETP), abiotic depletion potential for fossil (ADPf), and land use (LU). The three considered scenarios in this sensitivity analysis are the base case that assumes an NH_4^+ absorption capacity of 4.2 g/kg of biochar and scenarios 1 and 2 which assume 0.7 and 17.6 g/kg of biochar, respectively.

and field trials are recommended to determine actual replacement ratios for nutrient-enriched biochar for different agricultural contexts. A sensitivity analysis was performed, varying substitution ratios between the ones suggested above. Given the low influence of CAN and TSP even in the base case, which is a best case, it is easily understood that this did not change results in important ways. This analysis is therefore not shown here.

The stability of biochar in soil is a crucial factor for long-term carbon sequestration and soil health. Biochar is highly stable due to its resistance to microbial degradation, making it an effective amendment for increasing soil organic carbon (Kimetu and Lehmann, 2010). The loss of CO_2-C from soil after biochar application varies significantly depending on factors such as time, biochar type, application rate, soil characteristics, and environmental conditions. In this study, we assumed that all the C (100%) in biochar is sequestered for all relevant time, leading to long-term carbon storage. However, biochar C losses have been reported to range from 0.3% to 2.5% in the short term (60 days) (Grutzmacher et al., 2018) and from 0.4% to 6.4% over the long term (100 years) (this last range is calculated based on the data of Grutzmacher et al. (2018) – see SM). As can be understood from Fig. 2, even a 6.4% C loss will not significantly impact the GWP results. The use of biochar with the system view offered by configuration 2b will still lead to carbon neutrality in RAS fish production.

Also the EF for N_2O used to calculate the N_2O emissions from the MBBR, is a value that needs to be considered. When conducting this type of analysis, it is important to consider an EF specific to bioreactors. When the biofilter was considered to be replaced by the biochar filter in configurations 2a and 2b, the basic assumption was that to avoid the loss of nitrogen gas to air, build-up of bacterial N removal on the biochar should be avoided and N_2O emissions are then also kept low, assuming to be zero in our case. If and how this can be done in practice remains to be understood.

An additional limitation of our study is related to the fish feed. In particular, the use of data on feed for tilapia fish instead of feed for African catfish might be important, given the lack of information on the material composition and production processes. If actual upscaling is considered, future research should consider this since the fish feed makes a significant contribution to all the environmental impact categories. Since different types of feed have varying concentrations of N and P, beyond the upstream impact from feed production, the amount of nutrients retained in the biochar will differ based on the type of feed used. It should be noted that *Clarias* is an omnivorous fish species, which opens up avenues for exploring many different potentially sustainable feed sources.

4. Conclusions

A conceptual scaling up was performed to provide the data inventory for LCA of a novel RAS technology involving the use of biochar from pyrolysis. Two different system views were applied and the novel technology was also compared with a conventional RAS. The three systems compared in this study have slightly different rationales and inventory data quality and are therefore not fully comparable, but the study still enabled an exploration of orders of magnitudes, hot spots, dominant parameters, and improvement opportunities within and across configurations.

Except for HTPc and LU, RAS with biochar performed better than the RAS with biofilter due to the gains from using the enriched biochar as fertiliser and from changes in pH regulation. When the biochar is included within the system boundaries in configuration 2a, the large gains from the replaced heat further contribute to an improved situation.

For the conventional configuration, the main hotspots are related to fish feed production and electricity, while in configuration 2a the impacts are mainly related to forestry biomass production and pyrolysis technology construction, so fish feed plays a less prominent role. Except for GWP, configuration 2b performs better than the other two configurations across all the environmental impact categories, but the contribution impact shifts from forestry and pyrolysis plant construction to fish feed production and container construction.

There are several factors which influence C sequestration in practice. We assumed a range of 0% to 6.4% of the C in biochar is lost after agricultural application. Under these circumstances, the use of biochar in RAS facilitates long-term carbon storage, positioning this technology as a potential means to achieve carbon neutrality in RAS fish production.

Performing environmental LCA of a system such as an innovative RAS configuration that does not yet exist at commercial scale is challenging, but worthwhile to pre-empt design problems. It allows for the early identification and mitigation of potential environmental impacts, supports sustainable design, and helps in making informed decisions that can lead to the development of more environmentally friendly technologies.

CRediT authorship contribution statement

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

Declaration of competing interest

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

Acknowledgements

This study was part of the Nutribatt (nutrients batteries for sustainable aquaculture) project, financially supported by the Kamprad Family for Entrepreneurship, Research and Charity under grant 20220105. We are immensely grateful to all project participants, and especially to Henrik Brunberg, Pond Fish and Green AB, Edvard Hamilton, Hjelmsäters Fastigheter, and Efsthatios Reppas Chrysovitsinos, currently at IVL, who provided insights and expertise that greatly assisted the research.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2025.100233.

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