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Life cycle assessment of a recirculatory aquaculture system (RAS) – A case study of meagre (*Argyrosomus regius*) farming

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ABSTRACT

As global demand for seafood continues to rise, sustainable aquaculture plays a vital role in supplying high-quality food while reducing pressure on wild fish stocks and minimising their environmental impacts. Recirculating Aquaculture Systems (RAS) have emerged as a promising solution to overcome the negative impacts caused by other production systems, such as cages and ponds, offering controlled production environments with reduced water use and waste discharge. However, RAS also has environmental impacts that must be thoroughly assessed to ensure their viability as a sustainable alternative. This study applies Life Cycle Assessment (LCA) methodology to evaluate the environmental performance and identify potential improvements of a pilot-scale RAS farm of meagre (*Argyrosomus regius*) in Portugal. The environmental impact categories considered were global warming, freshwater eutrophication, marine eutrophication and land use. It was found that energy and feed production were the main contributors to most environmental categories, except for marine eutrophication, where the main contributors were oxygen and ozone system inputs. Main potential improvements include broader use of renewable energy in the system, use of more sustainable feed ingredients, such as the utilisation of by-products for fishmeal and fish oil ingredients, and relocating the hatchery to the grow-out farm which positively impacted all environmental categories by eliminating the need to transport juveniles. The insights gained from this study enhance the understanding of the environmental profile of RAS-based meagre farming and provide a foundation for improving environmental efficiency in future operations.

1. Introduction

Global aquaculture production has increased significantly over the last few decades. In 2022, it reached a record of 130.9 million tonnes, an increase of 6.2% compared to 2020, and the total aquatic animal production from aquaculture was estimated at 91 million tonnes, surpassing capture production for the first time in history (FAO, 2024). This is particularly relevant since the demand for animal protein is expected to increase due to the world's population raise together with the increase of income levels in developing countries (Wu et al., 2014). Seafood is considered a key component of the global diet due to its high-quality protein content, low levels of saturated fat, abundance of long-chain omega-3 polyunsaturated fatty acids, and richness in essential minerals and trace elements, offering nutritional advantages over land-based products (Tacon, 2023). Given the high nutritional value of seafood, projected populational growth and the fact that most fisheries resources have reached their exploration limits, aquaculture plays a critical role in enhancing food security and combating malnutrition (Pradeepkiran, 2019). By reducing pressure on wild fish stocks, aquaculture contributes also to the conservation of fish populations (Bogmans and van Soest, 2022).

Despite its advantages, the rapid development of aquaculture has led

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to significant environmental challenges, including resource depletion, marine pollution, and greenhouse gas (GHG) emissions that contribute to climate change (Nijdam et al., 2012). Wastewater from aquaculture farms contains large amounts of nutrients and suspended solids (Islam et al., 2004) and is often contaminated with chemicals and pharmaceutical residues (Rico and Van den Brink, 2014), all of which have a negative impact on the environment (Ahmad et al., 2022). Furthermore, aquaculture is highly dependent on fossil fuels to meet the energy demands for operations such as water pumping and aeration, water heating and feed production, contributing with 245 million tonnes of CO_2 eq, circa 0.5% of global anthropogenic GHG emissions in 2017 (MacLeod et al., 2020). Given this, the aquaculture industry has been driven to adopt more sustainable practices from environmental, societal and economic perspectives (Badiola et al., 2018).

Recirculating aquaculture systems (RAS) treat wastewater efficiently and produce high-quality effluent within a specific controlled timeframe compared to other aquaculture production systems (Badiola et al., 2012; van Rijn, 2013). Components of a RAS include the fish tank and equipment units related with particle removal, nitrogen removal, gas control and biosecurity. The tank is typically designed to optimise waste removal, enhance operational functionality, and maximise floor space utilisation (Badiola et al., 2012). In RAS, wastewater contains uneaten feed, faeces, and other organic matter that must be removed to prevent the accumulation of harmful substances such as ammonia and nitrites (Kim et al., 2000). Fish excrete excess dietary protein primarily as ammonia, while faecal waste and uneaten feed contribute to reduced dissolved oxygen levels and additional ammonia through bacterial decomposition, and, therefore, rapid removal of waste is essential to maintain water quality, support aquatic health, and ensure system sustainability (Almeida et al., 2020). RAS produce fish intensively with low water consumption and land use, decreasing potential environmental impacts related to eutrophication or water use (Martins et al., 2010). However, RAS are more energy intensive than more open production systems, such as net-pens or raceways, and electricity and feed are typically the dominant contributors to the life cycle impacts of RAS products, hampering their sustainability and cost-effectiveness (Badiola et al., 2012; Cooney et al., 2021; Song et al., 2019).

To effectively evaluate the environmental impacts of RAS farming and design responsible aquaculture systems it is crucial to account for the whole fish supply chain (Song et al., 2019). The life cycle assessment (LCA) is an assessment tool used to evaluate the environmental impacts of aquaculture systems (Bohnes et al., 2019; Henriksson et al., 2012). LCA is an international standardised method developed by the International Organization for Standardization (ISO) used to investigate and quantify the environmental impacts of a product or service within its life cycle (ISO, 2006a). LCA uses a complete approach to assess potential effects of aquaculture on the environment, considering all the involved factors, including raw materials, transportation, distribution, use, maintenance, recycling and waste management(Li et al., 2025). Several authors have used LCA to study the impacts of intensive farming systems with high economic value, including, for example, salmon (Philis et al., 2019), rainbow trout (Maiolo et al., 2021), seabass (Konstantinidis et al., 2021; Zoli et al., 2023) and tilapia (Yacout et al., 2016). Nowadays, LCA methodology is considered the conventional tool for evaluating environmental impacts of seafood production systems (Nijdam et al., 2012).

Meagre (*Argyrosomus regius*) is a sciaenid fish species found along the Atlantic European and African coasts, as well as in the Mediterranean (Monfort, 2010). It can grow up to 1 kg/year under good rearing conditions and accumulates low amounts of mesenteric and muscle lipids compared to other farmed species (Estevez et al., 2018). Due to their favourable traits, such as efficient feed conversion ratios, rapid growth, ease of cultivation, and effective broodstock management (Saavedra et al., 2023, 2022), it has been gaining popularity among aquaculture producers and consumers (Monfort, 2010). Meagre aquaculture started in the late 1990s, with the first commercial production in France in 1997, and expanded to nearby regions in the Mediterranean, with Italy, France, Spain and Portugal being current main producers (FAO, 2025). Global aquaculture production of meagre reached 13,670 tonnes, in 2021(FEAP, n.d). As of this day, only one study has been published regarding LCA of meagre aquaculture production by Konstantinidis et al. (2021), but it focused only on the packaging stage, and no studies have yet performed an LCA of meagre production in RAS.

The main goal of this study was to bridge existing knowledge gap by conducting an LCA of meagre production in RAS, covering the cradle to farm-gate life cycle. More specifically, the aim was to identify the primary environmental hotspots throughout the production cycle and determine the factors that contribute most significantly to overall environmental impacts. In addition, a sensitivity analysis was performed to evaluate how variations in key parameters may influence overall efficiency and sustainability. This approach not only enhanced the understanding of the environmental footprint of meagre production in RAS, but provided actionable insights to support the development of more sustainable and low-carbon aquaculture practices.

2. Materials and Methods

The LCA was conducted following ISO 14040 and 14044 (ISO, 2006a, 2006b). The four steps involved in any LCA study were followed as: (i) defining the goal and scope; (ii) conducting the life cycle inventory (LCI); (iii) performing the life cycle impact assessment (LCIA); and (iv) interpreting the results.

2.1. Goal and scope definition

The different phases and processes that comprise meagre production were analysed and environmental impacts caused by different emissions during the life cycle quantified. The functional unit was 1 tonne of live-weight meagre at the grow-out farm. System boundaries were established from “cradle-to-farmgate”, beginning with resource extraction, which includes all processes necessary to produce meagre, namely raw material production, energy, water, oxygen, hatchery and feed production, including all transportations, ending with harvest-ready meagre at the grow-out farm gate (Fig. 1). Results from the LCA were used to suggest improvements in efficiency and sustainability in meagre production in RAS.

The facility selected for this LCA operates as a pilot-scale, proof-of-concept unit, primarily aimed at demonstrating the technical and biological feasibility of rearing this species in RAS. In addition to production, the facility is actively engaged in multiple R&D initiatives focused on improving operational protocols and addressing broader themes such as traceability, fish nutrition and feeding strategies, waste valorisation, and broodstock and hatchery development. As such, its operational conditions differ substantially from those of commercial-scale farms optimised for maximum productivity. Results should therefore be interpreted with caution when compared to industrial RAS operations.

2.2. Data collection and life cycle inventory

The inventory data related to the hatchery phase were based in Kallitsis and Avramidis (2025) study. Data were analysed to calculate the material needed and energy consumed to produce one tonne of meagre fry. Meagre fries were produced at a hatchery in Olhão, Portugal, and data were adjusted to reflect the Portuguese energy mix. A weight of 5 g was assumed per meagre fry at the end of the production cycle since that is the average weight upon arrival at the RAS facility. Meagre fries were transported by car from the hatchery to the grow-out research facility in Peniche, Portugal, in a total of seven batches, with an assumed round-trip distance of 700 Km.

The hatchery production is based on an open circuit, and process begins with pumping seawater from the Ria Formosa (a lagoon located in the Algarve that has a system of barrier islands that connects to the sea through inlets), supplying the entire aquaculture facility. The water

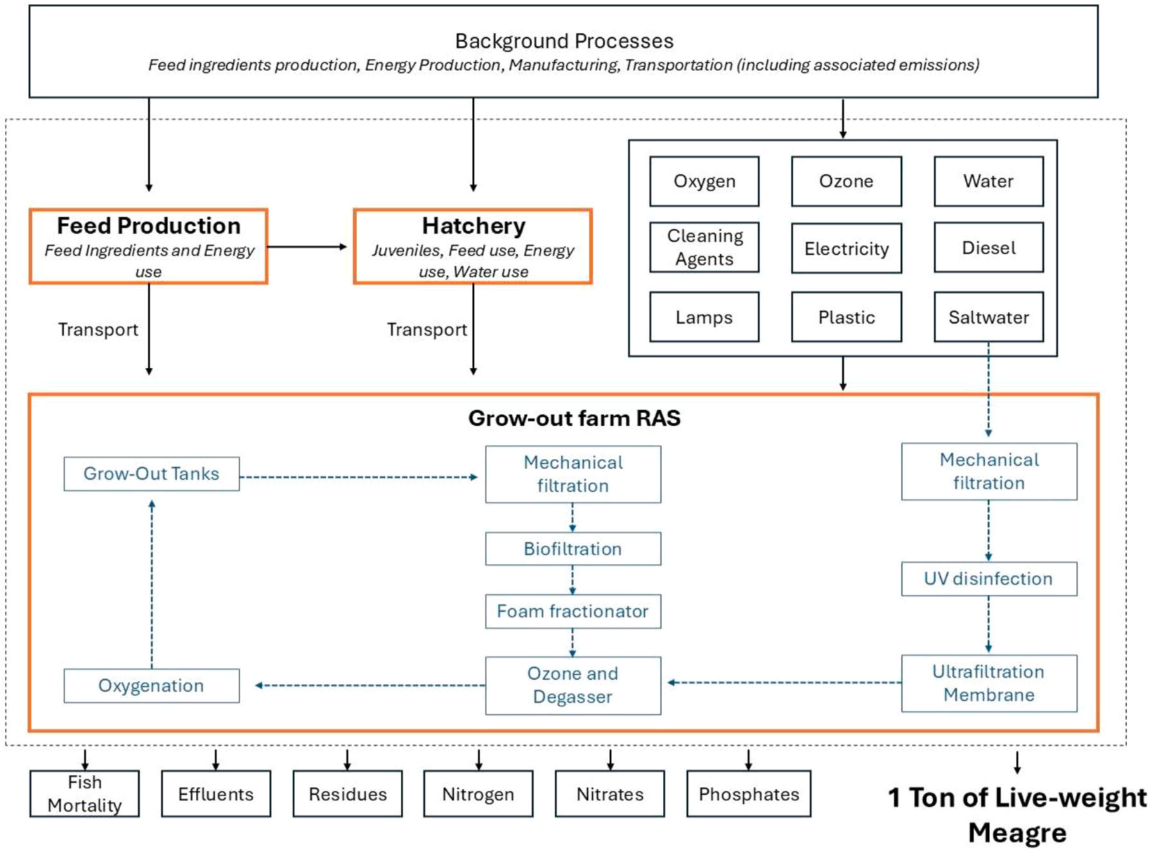

Fig. 1. System boundaries and material/energy flows of the LCA for meagre production in a RAS. The diagram illustrates the main subsystems: feed production, hatchery, and grow-out farm operations, as well as supporting background processes including energy, material inputs, and transportation. Water treatment (mechanical filtration, biofiltration, foam fractionation, ozone treatment, UV disinfection) is highlighted within the grow-out farm (in blue), indicating saltwater circulation route. Output emissions and waste streams—fish mortality, effluents, residues, nitrogen, nitrates, and phosphates—are represented to reflect environmental burdens considered in the assessment.

passes through a biological filter, sand filter, protein skimmer, and ultraviolet sterilisation. The system also includes temperature control mechanisms for heating or cooling the water as needed. Broodstock ages range from three to four years, and spawning can occur naturally or be induced through water temperature manipulation. Eggs are collected during the night using a decantation process since viable eggs float, simplifying the collection process. A one-gram sample, corresponding to about 1000 meagre eggs, is examined under a microscope to confirm their viability. Meagre larvae usually hatch within two days, depending on water temperature. Larvae remain in this stage for 20–30 days before developing into juveniles, which weigh between 2 and 3 g. In the early stages, larvae are fed on rotifers and Artemia (purchased as cysts). Both freshwater and seawater are used in the hatchery system and hydrogen peroxide is employed for cleaning purposes. Once juveniles reached the appropriate size for transfer (approximately 5 g), they were transferred to a separate RAS facility, where the grow-out and slaughtering stages were carried out.

Data related to fish farming in RAS, including grow-out and slaughtering, were gathered directly from a RAS farmer (Table 1; See supplementary information). The data represent averages of annual production, collected for 2024, when a total of 1287 Kg of live-weight meagre were obtained. The data estimated all the materials and energy consumption, and emissions sent to the environment when producing one tonne of meagre with individuals weighing 2.5 Kg at the end of the production cycle.

The studied system, occupying 123 m^2, is a closed saltwater system with permanent recirculating water. The system is composed of seven high-density polyethylene (HDPE) tanks, which were considered in the LCIA (see supplementary material). RAS equipment, such as water circulation system, heat and aeration pumps, was not considered in the analysis due to a lack of data and difficulty in allocating inputs of their long-life spans.

Salt water is pumped from the sea and electric pumps push the water into an untreated seawater tank, from which it is forced through a filtration system. Firstly, the water is mechanically filtered through a sand filter to retain coarse solid particles. The water is then sent to a cartridge filter to remove the finer solid residues that have passed through the previous filtration. Afterwards, the water passes through an ultraviolet light filter and an ultrafiltration membrane to filter out microorganisms and particles larger than 0.02 μm. The water is directed off-site again to be stored in a seawater-treated tank until it needs to be fed back into the system. The water that comes out from the tanks is channelled into a drum filter to remove all solid waste and passes through a biofilter, protein skimmer, ozone and degasser. Before returning the water to the tanks, it is oxygenated in an oxygen cone. An electric heat pump is used to keep the water at a constant temperature of 25 ºC. Sodium bicarbonate (food-grade) is used to control water alkalinity. Cleaning agents such as hydrogen peroxide, sodium hypochlorite, hydrochloric acid and acetic acid are used to disinfect equipment such as membranes, pumps, and piping. When fish reach 2.5 kg, they are slaughtered by hand through piercing the head (i.e., Ikejime method). Excretion data on nitrogen, nitrates and phosphorus of the RAS were directly obtained from the company through water quality analysis. Water effluents are sent to a water treatment facility, and biological, chemical and hospital residues are sent to a hazardous waste treatment facility. The main energy source used on the farm is electricity from the

Table 1
Inventory data for meagre production in a RAS expressed for the selected FU.

Description		Units	Amount per 1-tonne of live weight
INPUTS	Juveniles	Kg	51.26
	Fish feed	Kg	1185.85
	Transport – Car	Km	4900
	Transport – Truck	Km	350
	Land use	Ha	0.01
	Biofilter – Bio-balls (HDPE)	Kg	28.13
	Biofilter – Lid Plastic (HDPE)	Kg	0.08
	Tanks (HDPE)	Kg	52.41
	UV lamps	p	0.36
	LED lamps	p	4.29
	Oxygen	Kg	130.18
	Ozone	g	39119.02
	Seawater	m^3	1466.70
	Tap water	m^3	115.00
	Sodium bicarbonate	Kg	535.88
	Hydrogen peroxide	L	2.68
	Sodium hypochlorite	L	16.08
	Hydrochloric acid	L	2.68
	Acetic acid	L	37.51
	Electricity	KWh	47078.93
	Diesel	m^3	0.05
OUTPUTS	Meagre fish	Kg	1000
	Fish mortality	Kg	70.52
	Residues – Hospital Type	Kg	0.54
	Residues – Chemical Type	Kg	5.36
	Effluents	m^3	2405.55
	Nitrogen	Kg	298.29
	Nitrates	Kg	0.2406
	Phosphates	Kg	37.05

Portuguese grid and was modelled using the average Portuguese electricity mix. Diesel is also used in the RAS farm as an alternate source in case of power failure. Feed is transported by truck, and the distance assumed from the supplier to the RAS facility corresponds to 350 Km round trip.

Feed ingredients were supplied by a leading aquafeed producer in Portugal, who also provided primary data on ingredient quantities. The formulation included fishmeal, fish oil, various grains, and a vitamin mix. Specific proportions of these ingredients are not disclosed due to confidentiality agreements. Data for energy, diesel and water consumption to produce the aquafeed were based on Kallitsis and Avramidis (2025). Data on fishmeal included by-products from three small pelagic fish species coming from Morocco (*Sardina pilchardus*, *Scomber colias*, *Engraulis encrasicolus*), as well as by-products from three small pelagic fish, three tuna species and cod from Portugal (*Katsuwonus pelamis*, *Thunnus albacares*, *Thunnus alalonga*, *Sardina pilchardus*, *Scomber scombrus*, *Scomber colias, Gadus morhua*). For the fish production phase, a division was assumed based on the type of species, considering two different fish groups: small pelagic and tuna. Since there were four small pelagic fish species and three tuna species, it was assumed that 57% of the fish by-products in the fishmeal came from small pelagic species and 43% from tuna.

It was also assumed that by-products used in this fish meal came from fish canning processes, a common source of fish by-products to produce feed ingredients. Therefore, data from (Almeida et al., 2023), which assessed canned seafood products including Albacore tuna and Atlantic chub mackerel, were considered for fish by-products production from the canning industry. This study includes detailed data for the processing phase, during which by-products are generated, and data on fishing of small pelagic fish caught in Portugal came from purse seining fishery (Almeida et al., 2014) and tuna caught off the Cantabrian coast from purse seiners and longline/gillnets (Ceballos-Santos et al., 2023). To allocate inputs and outputs from the canning processing inventory between the main product, the canned fish and by-products, an economic allocation was done based on their market price. It was assumed a value of 0.20 € / Kg for fish by-products (personal communication from an expert in fish by-products and feed production), and an average market price of 14.27 € / Kg for canned sardine and 16.49 € / Kg for canned tuna (online data from the two biggest supermarket chains in Portugal). Therefore, the environmental burden allocated to canned fish by-products represented 1.4% and 1.2% for small pelagic fish and tuna species products, respectively (for further details, refer to the supplementary information). This approach was chosen to ensure consistency with established LCA practices and to align with the availability of detailed, geographically and methodologically relevant datasets.

As for the fish oil ingredient, the information from the feed producer included 100% by-products from Atlantic Salmon (*Salmo salar*) aquaculture. For the 'Fishmeal' and 'Fish oil' production phases, data from Basto-Silva et al. (2019) was used as a reference, which included electricity, fuel, biomass and pellets energy, water and plastic bags; and respective emissions to air, water and waste.

2.3. Life cycle impact assessment

The life cycle impact assessment (LCIA) was conducted using the ReCiPe Midpoint (H) v1.13 methodology, implemented in SimaPro v8.3 software. The selection of impact categories was guided by the environmental relevance of the processes involved in the production systems under study, and the goal and scope of this research (ISO, 2006a). The chosen categories for the grow-out RAS farm - global warming (GW), freshwater eutrophication (FE), marine eutrophication (ME), and land use (LD) - also reflect the most commonly reported impact categories in the majority of LCA studies on RAS. The GW characterizes the increase of temperature of the atmosphere by the emission of greenhouse gases (Kg CO_2 eq), FE and ME characterize the accumulation of nutrients in water overstimulating plant growth, consequently reducing the level of O_2 (Kg P eq and Kg N eq, respectively), and LD characterises the occupied transformed area (m^2 year).

Each input and output were attributed to a specific weighting factor (characterisation factors) to be evaluated for each impact category. Ten contributors were considered: energy (electricity and diesel), freshwater, transportation (car transport and truck transport), infrastructure (land use, biofilter with HDPE bio-balls and a HDPE lid, tanks made of HDPE, UV lamps and LED lamps), feed, hatchery, cleaning agents (sodium bicarbonate, hydrogen peroxide, sodium hypochlorite, hydrochloric acid, acetic acid), wastewater treatment, waste treatment (fish mortality, residues: hospital type and other residues as chemical type) and other consumptions (oxygen and ozone).

The LCIA of the feed production was also assessed for the most relevant impact categories, including GW, LD, terrestrial ecotoxicity (TE) and water consumption (WC). The TE and WC were added in the feed assessment since they evaluate the potential harm to terrestrial ecosystems from toxic substances (Kg 1,4-DB eq) and measure the potential for freshwater resource depletion (m^3), respectively. Eight contributors were considered to evaluate the impacts of the feed: energy (electricity, diesel, petrol and natural gas), fishmeal, fish oil, wheat (wheat grain and wheat gluten), maize, pea starch, hulled sunflower and vitamins.

2.4. Sensitivity analysis and alternative scenarios

Sensitivity analyses were performed to evaluate the influence of modelling decisions with alternative LCI parameters or alternative farming practices to identify potential improvements. Sensitivity analyses were conducted to investigate the following scenarios: (1) 30% utilisation of photovoltaic energy, (2) 100% utilisation of photovoltaic energy, (3) hatchery production on site (i.e., transportation from the hatchery to the meagre RAS grow-out farm system was removed, as it was no longer necessary) (4) substitution of fish meal ingredients from by-products to whole fish (sardine from purse seine fishing in Portugal was used, as an example, and canning processing phase was excluded) and (5) substitution of fish meal and fish oil ingredients from by-products to Peruvian anchovy. Deville et al. (2025) suggested that Peruvian *E. ringens* fishery is one of the most efficient in the world in terms of fuel use and fishing effort, and results obtained for fish meal and fish oil (FMFO) products had the lowest environmental impacts, also when compared to Portuguese FMFO from fish by-products.

3. Results

3.1. Inventory analysis

A total of 95.65 kg of meagre juveniles, each with an average individual weight of 5 g, were produced and subsequently transferred to the RAS grow-out facility during the hatchery production phase. By the end of 2024, the total harvest of meagre reached 1866.1 kg. For the inventory data expressed in the selected FU (1000 kg), the juveniles weight used was 51.26 kg and the fish mortality amounted to 131.60 kg, corresponding to a mortality rate of 7% per FU. Throughout the grow-out phase, freshwater consumption was recorded at 115 m^3 per tonne of live-weight meagre. Electricity use totalled 47078.93 kWh per FU, while diesel consumption amounted to 0.05 m^3.

Within the facility, the highest share of electricity was consumed by the water circulation pumps, which accounted for 27% of the total energy used. This was followed by the degasser pump at 12%, the foam fractionator at 4%, and the air conditioning system for the office and lab, which contributed 3% to overall electricity consumption. The total volume of effluent discharge, measured per FU, was 2405 m^3.

Feed use during the grow-out period averaged 1185.85 kg per tonne of live-weight meagre. The feed formulation was primarily composed of grains, followed by fish meal and fish oil, while the remainder consisted of a standard vitamin premix designed to meet the nutritional needs of the fish.

3.2. Life cycle impact assessment

Values of total emissions of the RAS farm are presented in Table 2. The total GW of meagre production in a RAS farm is 17765,41 Kg CO_2-eq per 1 tonne of live meagre. Results indicate that energy was the main contributor, accounting for more than half (61%) of the GW, followed by transportation (12%) and the hatchery (9%). The factors that contributed less to the GW were freshwater consumption (0.2%) and waste treatment (0.3%) (Fig. 2). The RAS farm emitted a total of 8.32 Kg P-eq, with wastewater treatment being the main contributor (45%) for FE, followed by energy (17%) and other consumptions (13%). Freshwater consumption (0.3%) and infrastructure (1.1%) were the least contributing factors (Fig. 2). As for ME, the RAS farm contributed a total of 104.45 Kg N-eq. The main contributor to ME was 'other consumptions', accounting for the majority of emissions (85%), followed by the wastewater treatment (12%) and the feed (2%). The least contributing factor was freshwater consumption (0.002%) (Fig. 2). The total LD of meagre produced in a RAS farm was 3200.45 m^2-year per 1 tonne of fish. The results indicate that feed is the main contributor, accounting for 70% of total LD. The second main contributor was energy consumption (19%), followed by the hatchery production (7%). Waste treatment was the factor that least contributed to LD, accounting for only 0.007% (Fig. 2).

Values of the total emissions analysed for the feed production used to rear meagre RAS are present in Table 3. The total GW of the feed was 0.91 Kg CO_2-eq per 1 kg of feed. The results indicate that grains are the main contributor, accounting for 43% of the GW, followed by energy (23%) and fishmeal (19%). The factor that contributed less to the GW was vitamins (3%). For the TE, the feed production emitted a total of 2.22 kg 1,4-DCB-eq per 1 kg of feed, with grains being the main contributor (39%), followed by fish oil (30%) and fishmeal (20%). Vitamins (6%) and energy (5%) were the least contributing factors. As for LD, the feed production contributed a total of 1.90 m^2-year per 1 kg of feed. The main contributor to LD was also grains, accounting for almost all the impact (94%). The least contributing factor was vitamins (0.05%). The total WC of the feed production was 0.06 m^3. The results indicate that grains were the main contributor, accounting for 94% of total WC. Vitamins were the factor that least contributed to WC, accounting for only 0.4% (Fig. 3).

3.3. Sensitivity analysis

Results for the sensitivity analysis are summarised in Table 4, highlighting the relative changes in key environmental impact categories compared to the baseline scenario. Incorporating 30% of photovoltaic energy into energy sources of the RAS led to a reduction of 13% in GW and 4% in LD, though it slightly increased FE, with more 9% of total impacts, and had a negligible effect on marine eutrophication. A shift to 100% photovoltaic energy yielded a more pronounced reduction in GW and LD, representing 42% and 15% lower impacts, respectively, and a small decrease in marine eutrophication. However, it was accompanied by notable increases in FE, with more 15% of impact.

The implementation of an on-site hatchery showed consistent environmental benefits, reducing GW by 9%, FE by 3%, marine eutrophication by 0.03%, and LD by 1%. In contrast, substituting fishmeal derived from by-products with whole fish led to significant increases in GW (+14%), while other impacts changed only marginally: FE (−0.04%), ME (−0.02%), and LD (−0.9%). However, replacing the baseline feed from by-products with anchovy-based feed resulted in modest increases in GW (+0.6%) and FE (+0.5%), a negligible change in ME (+0.002%), and a slight decrease in LD (−0.6%).

Table 5 presents the results of the sensitivity analysis and scenarios studied only for feed production, showing relative changes compared to the baseline feed formulation. Replacing fishmeal ingredients derived from fish by-products with whole fish led to a significant increase in GW, by 233%, and a rise in TE of up to 4%. In contrast, it resulted in a slight

Table 2
Life cycle impacts associated with the production of 1 tonne of live meagre in RAS.

	Global warming (kg CO_2 eq)	Freshwater Eutrophication (Kg P eq)	Marine Eutrophication (Kg N eq)	Land Use (m^2 year)
Total	17765,41	8.32	104.45	3200.45
Energy	10837.22	1.44	0.15	606.88
Freshwater	35.03	0.02	0.002	1.15
Transportation	2077.10	0.26	0.03	41.20
Infrastructure	95.16	0.10	0.02	3.82
Feed	1079.90	0.54	2.52	2238.42
Hatchery	1675.86	0.55	0.22	223.22
Cleaning agents	799.65	0.46	0.02	53.57
Wastewater treatment	857.28	3.78	12.76	23.31
Waste treatment	48.31	0.11	0.09	0.23
Other consumptions	260.90	1.06	88.63	8.67

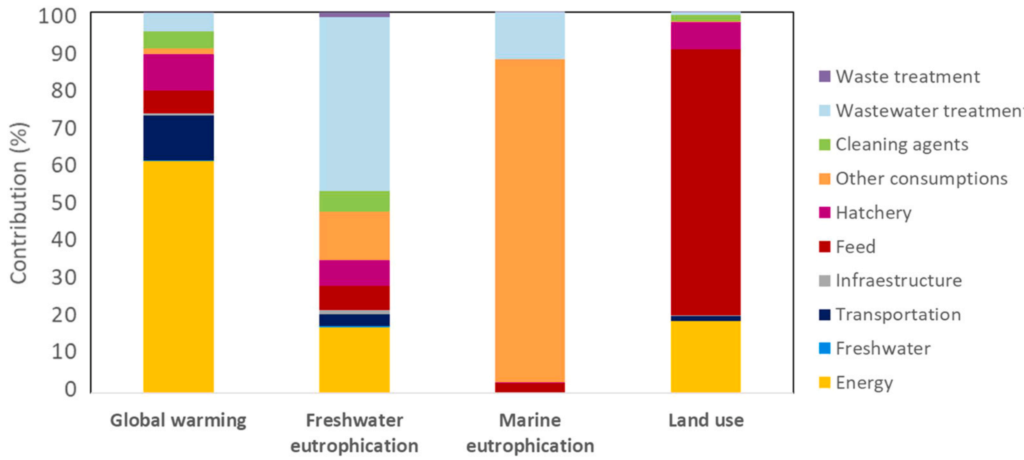

Fig. 2. Life cycle contribution analysis of the production of 1 tonne meagre harvested in the grow-out RAS farm.

Table 3
Life cycle impact associated with the production of 1 kg of meagre feed.

Impact Categories	Global warming (kg CO_2 eq)	Terrestrial ecotoxicity (kg 1,4-DCB eq)	Land Use (m^2 year)	Water Consumption (m^3)
Total	0.91	2.22	1.89	0.06
Energy	0.21	0.11	0.003	0.001
Fish meal	0.17	0.44	0.05	0.002
Fish oil	0.11	0.67	0.06	0.001
Grains	0.39	0.87	1.78	0.06
Vitamins	0.03	0.13	0.001	0.00

decrease in LD (1%) and WC (1%). Replacing the baseline fish meal and fish oil ingredients from fish by-products to Peruvian anchovy led to a moderate increase in GW (+11%) and TE (+11%), a slight decrease in LD (−0.9%), and a marginal reduction in WC (−0.07%).

4. Discussion

4.1. Environmental assessment of meagre aquaculture production in RAS

To date, no LCA study has been conducted specifically on the production of meagre in RAS, limiting the possibility of direct comparisons. It is also important to emphasise that the current assessment is based on a pilot-scale production system, which has not yet been fully optimised for efficiency or maximum biomass yield. The LCA results for the production of 1 tonne of live fish in RAS indicate that energy consumption and feed production are the prime contributors to environmental impacts across multiple categories. The GW is mainly driven by energy use (61% of the total GW), highlighting the intensive energy demands inherent to RAS technologies. As RAS depends on continuous water circulation, aeration, heating, and filtration to maintain optimal water quality for fish health and growth conditions, the significant role of energy consumption was expected (Bergman et al., 2020). The production of meagre in RAS is estimated to generate 17,765 kg CO_2 eq per tonne of live fish, which is higher when compared to other RAS-based aquaculture species. For instance, tilapia production in RAS has been reported to generate approximately 14,700 kg CO_2 eq (Bergman et al., 2020), while rainbow trout production ranged between 6103 kg CO_2 eq and 13,622 kg CO_2 eq, depending on system configuration and geographic context (Dekamin et al., 2015; Samuel-Fitwi et al., 2013). Several factors may contribute to the elevated emissions observed in meagre production. Notably, meagre is a saltwater species that requires specific environmental conditions, and when reared at temperatures lower than 18 °C, there is a reduction of feed intake and therefore growth (Saavedra et al., 2022). This thermal regulation, particularly in temperate climates, as it is the case in Portugal, can significantly increase energy demand. Additionally, the operation of a saltwater RAS is inherently more energy-intensive than freshwater systems due to higher corrosion risks, low efficiency of CO_2 removal, increased density, and salinity control, which may increase energy costs (Lindholm-Lehto, 2023; Moran, 2010). These factors likely contribute to the comparatively high carbon footprint of meagre production in RAS, suggesting a

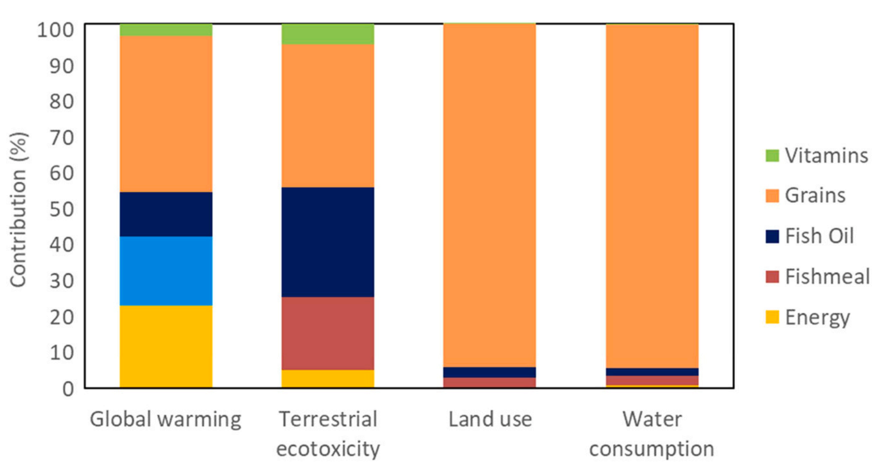

Fig. 3. Life cycle contribution analysis of the production of 1 Kg of meagre feed.

Table 4
Results for the sensitivity analysis for meagre production in RAS with the relative change in percentage compared to the baseline scenario.

	Global Warming	Freshwater eutrophication	Marine eutrophication	Land use
30% photovoltaic energy	- 13%	+ 9%	+ 0.003%	- 4%
100% photovoltaic energy	-42%	+ 15%	- 0.4%	- 15%
On-site hatchery	- 9%	- 3%	- 0.03%	- 1%
Whole fish fishmeal feed	+ 14%	- 0.04%	- 0.02%	- 0.9%
Anchovy feed	+ 0.6%	+ 0.5%	+ 0.002%	- 0.6%

Table 5
Results from the sensitivity analysis for the feed production with the relative change in percentage compared to the baseline scenario.

	Global Warming	Terrestrial ecotoxicity	Land use	Water consumption
Whole fish fishmeal feed	+ 223%	+ 4%	- 1%	- 1%
Anchovy feed	+ 11%	+ 11%	- 0.9%	- 0.07%

high potential for emissions reductions through the integration of renewable energy sources and improvements in energy efficiency. Furthermore, since all environmental impacts are expressed per functional unit of 1 tonne of live-weight meagre, the relatively high impact values may also reflect the lower production scale.

Feed production emerged as a significant environmental hotspot across multiple life cycle impact categories, reflecting its pivotal role in the overall sustainability of aquaculture production systems. This aligns with previous findings that highlight the considerable environmental burden associated with feed in aquaculture, from the extraction, cultivation, and processing of raw ingredients to the final manufacturing and transportation of feed products (Abdou et al., 2017). In the present study, feed accounted for approximately 6% of the GW (1079 kg CO_2 eq), highlighting its contribution to GHG emissions. However, the most substantial environmental impact associated with feed was observed in the LD category, where it contributed 2238 m^2·year, representing over 69% of the total land occupation. This is primarily attributed to the agricultural land required for the cultivation of feed crops such as grains, identified in the data obtained from the feed supplier. These crops not only require extensive land, but are also associated with upstream environmental impacts including soil degradation, water consumption, and use of fertilizers and pesticides, contributing to environmental issues related to agricultural production (Fry et al., 2016). These LD impacts highlight the environmental pressure caused by aquafeed production, especially when plant-based ingredients replace fishmeal and fish oil in feed formulations. While feed is a key factor in aquaculture, its environmental consequences, particularly in terms of LD, are relevant, and therefore, it is essential to mitigate feed's environmental footprint.

Wastewater treatment plays a critical role in nutrient-related impacts, especially freshwater eutrophication (4 kg P eq), where it contributes over 45% of the total. This indicates that despite the closed-loop nature of RAS, phosphorus leakage remains a concern, likely arising from insufficient nutrient recovery or treatment inefficiencies. Additionally, wastewater treatment contributes significantly to marine eutrophication (13 kg N eq), further emphasising the need for advanced nutrient stripping technologies or recovery strategies within effluent treatment systems. The studied system still sends 2405 m^3 of effluents per FU to the treatment facility, which can be considered a relatively high amount of water. The contribution of nitrate has reportedly been dominated, resulting from aquaculture effluents and animal feed operations (Akinnawo, 2023). This can be attributed to nitrogen losses occurring at various stages, including feed production, post-ingestion excretion by the fish, and inefficiencies in nitrogen assimilation. It directly contributes to nutrient enrichment and subsequent ecological degradation, such as algal blooms and hypoxic zones, degrading the water quality in aquatic ecosystems (Bali and Gueddari, 2019). These findings emphasise the importance of improving feed conversion ratios (FCR), enhancing nutrient retention in feed formulations, and developing low-impact feed ingredients, such as insect meal (Bingqian et al., 2024) or algae-based alternatives (Ansari et al., 2021).

To mitigate the impacts of excessive nitrate concentrations, the adoption of integrated multi-trophic aquaculture systems has gained popularity. These systems use accumulated organic matter to rear a secondary species, thereby reducing environmental impacts, promoting circular economy and increasing income for fish farmers. This underscores a critical opportunity for improvement within the RAS facility, as reducing this outflow could enhance both environmental and operational efficiency.

Anomalously, a high contribution to marine eutrophication was observed from the "other consumptions" category, which accounted for 88.63 kg N eq, representing over 84% of the total marine eutrophication impact in the system. This value is primarily attributed to the use of industrial oxygen and ozone in the studied RAS. These gases are critical for maintaining water quality and fish health (Tango and Gagnon, 2003), particularly since dissolved oxygen saturation decreases as water temperature rises. However, the use of these gases has indirect environmental burdens associated to their production and upstream supply chains, involving energy-intensive processes, such as cryogenic air separation or pressure swing adsorption, which are associated to significant emissions of nitrogen oxides (Variny et al., 2021).

Transportation, infrastructure, hatchery operations and cleaning agents each contributed modestly across most categories. However, their combined effects represent non-negligible environmental loads. For instance, transportation alone contributed 2077 kg CO_2 eq to GW and 41 m^2·year to land use, suggesting that localised sourcing of inputs and proximity to markets could yield meaningful reductions.

Because all environmental impacts are expressed relative to the functional unit of 1 tonne of live-weight meagre, the relatively high impacts observed can be partly attributed to the lower production scale and R&D-driven operation of the company, which prioritises experimentation over production efficiency. As the system is refined and scaled up, improvements such as enhanced feed conversion ratios, better energy management and increased production density are expected to reduce the per-unit environmental burdens significantly. Consequently, future commercial-scale operations of meagre production in RAS have the potential to achieve substantially lower environmental impacts per tonne of live fish, improving the overall sustainability profile of this aquaculture practice.

4.2. *Environmental improvements based on scenarios*

The results from the sensitivity analysis related to the different scenarios studied when producing one tonne of live-weight meagre in RAS reveal important trade-offs and highlight the critical influence of energy sourcing, feed composition and hatchery practices on environmental performance. The switch from the Portuguese energy mix to 30% and 100% renewable energy had some effects on the impact categories considered. Transitioning to photovoltaic energy significantly reduced global warming by 13% when 30% photovoltaic energy was applied and by a substantial 42% when a 100% photovoltaic energy scenario was analysed, demonstrating the climate benefits of renewable energy integration. In recent years, Portugal has made significant progress in adopting renewable energy, with renewables accounting for over 60% of electricity generation in 2023, primarily from wind, hydropower, and solar power (REN, 2024). Therefore, the GW would increase if the RAS farm were located in another country with a less energy-intensive mix. Despite this cleaner-than-average grid of Portugal, the analysis shows that increasing photovoltaic energy usage with 30% and even 100% still results in considerable reductions of GW. This demonstrates that even in a low-carbon energy context like Portugal's, direct integration of on-site photovoltaic systems offers climate benefits, reducing dependence on any residual fossil fuel and improving energy autonomy. However, the analysis also reveals that FE increases (9% and 15% more, respectively) with an increase of photovoltaic energy. This is likely due to the life cycle impacts of manufacturing solar panels, such as emissions from raw material processing and associated waste. These results suggest that on-site renewable integration remains an effective strategy for climate mitigation, but it must be paired with careful management of upstream supply chains to avoid shifting the environmental burden to other impact categories, especially affecting freshwater ecosystems.

Implementing an on-site hatchery consistently reduces environmental impacts across all categories, suggesting broader environmental benefits. These reductions are primarily attributed to the elimination of the transport of juvenile fish from the external hatchery to the grow-out facility, corresponding to 4900 Km. This transport is reliant on diesel-powered vehicles, which contribute significantly to GHG emissions and other environmental burdens, including air pollutants. By implementing an on-site hatchery, RAS farms can avoid these emissions and reduce dependency on external inputs. Additionally, on-site hatcheries may offer improved biosecurity and operational efficiency, further enhancing their environmental and economic viability. The results underscore the broader implication that logistical processes, especially those involving fossil fuels, can have disproportionately large environmental impacts in aquaculture systems, and reducing or eliminating these can yield meaningful environmental benefits.

Feed composition emerges as one of the most influential factors affecting the environmental footprint of RAS operations for meagre production. This is particularly relevant for the GW where the use of whole fish fishmeal feed leads to a 14% increase in GHG emissions relative to the baseline scenario. This is even more relevant when focusing the analysis on feed production only, where the GW has a 223% increase relative to the baseline feed composition for 1 tonne of feed. This sharp rise can be attributed to the high resource intensity and carbon footprint associated with harvesting wild fish exclusively for sardine fishmeal production, as there is a low efficiency of converting wild biomass into aquaculture inputs. It involves substantial fuel use in fisheries and the loss of biomass that could otherwise support marine ecosystems and direct human consumption (Naylor et al., 2009; Tacon and Metian, 2009). Additionally, this scenario also leads to a 4% increase in TE, further emphasising the broader environmental cost of relying on wild fish resources. Interestingly, it shows slight reductions in LD and WC, and when integrated into the grow-out system, a decrease in both FE and ME. However, these minor gains are heavily outweighed by the negative trade-offs, particularly in carbon emissions and ecosystem toxicity.

The use of anchovy-based feed results in modest increases across most environmental indicators (0.4% for GW, 0.5% for FE, and a slight rise in ME). When looking at feed production only, anchovy-based feed causes a 11% rise in GW and an even higher 12% increase in TE, while marginally decreasing LD (−0.95%) and WC (−0.07%). While less damaging than other whole fish fishmeal, anchovy-based diets still rely on wild fish stocks and are subject to the same systemic pressures, including marine resource depletion and environmental impacts of capture and processing. Such practices raise ethical and ecological concerns, as they may contribute to overfishing, biodiversity loss, and reduced ocean resilience. However, it is important to note that in terms of fuel use and fishing effort, the Peruvian anchovy fishery has proven to be one of the most efficient in the world (Deville et al., 2025). Also, when compared to terrestrial-based feed ingredients with a mass allocation, Peruvian fish meal and fish oil (FMFO) were found to have one of the best environmental performances, even when compared to Portuguese FMFO from fish by-products (Deville et al., 2025). Transport of juveniles also presents minor opportunities for improvement, and overall, a life cycle perspective is essential, but future sustainability efforts in land-based aquaculture should prioritise decarbonising energy inputs and enhancing system-level energy performance to achieve meaningful reductions in environmental impact.

When considering the overall environmental impact of RAS, energy use emerges as the primary contributor, contributing more than 60% to GW in the baseline analysis. This highlights the importance of improving energy efficiency, which should be a central focus of sustainable efforts in RAS. Transitioning to renewable energy sources can yield substantial reductions in GHG emissions and substantially reduce the overall environmental footprint. In the specific case of meagre, which requires higher water temperatures to achieve optimal growth rates, it is important to assess whether the energy costs of maintaining a temperature of 25 °C are justified by the resulting gains in growth performance. Rearing the species at slightly lower temperatures, such as 20–22 °C, may offer a more energy-efficient alternative with marginal trade-offs in productivity. A comprehensive cost-benefit analysis should be conducted to evaluate the economic and environmental viability of different temperature regimes. Considering the results, it also becomes clear that feed formulation is a critical determinant of sustainability in aquaculture. Feed production, especially when derived from wild fish, carries significant upstream burdens that can overshadow the operational efficiencies gained through cleaner energy use or system design improvements. The baseline analysis in this case shows that feed already mainly consists of by-products and does not present major environmental improvement opportunities. This strategy can drastically reduce dependence on wild fish, lower GHG emissions, and mitigate ecotoxicity, while aligning aquaculture more closely with principles of the circular economy and ecosystem conservation. Formulating effective and sustainable feeds presents a complex challenge as alternative ingredients must not only meet the nutritional requirements of the target species but also support optimal growth, feed conversion efficiency, and fish health. Moreover, these formulations must be economically viable and scalable for commercial production. Current research in aquaculture nutrition is increasingly focused on identifying and developing sustainable alternative feed ingredients to reduce the sector's environmental footprint (Saavedra et al., 2022). Furthermore, several promising novel feed ingredients have emerged, including single-cell proteins such as yeast, microbial biomass, microalgae, and insect-based meals. These alternatives offer advantages such as high protein content, essential amino acid profiles and a reduced environmental impact compared to traditional marine-derived inputs (Saavedra et al., 2023). Further research is needed to optimise inclusion rates, assess long-term impacts on fish health and product quality, and evaluate the environmental benefits of these alternatives. Nonetheless, the integration of novel feed ingredients holds substantial potential to improve the sustainability and resilience of aquaculture systems.

5. Conclusions

This study presents an LCA of producing one tonne of live-weight meagre in a RAS located in Portugal. To the best of our knowledge this is the first LCA study specifically focused on RAS-based meagre farming, providing a valuable reference point for future sustainability evaluations. Although the analysed facility is a pilot-scale farm, the results indicate that RAS has the potential to offer favourable environmental performance in aquaculture. Energy consumption emerged as the most significant contributor to the overall environmental impact of the system. The findings suggest that integrating alternative energy sources, particularly photovoltaic energy, could substantially reduce impact, especially in categories such as GW and LD. This study also underscores the importance of prioritising fish by-products rather than whole fish and exploring alternative feed ingredients to mitigate environmental burdens. The insights gained from this study enhance the understanding of the environmental profile of RAS-based meagre farming and provide a foundation for improving environmental efficiency in future operations. To further support the use of LCA as a decision-making tool in the aquaculture sector, future research should focus on expanding and refining aquaculture-specific LCI datasets and addressing impact categories unique to aquatic systems.

CRediT authorship contribution statement

Margarida Saavedra: Writing – review & editing. **Patrícia Canhão:** Data curation. **Inês Cacela-Rodrigues:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Cheila Almeida:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **P. L. Costa Ana:** Writing – review & editing, Data curation. **Amparo Gonçalves:** Resources, Project administration, Funding acquisition.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ana P. L. Costa reports a relationship with SEAentia-Food, S.A that includes: employment. Patricia Canhao reports a relationship with SEAentia-Food, S.A that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aqrep.2026.103641.

Data availability

Data will be made available on request.

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