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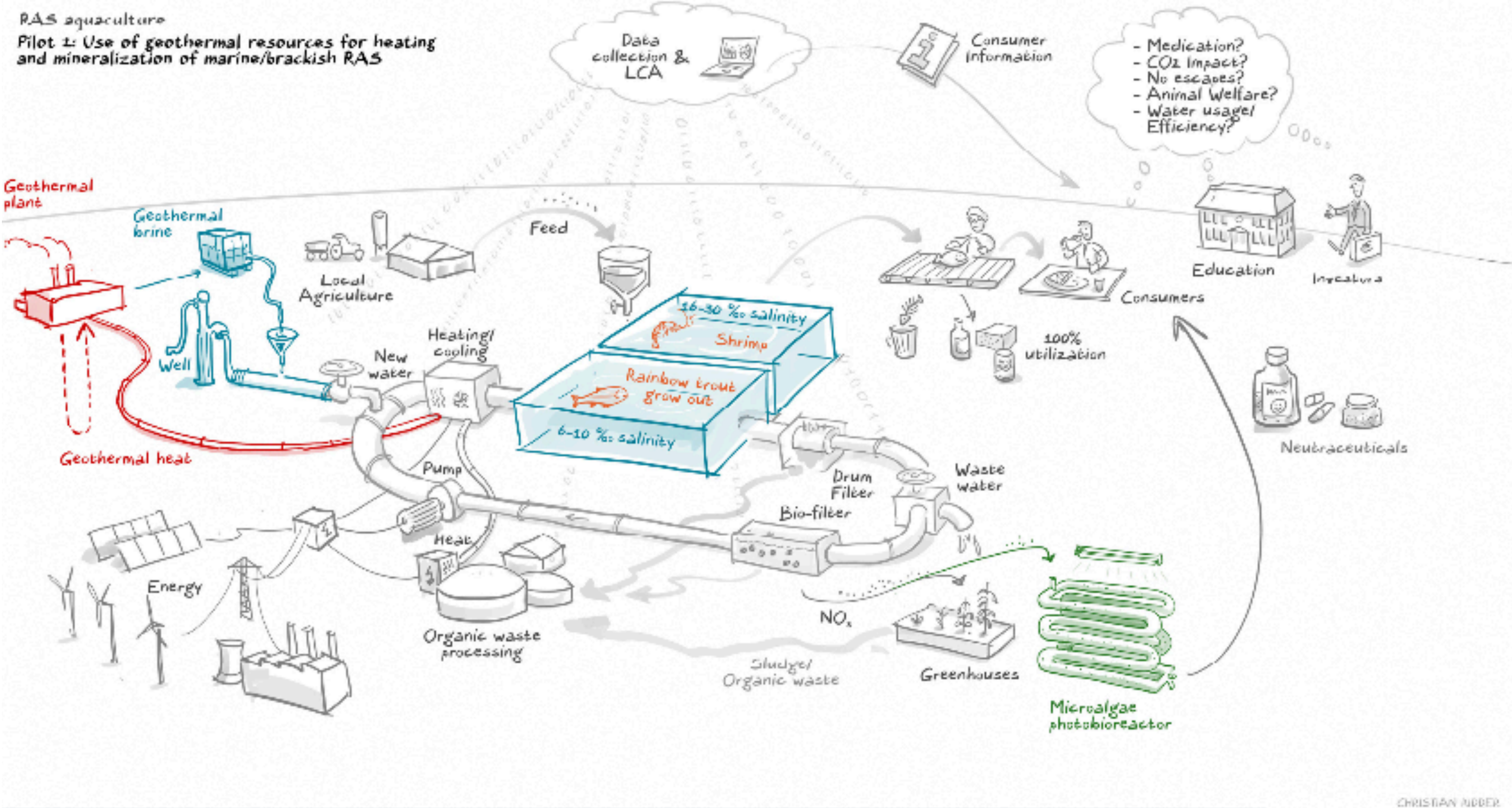

Life Cycle Assessment (LCA) of shrimp farming in a recirculating aquaculture system in Lithuania

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WATER-SMART SOCIETIES

Contents

1. Introduction

The aim of this report is to present the results of the Life Cycle Assessment (LCA) carried out on the experimental farming of whiteleg shrimp (*Litopenaeus vannamei*) at the Laboratory of Fisheries and Aquaculture of Klaipėda University (Lithuania). Unlike most shrimp aquaculture studies, this case study is unique because the aquaculture tanks are supplied with water heated by geothermal resources. This approach allows the system to take advantage of a locally available renewable energy source, which can significantly influence the environmental profile of the production process.

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 *Litopenaeus vannamei* in the experimental aquaculture facility of Klaipėda University and to identify the most impactful processes (hotspots) within the overall production system. The analysis was carried out on two distinct production cycles. This study allows for an assessment of the environmental profile of the farming system and highlights the influence of operational parameters on the overall sustainability of shrimp production.

2.1.1 Functional unit

In 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 provides the basis for all inputs and outputs to be related to a common denominator, ensuring transparency and comparability.

In aquaculture studies, the functional unit is typically expressed on a mass basis. Several previous LCA studies on shrimp production have adopted 1 kg of live shrimp harvested as the FU (Sun et al., 2023; Al Eissa et al., 2022; Cao et al., 2011). In line with this practice, the present study also employs 1 kg of live shrimp at the farm gate as the FU.

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 shrimp 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 they fall outside the scope of the experimental farming system.

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 Lithuanian energy mix;
- Combustible fuels required for transportation and upstream operations;
- Production and supply of post-larvae (juvenile shrimp);
- Construction, manufacturing, and life span of infrastructures and equipment (e.g., tanks, pumps, aeration and filtration systems);
- Production and supply of shrimp feed, which typically represents a major contributor to aquaculture impacts;
- Oxygenation using liquid oxygen, a key input for maintaining shrimp survival and growth;
- Farming operations (stocking, feeding, aeration, water heating, water management, monitoring);

- Harvesting of shrimp at the experimental facility gate.

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

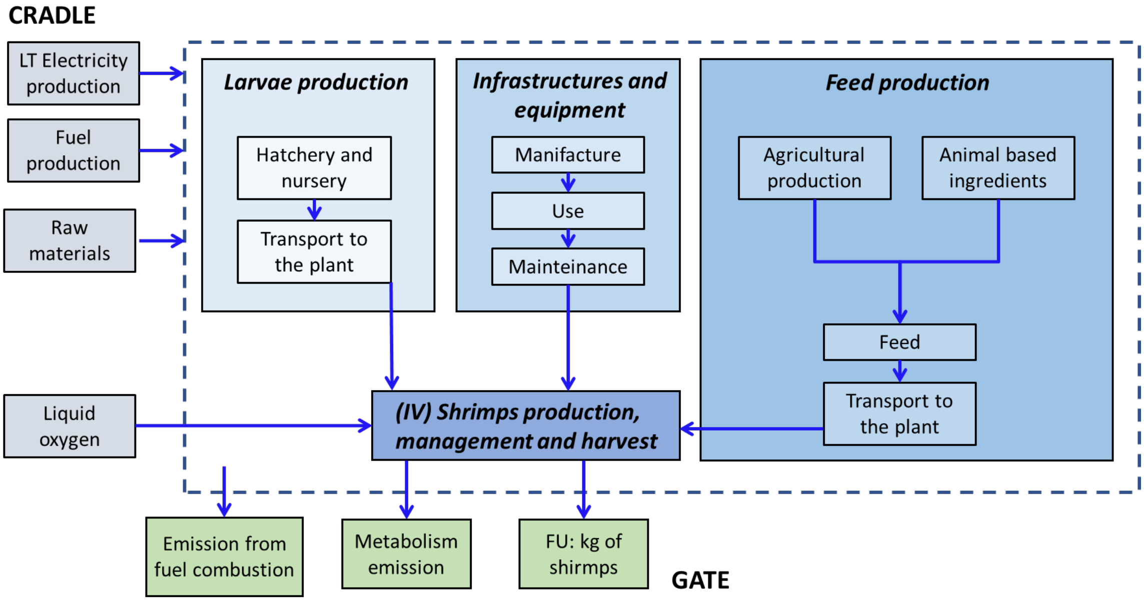

Figure 1: System boundaries of the shrimp farming LCA.

2.2 Inventory analysis

Two data streams were used:

- Primary data measured or recorded by Klaipėda University researchers for two production cycles (process durations, water use, juvenile transport, feed schedules, observed mortalities, feed conversion ratio—FCR, and infrastructure list).
- Secondary data from LCA databases and literature/engineering models (electricity intensity for shrimp RAS, oxygen demand factors, feed ingredient backgrounds, transport, and capital-goods datasets).

Given the pilot nature of the facility and ongoing optimisation, some primary readings (notably energy and oxygen supply) were not fully representative of steady-state operation. To avoid bias, literature/engineering values were adopted as baseline for electricity and oxygen (details below).

The experimental unit is a recirculating aquaculture system (RAS) with seven rearing tanks plus filtration/aeration. Water is continuously filtered and reused, which minimizes make-up water and allows stable water quality. Process water is geothermally warmed at the site; consequently, no on-site fossil heating is required.

Primary data cover two cycles:

- Cycle 1: 80 days; initial biomass of juveniles 0.60 kg; mortality 53%; FCR 1.53; harvested biomass 119.0 kg;

- Cycle 2: 92 days; initial biomass 0.24 kg; mortality 58%; FCR 1.54; harvested biomass 51.9 kg.

The lower output of Cycle 2 is consistent with issues reported during juvenile transport and early rearing.

Regarding energy inputs, literature benchmark for shrimp RAS electricity intensity of 4,860 kWh per tonne of shrimp (4.86 kWh/kg, average value retrieved by Sun et al., (2023); Al Eissa et al., (2022); Cao et al., (2011)) was applied. Scaled by the harvested biomass, this yields 578.4 kWh (Cycle 1) and 252.2 kWh (Cycle 2).

Site-level energy readings reflected commissioning/optimisation phases and were not comparable in order of magnitude with steady-state values reported in recent shrimp LCA studies. Using a literature intensity ensures comparability and avoids over- or under-estimation linked to atypical transient operation.

For oxygen demand, according to Timmons et al. (2002), each unit of feed requires 0.25 units of oxygen for fish metabolism. Using the total feed input for both cycles, the calculated oxygen demand amounted to 45.38 kg for the first cycle and 19.95 kg for the second cycle.

Primary data were collected regarding the quantities of feed administered during the two production cycles and the origin of the eight feed formulations used. In contrast, the inclusion rates of individual ingredients were treated as secondary data, derived through estimations aimed at meeting the target protein and lipid requirements. These formulations combined a range of ingredients, including marine proteins (e.g., fish meal 18–30%, krill meal 17–20%), plant-based proteins and carbohydrates (wheat gluten 15–20%, corn gluten 8–12%, wheat 5%), and minor components such as oils, yeasts, lecithin, and minerals.

A proportion of uneaten feed was assumed at 5% of the total feed offered. Feed supply was modelled with an average single-trip transport distance of 2,654 km by road freight, as reported by the research team.

The total amounts of feed provided per cycle, together with the estimated inclusion rates of each ingredient, are presented in Table 2.

Nutrient emissions into water were estimated using a mass balance model (Cho, 2004). All nitrogen and phosphorus flows (both dissolved and particulate) were calculated as the difference between the nutrient inputs provided through feed and the amounts effectively retained in shrimp biomass during growth. The model incorporated several key parameters: nutrient digestibility, shrimp body composition, the proportion of uneaten feed, and mortality rates. This approach allowed to distinguish between dissolved and solid fractions of N and P and to obtain a consistent estimate of the total metabolic emissions released into the aquatic environment.

Finally, information regarding infrastructures and equipment was collected through a questionnaire provided to the facility managers.

The details of the inventory analysis are reported in Tables 1 and 2.

Table 1. Main inventory data and information collected and used for the LCA study across the two shrimp production cycles.

Parameters	**unit**	**1st cycle**	**2nd cycle**
Cycle duration	days	80	92
Juveniles	kg	0.6	0.24
Juveniles transport	km	1,474	1,474
Freshwater	m^3	68	60
Geothermal water	m^3	30	8
Liquid oxygen	kg	45.38	19.95
Electricity	kWh	578.39	252.23
Mortality	%	53	58
FCR	/	1.53	1.54
Emissions			
Ammonia	kg	2.49	1.19
N ureic	kg	1.34	0.64
N solid	kg	2.20	0.83
Phosphate	kg	1.90	1.02
P solid	kg	1.29	0.57
Biomass output			
Shrimps	kg	119.01	51.9
Infrastructures	**Life span (y)**	**Amount #**	**Main material**
Rearing tanks	7	7	Fiberglass
Salt water mix tank	7	1	Polypropylene
Air pump for mix tank	2	1	aluminium/various electronics
Salt water reservoir	7	1	Polypropylene
Geothermal water storage tank	2	2	Polyethylene
Pump tank	7	1	Fiberglass
Mechanical filter	7	1	Polypropylene
Mechanic filter backwashing pump	7	1	Metal/aluminium/various electronics
Biofilter media	7	1m3	Polypropylene
Biofilter tank	7	1	Fiberglass
Biofilter air pump	2	1	aluminium/various electronics
Biofilter diffusors	5	4	bonded silica
Main water pump 1	7	1	PE/PP, PVC/Metal/aluminium
Main water pump 2	7	1	PE/PP, PVC/Metal/aluminium
Main water pump 3	7	1	PE/PP, PVC/Metal/aluminium
New water supply pump	7	1	PE/PP, PVC/Metal/aluminium
Water heater	2	1	Thermoplastic/Incoloy 825
Monitoring and control system + sensors	7	1	Plastic/ various electronics
PVC U valves	7	1	PVC U
PVC U drainage pipes	7	1	PVC U

PVC U pressure pipes	7	1	PVC U
Air pipes	7	1	Silicone/PVC/Teflon
Protein skimmer	7	1	PE/PP, PVC/Metal/aluminium
Skimmer water pump1	7	1	PE/PP, PVC/Metal/aluminium
Skimmer water pump2	7	1	PE/PP, PVC/Metal/aluminium
Ozonator	2	1	Plastic/ various electronics
UV lamp	7	1	Polypropylene
Oxygen reactor	7	1	Fiberglass
pH control pump	5	1	Polypropylene
Feeder	5	7	Polypropylene

Table 2: Composition of the different feeds, quantities administered, percentage of non-ingested feed, and transport information for the feeds used.

	Estimated inclusions (%)							
Feed	1	2	3	4	5	6	7	8
Ingredients								
Fish meal	30	30	30	20	20	18	22.38	26
Krill meal	20	20	20	20	20	17	17.85	/
Wheat gluten	15	15	15	15	15	16.3	17.85	19.5
Soybean meal	/	/	/	10	10	13.9	17.22	12
Corn gluten	/	/	/	8	8	11.9	17.22	8
Hydrolised fish protein	10	10	10	/	/		1.2	3.5
Horse beans	8	8	8	/	/	/	/	19.5
Crab	/	/	/	7	7	/	/	/
Squid flour	/	/	/	6	6	3.6	1.2	3.5
Tapioka starch	5	5	5	/	/	/	/	/
Wheat	5	5	5	5	5	/	/	/
Lecithin	5	5	5	/	/	/	/	/
Alfa protein concentrate	/	/	/	/	/	/	/	/
Fish oil	/	/	/	4	4	/	/	3
Yeasts	/	/	/	3	3	2.2	1.2	2
Algae	1	1	1	0.5	0.5	1.1	/	/
Cholesterol	/	/	/	1	1	1.7	1.2	1.5
Sodium chloride	0.5	0.5	0.5	/	/	/	/	/
Monocalcium phosphate	0.5	0.5	0.5	/	/	/	1.19	/
Seaweed meal	/	/	/	/	/	/	/	0.5
Natural charcoal	/	/	/	/	/	0.8	/	0.5
Monocalcium phosphate	/	/	/	/	/	/	/	/
Fish soluble	/	/	/	0.5	0.5	0.2	0.29	0.5
Feed amount (kg) (1st cycle)	0.1	0.1	0.32	4.2	8	21.9	75.5	71.4
Feed amount (kg) (2nd cycle)	0.853	0.853	1.203	2.1	1.1	27.4	35.8	10.5
Not ingested feed (1st cycle)	5%							
Not ingested feed (2nd cycle)	5%							
Transport	2,654 km							

2.2 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) was also calculated (Frischknecht et al., 2007).

3. Results

3.1 Absolute results

The environmental impacts per kg of live shrimp are reported in Table 4 for the two production cycles. Focusing on the Climate Change (CC) category, Cycle 2 shows a higher impact (10.82 kg CO_2 eq) compared to Cycle 1 (8.91 kg CO_2 eq). A similar trend is observed in most of the other categories, such as Freshwater ecotoxicity (FEx), Marine eutrophication (ME), Terrestrial eutrophication (TE), Resource use, fossils (RU-f), and Cumulative energy demand (CED), where Cycle 2 records higher values than Cycle 1. By contrast, some categories show slightly lower results in Cycle 2, for example Water use (WU), while others remain relatively comparable across the two cycles, such as Human toxicity (cancer and non-cancer effects). Overall, the results suggest that Cycle 2 is generally more impactful per kilogram of shrimp, with the exception of a few categories where the differences are negligible or slightly in favor of Cycle 2.

Table 3: environmental impact of producing 1 kg of live weight of Litopenaeus vannamei.

Impact category	***Unit***	**Cycle 1**	**Cycle 2**
AC	mol H+ eq	0.06	0.08
CC	kg CO2 eq	8.91	10.82
FEx	CTUe	176.85	204.93
PM	disease inc.*10^{-5}	0.07	0.09
ME	kg N eq	0.03	0.04
FE	kg P eq	0.02	0.02
TE	mol N eq	0.14	0.16
HT-c	CTUh*10^{-6}	0.01	0.01
HT-nc	CTUh*10^{-6}	0.39	0.26
OD	mg CFC11 eq	0.69	0.75
POF	kg NMVOC eq	0.04	0.04
RU-f	MJ	125.51	159.67
RU-mm	g Sb eq	0.11	0.23
WU	m^3 depriv.	32.58	32.04
CED	MJ eq	165.19	203.23

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.

3.2 Contribution analysis

The contribution analysis is a key step within Life Cycle Assessment (LCA), 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, oxygen supply, 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 Cycle 1 (figure 2) highlights that feed production is consistently the dominant contributor across most impact categories. In particular, it accounts for 61.1% of Climate Change (CC), 60.8% of Freshwater Ecotoxicity (FEx), and over 70% of Acidification (72.4%), Particulate Matter (76.6%), and Terrestrial Eutrophication (77.6%). Even in categories such as Cumulative Energy Demand (CED) and Resource use, fossils (RU-f), feed remains the largest contributor, with shares of 50.6% and 48.3%, respectively.

Nutrient emissions (nitrogen and phosphorus) emerge as the most relevant contributors to eutrophication-related impacts. They account for 88.6% of Freshwater Eutrophication (FE) and more than 50% of Marine Eutrophication (52.7%), confirming the critical role of nutrient releases in aquaculture systems.

Infrastructures and equipment have a relatively minor role in most categories but become significant in toxicity-related indicators. They contribute 12.5% to Particulate Matter (PM), 10.6% to Climate Change (CC), and more importantly, they are responsible for 62.7% of Resource use, minerals and metals (RU-mm). This indicates that capital goods and material requirements (fiberglass, plastics, metals) are particularly relevant when considering resource depletion and long-term system sustainability.

Electricity consumption contributes notably to several categories, representing 26.0% of CC, 24.8% of Human Toxicity (cancer effects, HT-c), and 33.4% of RU-f, highlighting the role of energy demand in a recirculating aquaculture system (RAS).

Oxygen supply, by contrast, plays a limited role, with contributions generally below 3–4% in all categories.

Finally, the impact of juveniles is negligible in all categories, consistently below 0.1%, confirming that their contribution to the overall environmental profile of the system is insignificant compared to feed, energy, and infrastructure-related processes.

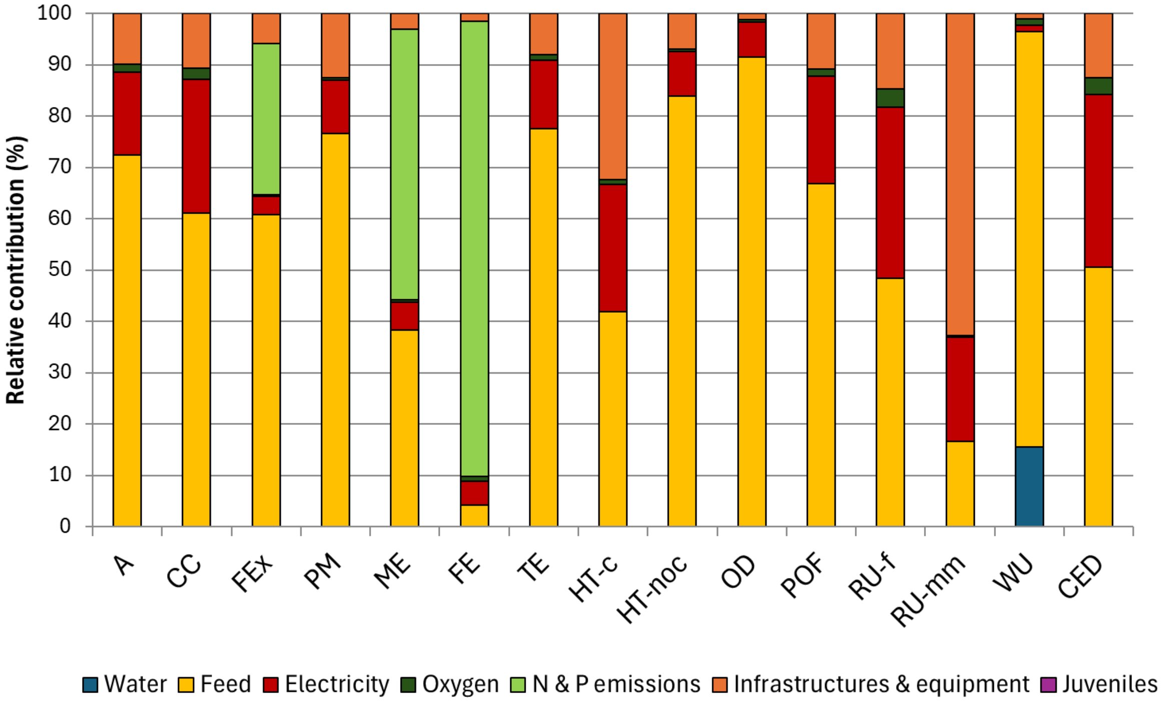

Figure 2: Analysis of the contributions to the environmental impact of 1 kg of shrimp (Cycle 1). A: Acidification; CC: Climate change; FEx: Freshwater ecotoxicity; PM: Particulate matter formation; ME: Marine eutrophication; FE: Freshwater eutrophication; TE: Terrestrial eutrophication; HT-c: Human toxicity, 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.

The contribution analysis of Cycle 2 (figure 3) confirms that feed production remains the dominant contributor across most impact categories. Feed is responsible for 53.7% of Climate Change (CC), 59.8% of Freshwater Ecotoxicity (FEx), and more than 65% of Acidification (65.3%), Particulate Matter (68.2%), and Terrestrial Eutrophication (68.9%). It also contributes significantly to Cumulative Energy Demand (CED, 43.2%) and Resource use, fossils (RU-f, 40.4%), indicating the central role of feed ingredients in shaping the environmental profile of shrimp aquaculture.

As in Cycle 1, nutrient emissions (N and P) are the main drivers of eutrophication impacts, contributing 86.5% to Freshwater Eutrophication (FE) and 51.5% to Marine Eutrophication (ME). These results highlight the importance of nutrient management and feed conversion efficiency for reducing eutrophication pressures.

Infrastructures and equipment contribute notably to toxicity-related categories and resource depletion. They account for 23.1% of CC, 25.4% of Particulate Matter (PM), and dominate Resource use, minerals and metals (RU-mm, 58.3%). Their relative importance is higher than in Cycle 1, reflecting the fact that infrastructure-related burdens are essentially constant, while the total shrimp biomass produced was lower in Cycle 2. When normalised to the functional unit, these fixed contributions weigh more heavily, thus increasing their percentage share.

Electricity use provides a secondary but relevant contribution in several categories, particularly 21.4% of CC, 16.9% of Human Toxicity (cancer effects, HT-c), and 26.3% of RU-f, reinforcing the role of energy efficiency in aquaculture systems. Oxygen supply remains marginal, generally below 3% in all categories.

Finally, the contribution of juveniles is negligible in every impact category, always below 0.1%, confirming their minimal influence on the overall life cycle impacts.

Overall, the contribution profile of Cycle 2 is very similar to that of Cycle 1, with feed, nutrient emissions, infrastructures, and electricity identified as the main hotspots, although the relative influence of infrastructures is more pronounced in Cycle 2 due to the lower production output

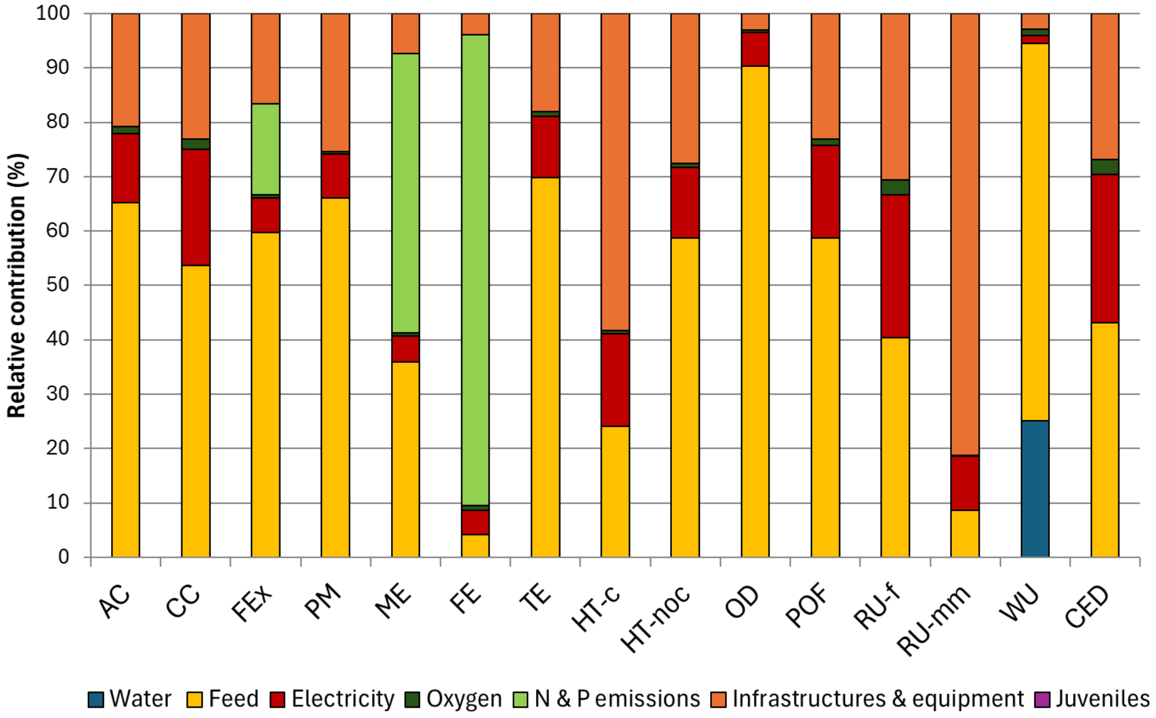

Figure 3: Analysis of the contributions to the environmental impact of 1 kg of shrimp (Cycle 2). A: Acidification; CC: Climate change; FEx: Freshwater ecotoxicity; PM: Particulate matter formation; ME: Marine eutrophication; FE: Freshwater eutrophication; TE: Terrestrial eutrophication; HT-c: Human toxicity, 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.

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 39.9% of the total data in the analysis (table 4-5). The results show that, while most impact categories display relatively low variability (CV < 10%), the categories related to human toxicity (cancer and non-cancer effects) present the highest levels of uncertainty. This is mainly due to the intrinsic variability and limited robustness of the characterization factors available for these impact categories, which makes their interpretation less reliable compared to others such as climate change or eutrophication.

Table 4: Statistical summary of impact categories per functional unit (1 kg live shrimp) for Cycle 1.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	6.1E-02	5.6E-02	1.9E-02	3.1E+01	5.0E-02	1.0E-01	5.9E-04
CC	kg CO2 eq	8.9E+00	8.9E+00	3.8E-01	4.2E+00	8.2E+00	9.7E+00	1.2E-02
FEx	CTUe	1.2E+02	1.7E+02	4.9E+03	4.2E+03	-9.8E+03	1.0E+04	1.6E+02
PM	disease inc.*10^{-5}	6.6E-07	6.4E-07	1.3E-07	1.9E+01	5.4E-07	9.3E-07	4.0E-09
ME	kg N eq	3.3E-02	3.3E-02	8.0E-04	2.5E+00	3.1E-02	3.5E-02	2.5E-05
FE	kg P eq	1.8E-02	1.8E-02	7.0E-04	3.8E+00	1.7E-02	2.0E-02	2.2E-05
TE	mol N eq	1.4E-01	1.4E-01	6.5E-03	4.8E+00	1.2E-01	1.5E-01	2.1E-04
HT-c	CTUh*10^{-6}	1.1E-08	1.1E-07	1.5E-06	1.4E+04	-3.1E-06	3.0E-06	4.8E-08
HT-nc	CTUh*10^{-6}	-7.7E-07	5.7E-06	3.6E-04	-4.7E+04	-7.2E-04	7.0E-04	1.1E-05
OD	mg CFC11 eq	6.8E-07	6.7E-07	1.2E-07	1.7E+01	5.0E-07	9.6E-07	3.7E-09
POF	kg NMVOC eq	3.5E-02	3.5E-02	2.8E-03	8.1E+00	3.1E-02	4.1E-02	9.0E-05
RU-f	MJ	1.3E+02	1.2E+02	8.3E+00	6.7E+00	1.1E+02	1.4E+02	2.6E-01
RU-mm	g Sb eq	1.1E-04	1.1E-04	1.7E-05	1.5E+01	8.4E-05	1.5E-04	5.4E-07
WU	m^3 depriv.	3.8E+01	4.2E+01	7.2E+01	1.9E+02	-1.1E+02	1.7E+02	2.3E+00
CED	MJ eq	1.7E+02	1.7E+02	9.3E+00	5.6E+00	1.5E+02	1.8E+02	2.9E-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.

Table 5: Statistical summary of impact categories per functional unit (1 kg live shrimp) for Cycle 2.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	7.6E-02	7.0E-02	2.3E-02	3.0E+01	6.2E-02	1.3E-01	7.3E-04
CC	kg CO2 eq	1.1E+01	1.1E+01	4.5E-01	4.2E+00	1.0E+01	1.2E+01	1.4E-02
FEx	CTUe	2.9E+02	5.2E+02	4.9E+03	1.7E+03	-1.0E+04	1.0E+04	1.6E+02
PM	disease inc.*10^{-5}	8.6E-07	8.3E-07	1.6E-07	1.9E+01	6.8E-07	1.2E-06	5.1E-09
ME	kg N eq	3.7E-02	3.7E-02	9.2E-04	2.5E+00	3.5E-02	3.9E-02	2.9E-05
FE	kg P eq	1.9E-02	1.9E-02	9.4E-04	5.0E+00	1.8E-02	2.1E-02	3.0E-05
TE	mol N eq	1.6E-01	1.6E-01	8.5E-03	5.3E+00	1.5E-01	1.8E-01	2.7E-04
HT-c	CTUh*10^{-6}	6.0E-08	1.3E-07	1.6E-06	2.7E+03	-3.1E-06	3.4E-06	5.0E-08
HT-nc	CTUh*10^{-6}	9.8E-06	1.7E-05	3.6E-04	3.7E+03	-7.6E-04	7.6E-04	1.2E-05

OD	mg CFC11 eq	7.5E-07	7.3E-07	1.4E-07	1.9E+01	5.3E-07	1.1E-06	4.5E-09
POF	kg NMVOC eq	4.3E-02	4.3E-02	3.2E-03	7.3E+00	3.8E-02	5.0E-02	1.0E-04
RU-f	MJ	1.6E+02	1.6E+02	1.0E+01	6.3E+00	1.4E+02	1.8E+02	3.2E-01
RU-mm	g Sb eq	2.3E-04	2.2E-04	4.1E-05	1.8E+01	1.7E-04	3.3E-04	1.3E-06
WU	m^3 depriv.	3.1E+01	3.5E+01	8.8E+01	2.8E+02	-1.5E+02	1.8E+02	2.8E+00
CED	MJ eq	2.0E+02	2.0E+02	1.1E+01	5.6E+00	1.8E+02	2.3E+02	3.6E-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.

4. Discussion and conclusions

This study represents one of the first applications of Life Cycle Assessment (LCA) to an experimental shrimp farming system in Lithuania, where cultivation was carried out in a recirculating aquaculture system (RAS) heated by geothermal water. The analysis covered two production cycles and provided insights into the environmental hotspots of the system. Across both cycles, feed production and nutrient emissions to water emerged as the dominant contributors to most impact categories, while infrastructures and equipment had a comparatively smaller but non-negligible influence, particularly in the less productive second cycle due to the lower biomass yield. Juveniles consistently showed a marginal contribution to the overall impacts.

When compared to existing literature on shrimp aquaculture LCA, the results obtained in this study appear relatively high in absolute terms. For instance, Cao et al. (2011) estimated the Climate change of Chinese shrimp farming systems between 2.7 and 5.3 t CO_2 eq. per ton of live weight, depending on whether farms were semi-intensive or intensive. Similarly, Al Eissa et al. (2022) reported values around 4.0 t CO_2 eq./t shrimp for intensive U.S. systems, with variation largely driven by feed formulation and electricity demand. Sun et al. (2023) provided comparable estimates, highlighting feed production and energy use as major hotspots and reporting a CC varying from 4.42 to 4.97 kg CO_2 eq/kg shrimps. In contrast, the CC values observed in this experimental facility exceeded these benchmarks.

Such differences are primarily attributable to the experimental scale of production. The Klaipėda system was designed for research rather than commercial output, resulting in low production efficiency, high mortality rates, and consequently a higher environmental burden allocated per unit of shrimp produced. In particular, the fixed impacts of infrastructures and the relatively high electricity use, despite geothermal heating reducing thermal energy requirements, were distributed over a limited biomass yield, amplifying the per-kilogram results. This scaling effect is well documented in aquaculture LCA and should be carefully considered when comparing experimental systems with commercial-scale operations.

Despite these limitations, the study highlights several robust findings. Feed remains the primary environmental hotspot, consistent with global literature. Nutrient emissions from metabolism and uneaten feed significantly contribute to eutrophication categories, underscoring the importance of improving feed formulation and management strategies. Infrastructure and equipment, though usually minor contributors in large-scale farms, can become relevant in small experimental systems.

In conclusion, while the absolute impact values of this study are higher than those reported for commercial shrimp aquaculture, they provide a valuable benchmark for understanding the environmental performance of experimental RAS facilities in northern Europe. The results emphasize the need to improve production efficiency, reduce mortality, and optimize feed use to approach the environmental performance of established shrimp farming systems. Future steps should focus on the development and assessment of alternative scenarios, defined and discussed jointly with aquaculture experts and stakeholders involved in the project, to identify strategies that can improve production efficiency, reduce environmental burdens, and enhance the scalability of such systems.

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