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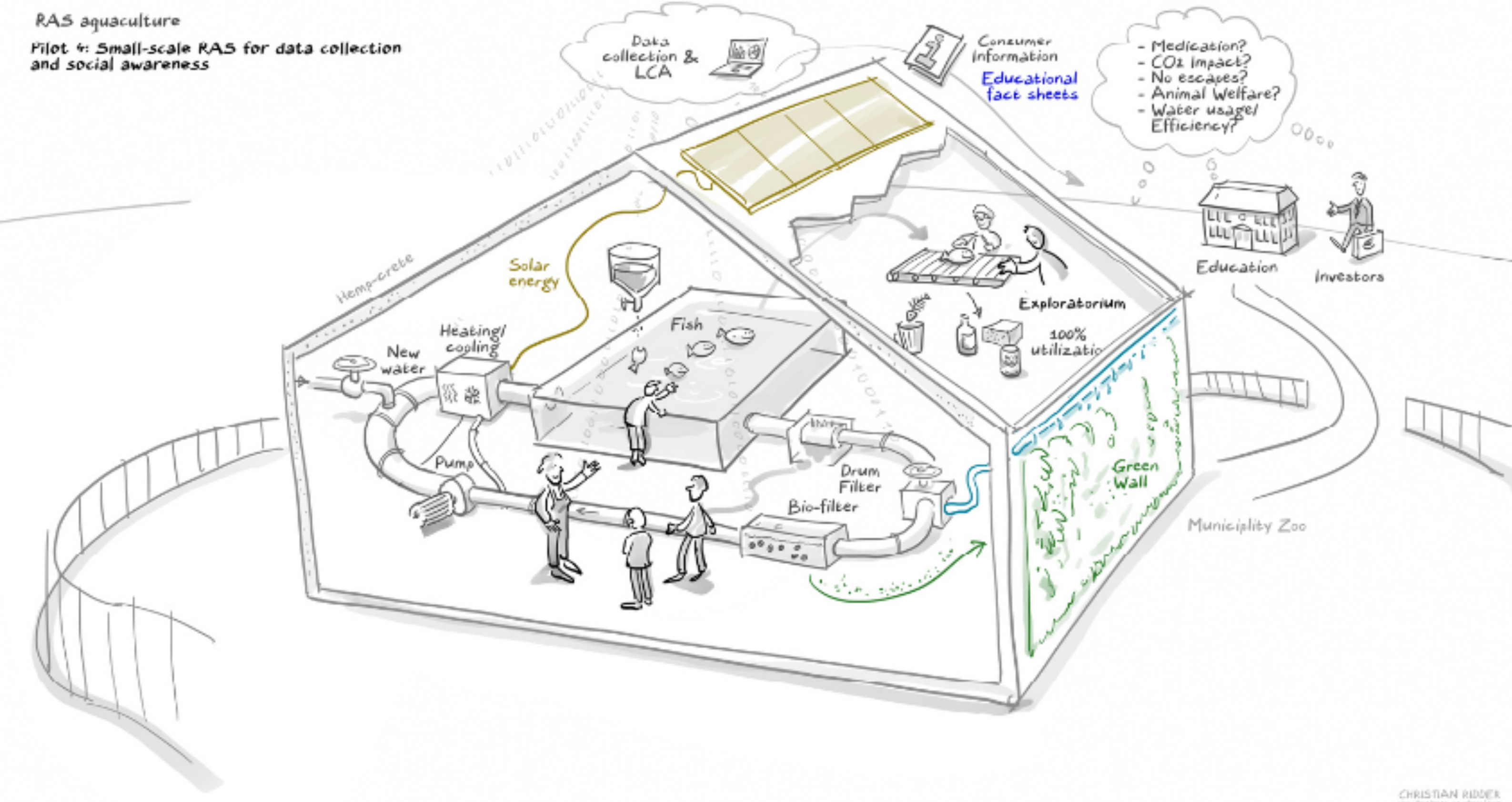

Life Cycle Assessment (LCA) of African catfish (Clarias gariepinus) in a recirculating aquaculture system in Denmark

Pilot Owner:

GULDBORGSUND

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WATER-SMART SOCIETIES

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1. Introduction

This report presents the environmental profile of African catfish (*Clarias gariepinus)* produced in a pilot recirculating aquaculture system (RAS) located in Guldborgsund Municipality (Denmark). The primary purpose of the pilot was physical demonstration and awareness-raising on RAS fish production and on the suitability of African catfish for intensive farming in Denmark.

The LCA approach was applied according to the standards ISO 14040 and ISO 14044. According to these, an LCA analysis is composed of 4 different stages:

1. Goal and scope definition;
2. Inventory analysis;
3. Impact assessment;
4. Discussion and interpretation of the results.

2. Application of Life Cycle Assessment approach

2.1 Goal and scope definition

The goal of this study is to evaluate the environmental impacts associated with the production of African catfish (*Clarias gariepinus*) in a pilot recirculating aquaculture system (RAS) located in Guldborgsund (Denmark), and to identify the most impactful processes (hotspots) within the production system. The analysis refers to the demonstration cycle conducted at the pilot unit and provides an environmental profile that can support communication in a Danish regulatory context and inform about environmental impact accounting. Furthermore, the study can serve as a decision-support tool to guide future developments and implementations of intensive RAS production of African catfish, and to identify potential areas for improvement in the system's overall environmental performance.

2.1.1 Functional unit

In Life Cycle Assessment (LCA), the Functional Unit (FU) is defined as the "quantified performance of a product system for use as a reference unit" (ISO 14044; Jolliet et al., 2016). It serves as the basis for relating all input and output data to a common denominator, ensuring transparency and comparability across studies.

In aquaculture-related LCAs, the functional unit is most commonly expressed on a mass basis. Several previous studies on different aquaculture species have adopted this approach (Zoli et al., 2023; Bergman et al., 2020; Bosma et al., 2011). In line with this convention, the present study employs 1 kg of live weight of fish as the functional unit.

However, aspects related to processing and by-product generation are also considered and discussed in the Discussion section, to account for alternative allocation approaches and downstream valorisation routes.

2.1.2 System boundaries

Defining the system boundaries is a fundamental step in LCA, as it determines which processes are included or excluded in the assessment. The boundaries should ideally encompass all relevant processes required to deliver the defined function (Jolliet et al., 2016).

In this study, a "cradle-to-gate" approach was adopted, meaning that the analysis includes all processes from the extraction of raw materials up to the point of fish harvesting at the aquaculture facility. The subsequent stages (processing, distribution, consumption, and end-of-life of packaging and waste) are not considered in this assessment.

As illustrated in Figure 1, the system boundaries include the following processes:

- Raw material extraction and upstream processes, such as mining, refining, and chemical production used for feed and equipment manufacturing;
- Production and supply of electricity, including the Denmark energy mix;
- Combustible fuels required for transportation and upstream operations;
- Production and supply of juvenile fish;
- Construction, manufacturing, and life span of infrastructures and equipment (e.g., tanks, pumps, aeration and filtration systems);

- Production and supply of aquafeed, which typically represents a major contributor to aquaculture impacts;
- Farming operations (stocking, feeding, aeration, water management, monitoring);
- Harvesting of fish at the experimental facility gate;
- Wastewater treatment of the discharged water;
- Emission of fish metabolism (nitrogen and phosphorus compound) in the environment.

Excluded from the system boundaries are processes related to processing (cooking, freezing), packaging, retail, consumption, and waste management. as these go beyond the defined goal of assessing the farming stage.

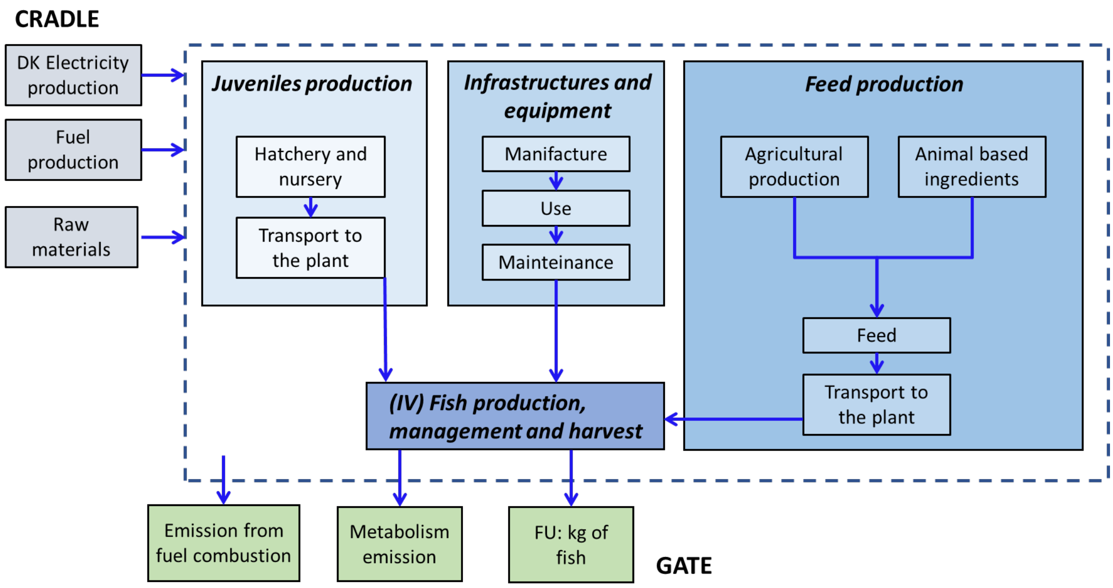

Figure 1: System boundaries of the African catfish farming LCA.

2.2 Inventory analysis

Two types of data were used to model the analysed system:

- Primary data, directly measured or recorded at the pilot RAS during the demonstration cycle (rearing duration, water recirculation and make-up flows, feed inputs, mortalities, electricity consumption, and infrastructure inventory);

- Secondary data, obtained from life cycle databases (Ecoinvent 3.9, Agri-Footprint) and published sources (feed ingredient datasets, Danish electricity mix, capital goods, and nutrient emission factors).

The analysed system is a pilot-scale recirculating aquaculture system (RAS) designed for the rearing of African catfish. The system includes two rearing tanks (approximately 4 m³ each), for a total effective water volume of 9.5 m³. The rearing cycle lasted 201 days, starting from an initial biomass of 60 kg (about 600 juveniles of 100 g each) and reaching a final biomass of 842.5 kg, corresponding to a net weight gain of 782.5 kg. The feed conversion ratio (FCR, kg feed supplied per kg net weight gain) was 1.05, based on a total feed input of 820 kg. The mortality rate during the cycle was estimated at 10%.

Water was continuously recirculated at a rate of 9.0 m^3/day, with an additional 0.475 m^3/day of freshwater added to compensate for evaporation and losses (approximately 5% of the total volume). Oxygen levels were maintained through air blowers and air-lift systems, while no liquid oxygen was used. The total water discharged during the cycle amounted to 104.9 m^3.

Feed supply was based on a commercial extruded pellet (Alltech Coppens – Special Pro EF, 4.5 mm) containing 44% crude protein, 14% crude fat, 6.4% ash, and 19.9 MJ/kg of digestible energy. The formulation includes fishmeal, fish oil, poultry by-product meal, hydrolysed feather meal, wheat gluten, barley protein concentrate, and yeast derivatives. Since the exact inclusion rates of individual ingredients were not disclosed by the manufacturer for confidentiality reasons, they were reconstructed based on the nutritional composition of the feed and the characteristics of each ingredient (**see Table 1**). Uneaten feed was assumed to represent 5% of the total amount distributed.

Electricity consumption, recorded at 10,275.9 kWh per cycle, was modelled according to the Danish national electricity mix, which includes both renewable and fossil-based energy sources.

Data on capital goods, infrastructures, and equipment (materials, lifespan, and power specifications) were collected from facility managers and modelled using secondary datasets from Ecoinvent, based on their technical lifespan and operational characteristics.

Nutrient emissions (N and P) were estimated using a mass-balance approach (Cho, 2004) calculated as the difference between the nutrients provided in the feed and those retained in fish biomass. Average body composition values for African catfish were derived from the literature and combined with apparent digestibility coefficients. The resulting dissolved and particulate fractions were inventoried as emissions to water, including solid nitrogen, ammonia, ammonium, and nitrate for nitrogen compounds, and solid phosphorus and phosphate (PO_4^{3-}) for phosphorus compounds.

Literature data were also used to model the impact of juvenile production (Bergman et al., 2020). For background processes, such as the production of feed ingredients, materials, and disinfectants, secondary data from standard LCA databases were adopted, including Ecoinvent, Agribalyse, and Agri-Footprint.

A summary of all inventory flows and parameters is provided in **Tables 1** and **2.**

Table 1: Estimated composition, input and administered quantities of the feed

Feed ingredients	Estimated inclusion
Fish meal	22.5
Poultry meal	20
Wheat	17
Wheat gluten	13
Rapeseed oil	8
Barley protein meal	7

Hydrolised feather protein meal	5
Fish oil	5
Yeast products	2.5
Other input per ton of feed	
Electricity	35 kWh
Heat	145 MJ
Water	56 kg
Feed amount provided	820 kg

Table 2: Main inventory data and information collected and used for the LCA study across the Africa catfish production cycle

Parameters	Unit	Value
Cycle duration	days	201
Juveniles	kg	60
Juveniles single weight	kg	0.1
Total plant volume	m^3	9.5
Water daily recirculation	m^3	9.025
Daily added freshwater	m^3	0.475
Oxygen concentration	mg/l	2.5
Disinfectants (H2O2 footbath)	l	1
Disinfectant - H2O2 hand pump	l	5
Bicarbonate of Soda	kg	107
Sea salt	kg	18
Electricity	kWh	10,275.9
Mortality	%	10
FCR	/	1.05
Emissions		
Ammonia	kg	0.39
N ammonium	kg	17.95
Nitrate	kg	10.89
N solid	kg	8.15
Phosphate	kg	1.62
P solid	kg	3.67
Biomass output		
Fish live weight	kg	842.5
Wastewater	m^3	104.9

2.3 Life Cycle Impact Assessment

In this phase, all the collected inventory data is converted into different impact categories (environmental effects) using a characterization method. The characterization method chosen for this study is Environmental Footprint 3.1 (Andreasi bassi et al., 2023), as it represents the most updated and recent European characterization method. It includes the following impact categories: Acidification (AC, mol H+ eq), Climate change (CC, kg CO2 eq.), Ecotoxicity, freshwater (FEx, CTUe), Particulate matter (PM, disease incidence), Eutrophication, marine (ME, kg N eq.), Eutrophication, freshwater (FE, kg P eq.), Eutrophication, terrestrial (TE, mol N eq.), Human toxicity, cancer (HT_c, CTUh), Human toxicity, non-cancer (HT-nc, CTUh), Land use (LU, Pt), Ozone depletion (OD, kg CFC11 eq.), Photochemical ozone formation (POF, kg NMVOC eq.), Resource use, fossils (RUF, MJ), Resource use, minerals and metals (RUMM, kg Sb eq.), and Water use (WU, m^3 deprived). In addition, the Cumulative Energy Demand (CED, MJ eq) (Frischknecht et al., 2007) and Net Primary Production Use (Papatryphon et al., 2004) impact categories were also calculated. In particular, CED quantifies the total primary energy (renewable and non-renewable) extracted from nature to support the life cycle, aggregated across all energy carriers; NPPU measures the appropriation of net primary production, i.e., the amount of biogenic carbon required in aquafeed ingredients (directly and indirectly) by the system, indicating pressure on ecosystems and trophic resources.

3. Results

3.1 Absolute results

The environmental impacts calculated for the impact categories (environmental effects) described above are reported in **Table 3**.

Table 3: Environmental impact of producing 1 kg of live weight of African cat fish (Claris gariepinus).

Impact category	***Unit***	***Impacts***
AC	mol H+ eq	0.03
CC	kg CO_2 eq	4.50
FEx	CTUe	131.85
PM	disease inc.*10^-6	0.27
ME	kg N eq	0.03
FE	kg P eq	0.01
TE	mol N eq	0.09
HT-c	CTUh*10^{-8}	0.35
HT-nc	CTUh*10^{-6}	0.12
OD	kBq U-235 eq	0.31
POF	mg CFC11 eq	0.31
RU-f	kg NMVOC eq	0.02
RU-mm	MJ*10^{-5}	65.54
WU	kg Sb eq	9.21
CED	m^3 depriv.	3.36
NPPU	kg C	1.01

A: Acidification; CC: Climate change; FEx: Freshwater ecotoxicity; PM: Particulate matter formation; ME: Marine eutrophication; FE: Freshwater eutrophication; TE: Terrestrial eutrophication; HT-c: Human toxicity, cancer effects; HT-nc: Human toxicity, non-cancer effects; OD: Ozone depletion; POF: Photochemical ozone formation; RU-f: Resource use, fossils; RU-mm: Resource use, minerals and metals; CED: Cumulative energy demand. NPPU: Net Primary Production Use.

3.2 Contribution analysis

The contribution analysis is a key step within LCA studies, as it breaks down the overall environmental impacts into the relative shares of each process or subsystem included within the system boundaries. This type of analysis allows the identification of hotspots, i.e. the processes, inputs, or life cycle stages that contribute most significantly to each impact category. By quantifying the percentage contribution of feed, energy use, infrastructures, nutrient emissions, and juveniles, it becomes possible to highlight the main environmental drivers of the system and to prioritise interventions for impact reduction.

The contribution analysis for the African catfish production system (**Figure 2**) shows that feed production is the dominant contributor across most impact categories. In particular, feed accounts for 42–53% of the total impact in Acidification (A), Particulate Matter (PM), and Terrestrial Eutrophication (TE), and up to 76.8% in Ozone Depletion (OD). It also represents a major contributor to Climate Change (CC) and Photochemical Ozone Formation (POF), with shares of 27.7% and 39.1%, respectively. These results confirm that the production and transport of feed ingredients, especially marine- and animal-derived proteins, remain the most critical hotspot in aquaculture life cycles.

Electricity consumption is the second-largest contributor, ranging from 32% to 72% depending on the impact category. It dominates the results for Climate Change (59.7%), Cumulative Energy Demand (71.6%), and Resource use, fossils (66.4%), underlining the energy-intensive nature of RAS. Similarly, electricity use contributes substantially to Human Toxicity, non-cancer effects (66.3%), and Resource use, minerals and metals (64.6%), reflecting the relevance of energy supply chains in the Danish electricity mix.

Nutrient emissions play a significant role in eutrophication-related impacts. Nitrogen emissions account for 64% of Marine Eutrophication (ME), while phosphorus emissions are responsible for 61% of Freshwater Eutrophication (FE). This pattern highlights the importance of managing nutrient retention efficiency and waste treatment to mitigate eutrophication in intensive fish farming systems.

Infrastructures and equipment have a moderate but non-negligible contribution, particularly in categories linked to resource use and toxicity. They represent 24.2% of Resource use, minerals and metals (RU-mm) and 20.7% of Human Toxicity, cancer effects (HT-c), mostly due to the materials used in tanks, piping, and filtration units (fiberglass, metals, plastics).

Production factors, such as disinfectants and minor consumables, show small but consistent shares (3–8%) across several categories, especially Acidification and Particulate Matter, reflecting upstream emissions from their manufacture and transport.

The contribution of juveniles remains limited, generally below 3% in all categories, confirming their minor role compared to feed and energy inputs. Water use contributes significantly only to the Water Use (WU) category (≈2%), as expected, while wastewater treatment shows small but visible shares (up to 5%) in categories such as Freshwater Eutrophication and Particulate Matter, associated with the management of discharged effluents.

Overall, these results indicate that, as in most RAS systems, feed and electricity jointly dominate the environmental profile of African catfish production, while nutrient emissions and material-related processes determine the variability across impact categories.

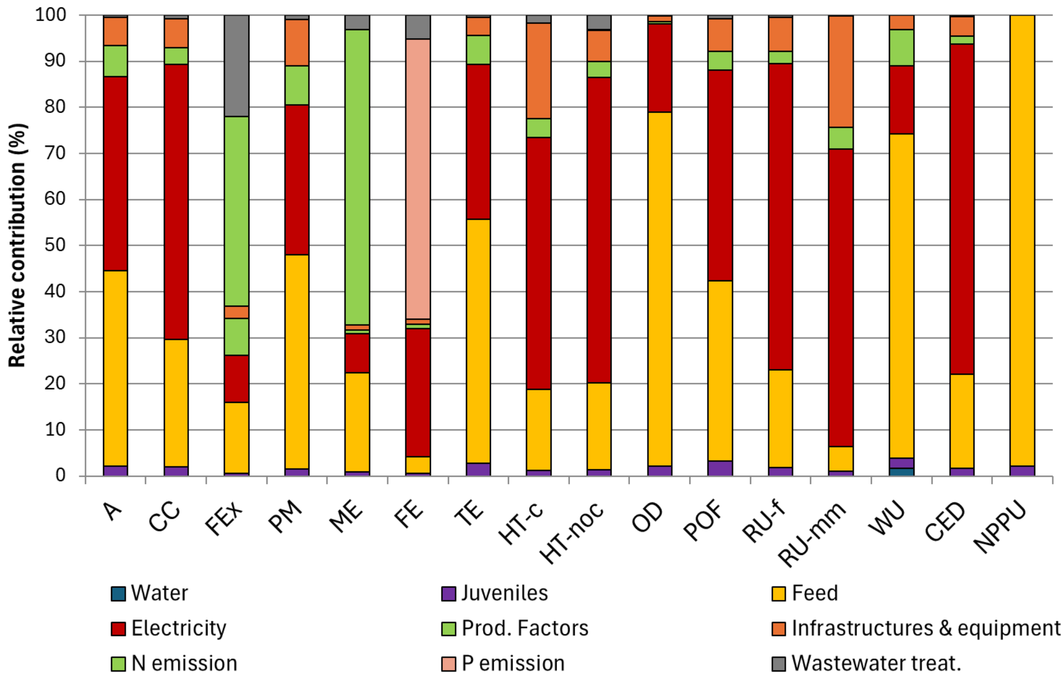

Figure 2: Analysis of the contributions to the environmental impact of 1 kg of African catfish live weight. A: Acidification; CC: Climate change; FEx: Freshwater ecotoxicity; PM: Particulate matter formation; ME: Marine eutrophication; FE: Freshwater eutrophication; TE: Terrestrial eutrophication; HT-c: Human toxicity, cancer effects; HT-nc: Human toxicity, non-cancer effects; OD: Ozone depletion; POF: Photochemical ozone formation; RU-f: Resource use, fossils; RU-mm: Resource use, minerals and metals; CED: Cumulative energy demand. NPPU: Net primary production use.

3.3 Uncertainty analysis

An uncertainty analysis was carried out using the Monte Carlo technique (1000 iterations and a 95% confidence interval) to verify the robustness of the results obtained with respect to the selection and use of the background data (database). It is therefore important to note that the data considered in the uncertainty analysis represent 41.9% of the total data in the analysis (**table 4**). The results indicate good robustness for the CC, AC, ME, FE, RU-f and CED all show low dispersion (CV ≲ 5–10%) and narrow confidence intervals. By contrast, human toxicity (HT-c/HT-nc) and a few categories with very small means (TE, WU, FEx) exhibit high relative uncertainty, including wide CIs and occasional negative lower bounds, reflecting known limitations/variability in characterization factors and the effect of dividing by near-zero means. These results support relying primarily on the more stable categories (e.g., CC and eutrophication) for comparative statements.

Table 4: Statistical summary of impact categories per functional unit (1 kg fish live weight).The table reports the mean, median, standard deviation (SD), coefficient of variation (CV), 95% confidence interval (2.5% and 97.5% percentiles), and standard error of the mean (SEM) for selected impact categories.

Impact cat.	***Unit***	***Mean***	***Media***	***SD***	***CV***	***2.50%***	***97.50%***	***SEM***
AC	mol H+ eq	3.2E-02	3.2E-02	1.8E-03	5.7E+00	2.9E-02	3.6E-02	5.7E-05
CC	kg CO2 eq	4.5E+00	4.5E+00	2.3E-01	5.1E+00	4.1E+00	5.0E+00	7.2E-03
FEx	CTUe	1.4E+02	1.5E+02	3.4E+02	2.4E+02	-5.1E+02	8.3E+02	1.1E+01
PM	disease inc.*10^{-5}	8.2E-03	7.9E-03	1.4E-03	1.7E+01	6.7E-03	1.2E-02	4.4E-05
ME	kg N eq	3.1E-02	3.1E-02	6.3E-04	2.0E+00	3.0E-02	3.2E-02	2.0E-05
FE	kg P eq	9.0E-02	9.0E-02	4.0E-03	4.5E+00	8.3E-02	9.9E-02	1.3E-04
TE	mol N eq	3.6E-08	-6.3E-10	6.9E-07	1.9E+03	-1.4E-06	1.5E-06	2.2E-08
HT-c	CTUh*10^{-6}	4.5E-06	3.5E-06	8.5E-05	1.9E+03	-1.6E-04	1.7E-04	2.7E-06
HT-nc	CTUh*10^{-6}	3.1E-07	3.1E-07	5.6E-08	1.8E+01	2.2E-07	4.5E-07	1.8E-09
OD	mg CFC11 eq	2.7E-07	2.7E-07	2.3E-08	8.5E+00	2.4E-07	3.2E-07	7.4E-10
POF	kg NMVOC eq	1.6E-02	1.6E-02	9.9E-04	6.1E+00	1.4E-02	1.8E-02	3.1E-05
RU-f	MJ	6.6E+01	6.5E+01	6.1E+00	9.3E+00	5.5E+01	7.9E+01	1.9E-01
RU-mm	g Sb eq	9.2E-05	8.8E-05	1.8E-05	2.0E+01	6.4E-05	1.4E-04	5.8E-07
WU	m^3 depriv.	3.6E+00	8.5E+00	6.4E+01	1.8E+03	-1.4E+02	1.1E+02	2.0E+00
CED	MJ eq	1.3E+02	1.3E+02	6.6E+00	5.3E+00	1.2E+02	1.4E+02	2.1E-01
NPPU	kg C	1.0E+00	1.0E+00	7.8E-08	7.7E-06	1.0E+00	1.0E+00	2.5E-09

A: Acidification; CC: Climate change; FEx: Freshwater ecotoxicity; PM: Particulate matter formation; ME: Marine eutrophication; FE: Freshwater eutrophication; TE: Terrestrial eutrophication; HT-c: Human toxicity, cancer effects; HT-nc: Human toxicity, non-cancer effects; OD: Ozone depletion; POF: Photochemical ozone formation; RU-f: Resource use, fossils; RU-mm: Resource use, minerals and metals; CED: Cumulative energy demand; NPPU: Net primary production use.

4. Discussion and Conclusions

This study presents an attributional LCA of pilot-scale RAS production of African catfish (*Clarias gariepinus*) in Denmark, yielding a climate change result of 4.50 kg CO_2 eq per kilogram of live fish. The hotspot pattern is led by electricity (59.7% of CC), followed by feed (27.7%) and infrastructures/equipment (6.3%). Eutrophication impacts are governed by nutrient emissions, with nitrogen driving Marine Eutrophication (64%) and phosphorus driving Freshwater Eutrophication (61%). This structure is consistent with African catfish and other warm-water fish produced in commercial RAS, where feed typically dominates most categories and electricity is the second contributor, while capital goods appear primarily in minerals/metals use and toxicity indicators (Bergman et al., 2020). The notable difference here is the relatively low feed share in CC, credibly explained by the excellent FCR (≈ 1.05), which depresses feed-related burdens per kilogram of fish, whereas electricity assumes a proportionally larger role in this demonstration-scale context. The link between biological performance and environmental outcomes in African catfish RAS is also consistent with bio-economic/LCA modelling showing that improving FCR systematically reduces impacts across categories, while faster growth lowers impacts only when production is density-limited (Besson et al., 2016).

Side-stream management provides additional levers beyond the farm-gate scope applied here. At the processing step, fillet (250 kg), soup (75 kg), pet food (25 kg), skins (0.6 kg), and fish remains (490 kg) were produced. If downstream processing is included in future modelling, upstream grow-out burdens can be partitioned among fillets and co-products via ISO-consistent allocation (mass- or economic-based); in practice this tends to lower the per-kilogram footprint of the edible fraction compared with assigning all upstream loads to fillet alone, also highlighted as an improvement option for RAS fish in Sweden (Bergman et al., 2020). Alternatively, system expansion (avoided burden) can be applied to the anaerobic digestion pathway: if digestion of fish remains yields heat and/or electricity that displaces fossil energy, the system can claim credits that reduce net CC and fossil resource use. The magnitude of these credits should be assessed explicitly, considering the methane potential of the fish remains and local conversion efficiencies; nonetheless, this route would almost certainly provide an environmental benefit attributable to the aquaculture system.

Taken together, the results and literature suggest a coherent improvement trajectory. Maintaining and, where possible, further improving FCR while reducing uneaten feed (assumed 5%) will yield cross-category benefits; modest reformulations toward lower-impact protein and lipid sources can contribute without compromising performance, in line with African catfish RAS evidence that FCR is the most reliable lever for impact reduction. Electricity's prominence in this pilot points to operational efficiency in aeration/air-lift and pumping and to greener power procurement as immediate opportunities to cut CC, CED, and RU-f. On the water-quality side, tightening solids capture and clarifying N versus P partitioning in the mass balance can target eutrophication reductions effectively.

Finally, as throughput increases from demonstration to more stable operation, fixed burdens from capital goods will dilute; where replacements are planned, choosing materials and technologies with lower embodied impacts can further reduce contributions to minerals/metals use and toxicity.

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In conclusion, the pilot's footprint and hotspot ranking are fully consistent with the African catfish RAS evidence base: feed and electricity remain the principal levers, nutrient management shapes eutrophication outcomes, and side-stream valorisation, either via allocation or system expansion crediting AD-to-energy, offers a credible pathway to lower net impacts while strengthening circularity.

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