Life Cycle Assessment of Aquaculture Systems: Environmental Hotspots, Methodological Challenges, and Pathways Towards Sustainable Production

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Abstract

Aquaculture has become a critical contributor to global food and nutritional security; however, its rapid expansion has raised concerns regarding resource use, emissions, and ecosystem degradation. Life Cycle Assessment (LCA), standardized under ISO 14040/14044, has emerged as a key framework for quantifying the environmental impacts of aquaculture systems across diverse species, production technologies, and geographic contexts. This review synthesizes 105 peer-reviewed LCA studies to evaluate environmental hotspots, methodological practices, and emerging trends in aquaculture sustainability assessment. Comparative analysis reveals that feed production and energy consumption dominate environmental impacts, particularly global warming potential, eutrophication, and acidification, irrespective of species or culture intensity. While intensive and closed systems such as recirculating aquaculture and biofloc technologies enhance water and nutrient management, they often incur higher climate impacts due to elevated electricity demand. Significant methodological variability exists across studies, particularly in the selection of functional units, system boundaries, allocation procedures, and treatment of uncertainty, limiting cross-study comparability and hence the relevance of decision making. Critical gaps are also identified in the assessment of biodiversity, disease-related impacts, and dynamic system behaviour. Building on these findings, the review outlines future directions for aquaculture LCA, emphasizing renewable energy integration, sustainable aquaculture feed development, circular economy strategies, and the incorporation of emerging tools such as dynamic LCA, social LCA, artificial intelligence, and planetary boundary frameworks. By consolidating the existing and current knowledge and identifying priority research needs, the review provides a robust foundation for advancing environmentally resilient and resource-efficient aquaculture systems aligned with global sustainability goals.

Introduction

The aquaculture industry has witnessed remarkable growth, with annual output increasing by 609% from 1990 to 2020 at an average rate of 6.7% per year (Food and Agriculture Organization of the United Nations [FAO], 2022a). While this expansion has supported food security and international supply chains, it has simultaneously intensified the ecological footprint of the sector. Aquaculture contributes substantially to anthropogenic greenhouse gas (GHG) emissions, with projections indicating a significant rise by 2030 to 3.83×10^{11} g of CO_2 equivalent, accounting for approximately 5.72% of nitrous oxide (N_2O) emissions (Raul, Pattanaik, & Prakash, 2020). Environmental impacts are largely driven by intensive production models; approximately two-thirds of finfish and crustacean systems depend on feed-based inputs, with fishmeal and fish oil serving as primary components (Boyd, McNevin, & Davis, 2022). The estimated demand for 73.15 million tons

of aquafeed by 2025 further highlights the increasing reliance on traditional resources (Boyd et al., 2020). To address these sustainability challenges, the Food and Agriculture Organization's (FAO) Blue Transformation initiative advocates for climate-smart practices and innovative management strategies to foster sustainable sectoral growth (FAO, 2022b).

Quantifying these impacts requires Life Cycle Assessment (LCA), an International Organization for Standardization (ISO) methodology that evaluates environmental burdens across the entire life cycle of aquatic food products (Lee & Inaba, 2004). While Life Cycle Thinking (LCT) provides the conceptual framework to prevent burden-shifting, LCA employs quantitative tools to identify environmental hotspots and guide policy formulation (Das & Edwin, 2016; Ravi, Das, & Edwin, 2020; Sala, Amadei, Beylot, & Ardente, 2021). Despite its utility, the efficacy of LCA in aquaculture is often constrained by data quality, methodological inconsistencies in allocation, and the current inability to fully capture biotic impacts like the spread of diseases (Flores-Pérez et al., 2023).

This review critically synthesizes LCA literature on aquaculture systems to evaluate the sector's role in supporting global sustainability objectives. The primary objectives are to systematically analyze the current state of LCA research in aquaculture while identifying hotspots and the dominant impact categories of global warming, eutrophication, and acidification. Furthermore, the study evaluates methodological variations, specifically the selection of functional units, system boundaries, and the transparency of allocation methods, to improve research standardization. Finally, this work proposes strategies for future research, emphasizing technological decoupling through photovoltaic energy integration, the adoption of low impact aquafeed formulations, and the integration of circular economy principles to align with Sustainable Development Goal (SDG) targets. By advancing the understanding of LCA applications, this review facilitates strategic planning for a more environmentally resilient and resource-efficient aquaculture industry.

Review Methodology

Literature Search and Selection Criteria

A systematic review of LCA in aquaculture was conducted using Scopus, Web of Science, Google Scholar, and ScienceDirect. To ensure taxonomic and technological breadth, Boolean operators combined core LCA terms with variables such as "Recirculating Aquaculture Systems", "Biofloc", "Aquaponics", etc., and specific species taxonomy. Following the PRISMA guidelines, 136 records were identified; after rigorous screening, 105 peer-reviewed studies were selected for synthesis. Inclusion required strict adherence to ISO 14040/14044 standards and quantitative evaluation of at least two impact categories. Studies were categorized by system intensity, species, and methodological choices, including functional units and system boundaries, to identify environmental hotspots and research gaps.
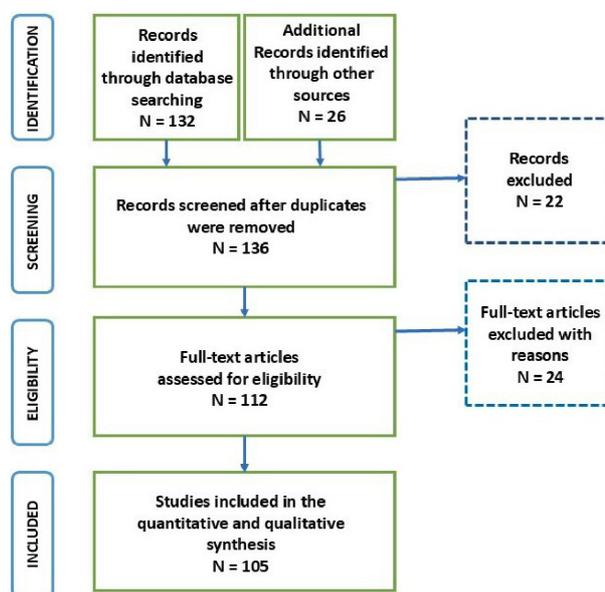

Fig. 1. Selection of articles using the PRISMA method

LCA Framework and Key Methodological Concepts

The LCA methodology adheres strictly to the ISO standards, providing an iterative framework for evaluating the environmental performance of aquaculture systems. As illustrated in Fig. 2, the process is structured into four interdependent phases: Goal and Scope Definition (ISO 14041), Life Cycle Inventory (LCI; ISO 14041), Life Cycle Impact Assessment (LCIA; ISO 14042), and Interpretation (ISO 14043).

In the initial Goal and Scope phase, the study's intended application and reference flows are established, encompassing critical decisions such as the selection of functional units, definition of system

boundaries, and identification of relevant impact categories. While practitioners frequently adopt standardized boundaries, significant methodological inconsistencies persist regarding the handling of multi-functionality (allocation) and the depth of LCIA modelling. These variations underscore a critical need for harmonized methodologies and consistent inventory data to ensure the reliability and comparability of results across diverse production systems.
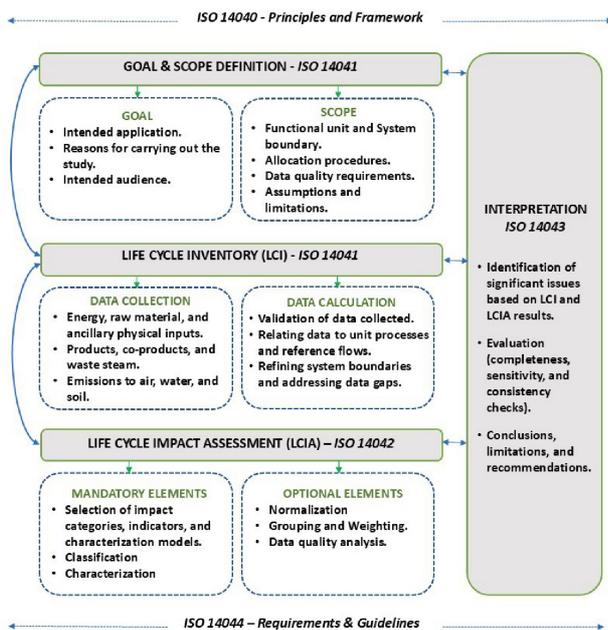

Fig. 2. LCA Expanded Framework (Based on ISO Environmental Management — Life Cycle Assessment)

The LCI phase involves the meticulous quantification of inputs, such as energy, raw materials, and ancillary physical flows, against outputs, including products, co-products, and multi-media emissions. These data are then translated in the LCIA phase into comprehensive environmental metrics, enabling the assessment of impacts and various forms of chemical toxicity affecting both human health and ecosystem quality. Finally, the Interpretation phase synthesizes these results to identify environmental hotspots, provide policy recommendations, and address inherent limitations. Standardizing these methodological choices is essential for reducing inconsistencies and facilitating meaningful, evidence-based comparisons across global aquatic food systems.

Key findings and Synthesis

Taxonomic and Geographic Trends in LCA Applications

The current landscape of aquaculture LCA research demonstrates a significant taxonomic and geographic expansion, driven by global market demands and sustainability imperatives. As illustrated in Fig. 3, crustaceans (shrimp and prawns) represent the most researched taxonomic group, dominating the LCA literature with over 30 dedicated studies. This intensive focus correlates with their high economic valuation and the environmental complexities of their production cycles. Analysis of the reviewed dataset shows that crustacean research is geographically widespread, with a strong concentration of studies in China, Brazil, Mexico, and Vietnam, alongside contributions from Thailand, Colombia, Taiwan, Indonesia, and the United States. Other prominent clusters include Salmonidae (Atlantic Salmon/Trout) with 18 studies and Bivalvia (Clams/Oysters/Mussels) with 12 studies. The geographic spread of Salmonid research is notably centred in Europe, with a high density of studies originating from Italy, Sweden, Germany, and France, as well as contributions from Scotland (UK), China, and Canada. Notably, Italy and China emerge as the primary research hubs, consistently contributing the highest volume of high-resolution LCA data across multiple species. Conversely, species such as Tiger Puffer, Milkfish, and Lumpfish remain underrepresented, highlighting critical gaps in the current literature. This data-centric analysis reveals that while aquaculture output drives scientific investment, the specific species targeted for sustainability metrics are heavily influenced by regional economic priorities.
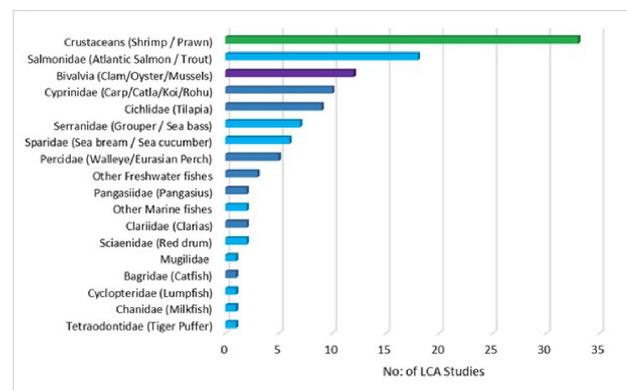

Fig. 3. Distribution of LCA studies across Taxonomic Families

Culture Systems

The environmental profile of aquaculture is fundamentally shaped by the interaction between species-specific biological requirements and the chosen production technology. LCA literature reveals a diverse array of culture systems, ranging from traditional ponds and cages to intensive Recirculating Aquaculture Systems (RAS) and Biofloc technology, across major taxonomic groups. Methodological comparisons highlight critical performance trade-offs. For instance, sea-based systems generally exhibit lower operational energy demands than land-based designs but often record higher Feed Conversion Ratios (FCR), indicating reduced feed-use efficiency. Furthermore, open-sea systems frequently contribute more to eutrophication due to direct nutrient discharge, whereas closed or land-based systems offer superior waste containment at the cost of higher energy intensity for water circulation and filtration (Philis et al., 2019). Technological management also drives variance; trout systems often require more infrastructure and chemotherapeutic agents than salmon systems. Overall, while aquaculture generally maintains a lower footprint than terrestrial livestock, optimizing the balance between energy inputs, nutrient recy-

Table 1. Major aquaculture species, culture systems, and key references in LCA studies

Species Group	Representative Species	Culture Systems	References
Crustaceans	Shrimp, Prawn	Ponds, RAS, Biofloc	Mungkung and Clift (2004); Cao, Diana, Keoleian, & Lai (2011); Jonell and Henriksson (2015); Orozco and Ramírez (2015); Santos, Aubin, Corson, Valenti, and Camargo (2015); Yacout, Soliman, and Yacout (2016); Chang, Chang, Lin, and Wu (2017); Medeiros, Aubin, and Camargo (2017); Järviö, Henriksson, and Guinée (2018); Biermann and Geist (2019); Chen, Yang, Zhang, and Sun (2019); Henriksson et al. (2019a); Song et al. (2019); Sherry and Koester (2020); Cortés et al. (2021); Maiolo, Forchino, Faccenda, and Pastres (2021); Marzban, Elhami, and Bougari (2021); Noguera et al. (2021); Al Eissa, Chen, Brown, and Huang (2022); Bordignon et al. (2022); Ghamkhar, Hartleb, Rabas, and Hicks (2022); Haslawati, Saadiah, Siti-Dina, Othman, and Latif (2022); Wind, Schumann, Hofer, Schulz, and Brinker (2022); Elnour, Haller, and Martin (2023); Flores-Pérez et al. (2023); Sun et al. (2023); Xing-Guo et al. (2023); Arbour, Bhatt, Simsek, Brown, and Huang (2024); de Almeida et al. (2024); Rong, Liu, Zhu, and Qin (2025)
Cichlidae	Tilapia	Ponds, Lakes, Aquaponics, Cages, RAS	Yacout et al. (2016); Cohen, Malone, Morris, Weissburg, and Bras (2018); Avadí and Vázquez-Rowe (2019), Henriksson et al. (2019b); Avadí, Vázquez-Rowe, Symeonidis, and Moreno-Ruiz (2020); Bergman et al. (2020); Dullah, Malek, and Hanafiah (2020); Bhakar, Kaur, and Singh (2021); Ghamkhar et al. (2022)
Bivalvia	Clams, Oysters, Mussels, Cockles	Lagoons, Offshore Long-lines, Bouchot Culture	Lourguioui, Brigolin, Boulahdid, and Pastres (2017); Aubin, Fontaine, Callier, and d'orbcastel (2018); Ray, O'Meara, Wiliamson, Izursa, and Kangas (2018); Tamburini, Fano, Castaldelli, and Turolla (2019); Tamburini, Turolla, Fano, and Castaldelli (2020); Turolla, Castaldelli, Fano, and Tamburini (2020); Tamburini, Turolla, Lanzoni, Moore, and Castaldelli (2022); Pahri, Yana, and Danial (2023); Summa et al. (2023)

Cyprinidae	Carp, Catla, Koi, Rohu	Ponds, Cages, Aquaponics, Rice–Fish Systems	Henriksson Belton, Jahan, and Rico (2018); Biermann and Geist (2019); Jaeger, Foucard, Tocqueville, Nahon, and Aubin (2019); Paramesh et al. (2019); Bhakar et al. (2021); Marzban et al. (2021); Xing Guo et al. (2023)
Salmonidae	Atlantic Salmon, Trout	Net-pens, Open Cages, Flow-through Systems, Ponds, Aquaponics	Forchino, Lourguioui, Brigolin, and Pastres (2017); Newton and Little (2018); Song et al. (2019); Sherry and Koester (2020); Maiolo et al. (2021); Bordignon et al. (2022); Wind et al. (2022); Elnour et al. (2023); Langeland, Ziegler, and Wocken (2023); Wilfart et al. (2023)
Serranidae	Grouper, Seabass	Ponds, Cages, IMTA	Abdou, Lasram, Romdhane, Le Loc'h, and Aubin (2018); Beltran et al. (2018); García, Jiménez, Aguado-Giménez, and García (2019); Kallitsis, Korre, Mousamas, and Avramidis (2020); Maiolo (2020); Briones-Hidrovo, Quinteiro, & Dias (2023); Hou et al. (2023); Zoli et al. (2023)
Sparidae	Sea Bream, Sea Cucumber	Sea Cages, IMTA	Abdou et al. (2018); Beltran et al. (2018); Hou et al. (2019); Chary et al. (2020); Kallitsis et al. (2020); Zoli et al. (2023)
Percidae	Walleye, Eurasian Perch	Aquaponics, RAS	Ghamkhar, Hartleb, Wu, and Hicks (2020); Cooney, Tahar, Kennedy, and Clifford (2021); Ghamkhar et al. (2022)
Sciaenidae	Meagre, Red Drum, Croaker	Sea Cage Farming, IMTA	Chary et al. (2020); Konstantinidis, Perdikaris, and Ganias (2021); Liu et al. (2023)
Clariidae	Clarias (African Catfish)	Ponds, Cages, RAS	Bergman et al. (2020)
Pangasiidae	Pangasius	Ponds, Cages	Henriksson et al. (2018); Henriksson et al. (2019a)
Tetraodontidae	Tiger Puffer	RAS, Sea Cage Farming	Hou et al. (2022)
Chanidae	Milkfish	Ponds, Cages	Henriksson et al. (2019b)
Cyclopteridae	Lumpfish	Flow-through Seawater Systems (Raceways/Tanks)	Gaeta, Parolini, and Bacenetti (2022)
Bagridae	Catfish	Ponds	Fouda, Elrayes, and Elhanafy (2022)
Carangidae	Greater Amberjack	Cages	Bordignon et al. (2023)
Other Freshwater / Marine Fishes	–	Flow-through Systems, RAS, Sea Cages	Bohnes and Laurent (2021), Jones et al. (2022)

cling (e.g., via IMTA), and feed efficiency remains essential for sustainable sectoral growth (Bibbiani, Fronte, Incrocci, & Campiotti, 2018; Bohnes, Hauschild, Schlundt, & Laurent, 2019).

Functional Units

According to ISO 14040, identifying the reference flow in each system is critical for fulfilling the intended function of an LCA. Functional units (FUs) serve as the basis for quantifying the performance attributes of a product system. The mass-based functional unit remains the most prevalent metric in aquaculture LCA literature. This approach expresses environmental impacts per unit of weight, typically per kilogram or ton, of the aquatic product. This review categorizes mass-based FUs into two distinct subtypes:

· **Harvested Weight-Based FUs:** This focuses on the live weight at the farm gate prior to processing (e.g., 1 ton of live weight). It is the most frequently employed unit, found in 86% of reviewed literature, effectively capturing upstream impacts such as farming and capture operations.

· **Processed Product-Based FUs:** Utilized in approximately 14% of studies, this unit accounts for weight after cleaning, filleting, or packaging (e.g., 1 kg of fish fillet). This provides product-oriented insights for consumer-facing assessments and value-added supply chains.

A significant methodological evolution is the adoption of protein-based functional units, which normalize environmental burdens based on nutritional output rather than gross weight (Chary et al., 2020). Unlike mass-based metrics, these units assess impacts per kilogram of edible protein, accounting for the inherent variability in nutrient density across species. This nutrition-based perspective offers a more scientifically rigorous lens for evaluating contribution of aquaculture to global food security and human health, preventing the overestimation of sustainability in species with higher bone or water content.

System Boundaries

In LCA, the definition of system boundaries is a foundational phase that delineates the unit processes under study, facilitating comparative analyses across diverse temporal and geographical contexts (Avadí, Henriksson, Vázquez-Rowe, & Ziegler, 2018). These boundaries are established through the strategic inclusion or exclusion of life cycle stages, ranging from upstream input production to end-of-life disposal, guided by transparent cut-off criteria such as mass, energy contribution, or environmental relevance (ISO, 2006a; 2006b). In aquaculture LCA studies, certain specific processes are often omitted based on the assumption of negligible impact, expert judgment, or established literature precedent (Philis et al., 2019). However, such exclusions risk underestimating the cumulative environmental burdens of minor processes, potentially resulting in incomplete impact characterizations. The complexity of these various boundary tiers is illustrated in Fig. 4, which visually maps the transition from narrow "Gate" assessments to expansive "Grave" frameworks.
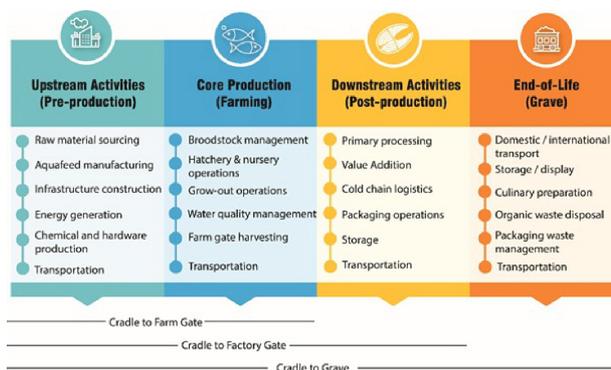

Fig. 4. LCA System Boundaries in Aquaculture Supply Chain

The systematic analysis of the selected LCA literature highlights a significant skew in methodological boundary selection, with 80% of assessments adopting a Cradle-to-Farm Gate scope to isolate farm-level efficiencies and circumvent the high data uncertainty inherent in international supply chains. A smaller subset extends this boundary to Cradle-to-Factory Gate (13%), including primary and secondary processing, while only a minority (7%) adopts a comprehensive Cradle-to-Grave perspective. This heavy reliance on narrower boundaries may overlook critical instances of burden shifting, where environmental improvements achieved at the farm gate are offset by high-impact downstream activities, such as energy-intensive cold chains or global air-freight distribution.

Allocation in Multi-Functional Processes

Allocation is a pivotal methodological step in LCA that distributes environmental burdens among co-products within multi-functional systems. The choice of allocation method significantly affects results and should align with system characteristics and study goals. As illustrated in Fig. 5, mass allocation was the most prevalent specified method (Beltran et al., 2018; Newton & Little, 2018), utilized in 28% of the reviewed literature. This approach is favoured for its transparency and simplicity in material flow analysis. Economic allocation followed closely at 22%, aligning environmental impacts with financial value, though it remains susceptible to market price volatility (Bergman et al., 2020). Energy content allocation accounted for only 4% of studies, primarily in energy-intensive contexts. Notably, 16% of studies were categorized as allocation-free, typically representing monofunctional systems where such partitioning was unnecessary. System expan-

sion remains a robust alternative, as demonstrated by Bohnes and Laurent (2021) and Bordignon et al. (2022), by incorporating substituted or avoided products to provide a consequential modelling perspective. However, a significant transparency gap persists, with 30% of cases failing to specify the allocation method employed. Ensuring scientific robustness and comparability in future aquaculture LCAs necessitates strict adherence to ISO 14044 guidelines for documented, hierarchical allocation procedures.
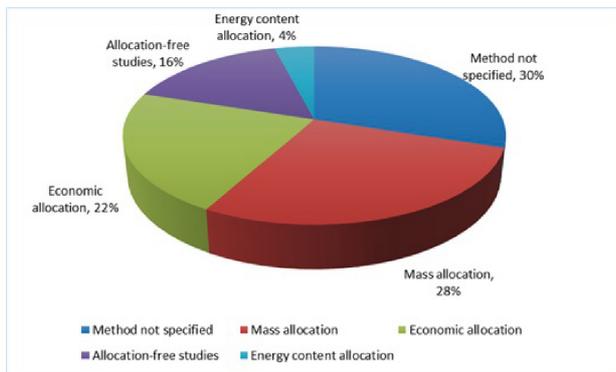

Fig. 5. Allocation for multi-functional process handling

Environmental Impact Assessment

Life Cycle Impact Assessment (LCIA) represents the pivotal phase within the LCA framework where Life Cycle Inventory (LCI) data, comprising thousands of individual elementary flows, are translated into measurable environmental impact scores. According to ISO 14044 (ISO, 2006b), this process is designed to evaluate the magnitude and significance of potential environmental effects by bridging the gap between raw emission/resource data and real-world consequences. This translation is achieved through scientifically established characterization factors that relate specific environmental interventions to predefined Areas of Protection (AoPs), such as human health, ecosystem quality, and resource availability (Hauschild & Huijbregts, 2015; Omolayo, Feingold, Neff, & Romeiko, 2021). The conceptual mapping of this assessment framework, from the initial inventory of elementary flows to the characterization of midpoint and endpoint impacts, is visually synthesized in Fig. 6.

Analysis of the reviewed studies indicates that researchers utilize a variety of established LCIA methodologies to quantify these effects, including CML Baseline, ReCiPe (2008/2016), IMPACT World+,
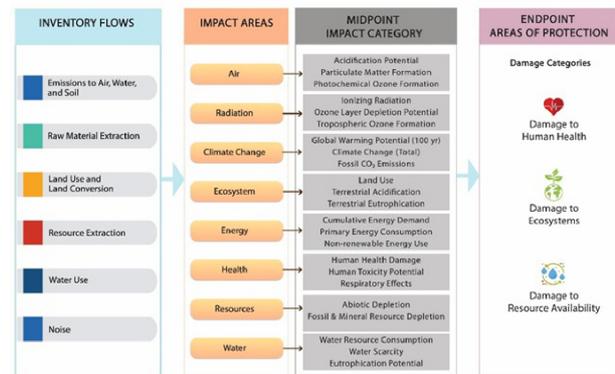

Fig. 6. The Life Cycle Impact Assessment (LCIA) conceptual framework

USEtox, Eco-indicator 99, and TRACI. These methods transform raw inventory flows into environmental impact scores using characterization factors, which express the environmental burden per unit emission or resource use (Guinée, Cucurachi, Henriksson, & Heijungs, 2018). This process allows LCIA practitioners to condense thousands of inventory flows into a manageable set of environmental indicators, typically representing 10–20 impact categories. LCIA methods are generally categorized into three major families (Goedkoop & Spriensma, 2000; Itsubo & Inaba, 2012):

· Midpoint-oriented methods: These focus on problem-oriented indicators with scientifically robust causal pathways, translating elementary flows like CO_2 or SO_2 into specific environmental themes. Midpoints provide a more direct and less assumption-intensive quantification of environmental issues, which is particularly valuable for policy development, process optimization, and industry benchmarking.

· Endpoint-oriented methods: These assess damage-oriented categories by modelling complex pathways to determine final impacts on biodiversity, human longevity, or resource scarcity.

· Hybrid methods: These integrate both approaches to provide a comprehensive view of environmental damage from intervention to ultimate impact.

The results demonstrate that Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP) emerge as the most frequently reported impact categories across the

Table 2. Mean environmental footprints for key aquaculture species

Species	Culture Intensity	Farming System	Count (n)	Mean GWP (kg CO_2 -eq/kg)	Mean AP (kg SO_2 -eq/kg)	Mean EP (kg PO_4^{3-} -eq/kg)
Litopenaeus vannamei (Whiteleg shrimp)	Semi-intensive	Pond Culture	7	5.59	0.0297	0.0194
	Intensive	Pond Culture	4	6.22	0.0470	0.0580
	Intensive	Biofloc tanks	2	5.18	0.0505	0.0260
	Intensive	RAS	2	9.10	-	-
	Super-intensive	Biofloc tanks	2	5.29	0.0425	0.0185
Macrobrachium amazonicum (Amazon River prawn)	Semi-intensive	Pond Culture	3	6.93	0.0300	0.1680
Macrobrachium rosenbergii (Giant River prawn)	Semi-intensive	Pond Culture	1	3.67	0.0220	0.1270
Oreochromis spp. (Tilapia)	Semi-intensive	Ponds	1	6.13	0.0244	0.0063
	Intensive	Ponds	1	8.45	0.0918	0.0825
	Intensive	Cages	1	7.95	0.0894	0.0873
	Intensive	Aquaponics	1	20.2	0.2000	0.1051
Cyprinus carpio (Common carp)	Semi-intensive	Earthen ponds (Conv. + Organic)	2	5.15	0.0064	0.0061
Ctenopharyngodon idella (Grass carp)	Intensive	Pond Culture	1	6.64	0.0275	0.0039
Oncorhynchus mykiss (Rainbow trout)	Intensive	Flow-through systems	4	1.66	0.0069	0.00098
	Intensive	Aquaponics	2	0.83	-	-
Salmo salar (Atlantic Salmon)	Intensive	Indoor RAS	1	16.7	0.1060	0.0024
	Intensive	Aquaponics	3	5.57	0.0400	-
	Intensive	Marine net-pens	1	2.26	0.0240	0.3380

literature. This prevalence reflects the aquaculture sector's critical focus on greenhouse gas emissions, atmospheric pollutants, and nutrient discharge into aquatic environments. Methodologically, the data reveal a dominant reliance on midpoint assessments, with CML Baseline (45%) and ReCiPe (H) (39%) being the primary choices due to their scientific maturity and transparency. However, a notable portion of studies failed to specify their LCIA methodology, identifying a transparency gap that must be addressed to ensure the reproducibility and comparative value of future aquaculture LCA research.

Comparative Analysis of Environmental Impacts and Identification of Hotspots

To facilitate a robust evaluation of the aquaculture sector's environmental performance, the impact results from the selected reviewed studies were synthesized into a comparative framework. Table 2 consolidates the mean environmental footprints for key aquaculture species, categorized by culture intensity and farming system, focusing on the three primary midpoint categories: GWP, AP, and EP. All impact values were recalculated and harmonized using 1 kg of live fish/shrimp at the farm gate as the functional unit, and 'n' represents the number of published LCA studies used to derive the reported mean values.

The comparative synthesis of LCA results revealed pronounced variability in environmental performance, primarily driven by technological configuration, duration of culture and input intensity. Across the reviewed systems, GWP spans nearly two orders of magnitude, underscoring the importance of system-specific drivers rather than species

alone. For instance, GWP values range from as low as 0.83 kg CO_2-eq/kg for intensive *Oncorhynchus mykiss* produced in aquaponic systems to as high as 20.2 kg CO_2-eq/kg for intensive *Oreochromis* spp. in aquaponics, highlighting the decisive role of energy demand and system design. High GWP values observed in Indoor RAS (16.7 kg CO_2-eq/kg for *Salmo salar*) and intensive tilapia aquaponics (20.2 kg CO_2-eq/kg) are largely attributable to substantial electricity requirements for aeration, pumping, recirculation, temperature control, and filtration. When electricity is sourced from fossil fuel–dominated grids, cumulative energy demand becomes the dominant midpoint contributor, significantly inflating climate change impacts. These patterns are consistent with the results presented in Fig. 7, where energy consumption accounts for a substantial share of total environmental burdens, and align with earlier reports identifying energy use as a critical hotspot in intensive and high-tech aquaculture systems (Cooney et al., 2021; Bordignon et al., 2022; Hou et al., 2022).
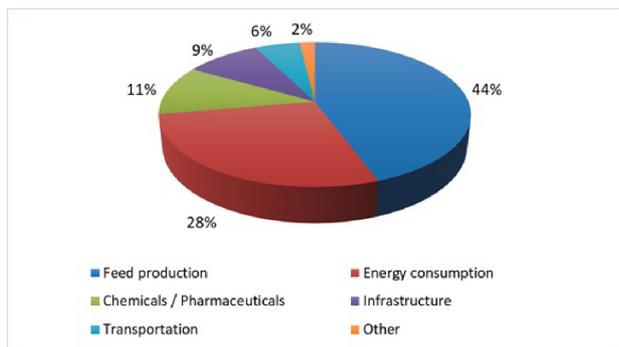

Fig. 7. Frequency distribution of environmental hotspots reported in aquaculture LCA studies.

Feed production emerges as the most consistent and influential hotspot across all systems, contributing substantially to the environmental footprint. The sensitivity of AP and EP to feed formulation is evident in the compiled dataset, particularly in systems reliant on high-protein diets with elevated phosphorus content. For example, the extremely high EP observed in marine net-pen farming of *Salmo salar* (0.338 kg PO_4^{3-}-eq/kg) reflects the direct release of feed-derived nutrients into receiving waters as elementary flows. Numerous studies corroborate feed as the dominant contributor to environmental burdens due to fishmeal and fish oil use, as well as energy-intensive feed processing (Aubin et al., 2018; Henriksson et al., 2019a; Bohnes,

Hauschild, Schlundt, Nielsen, & Laurent, 2022; Wind et al., 2022; Sun et al., 2023).

In *Litopenaeus vannamei* production, GWP values range from 5.18 to 9.1 kg CO_2-eq/kg across farming systems, with RAS exhibiting the highest carbon footprint among reported categories. Pond-based systems (5.59–6.22 kg CO_2-eq/kg) are additionally influenced by land use and land-use change impacts, particularly where mangrove conversion has occurred, which are classified as critical environmental interventions within the LCIA framework (Pazmiño, Chico-Santamarta, Boero, & Ramirez, 2025). While intensive systems such as RAS and biofloc technologies demonstrate advantages in water use efficiency and nutrient containment, these benefits are offset by higher primary energy consumption.

Beyond feed and energy, other hotspots include material use, particularly plastics in aquaponics, contributing to fossil resource depletion and ecotoxicity (Bhakar et al., 2021), transport logistics, and fuel use in boat-dependent systems such as shellfish and cage cultures (Tamburini et al., 2019; Tamburini et al., 2020; Turolla et al., 2020). Additionally, the use of antibiotics and pharmaceuticals represents a growing concern due to risks of antimicrobial resistance and aquatic contamination (Bibbiani et al., 2018; Paramesh et al., 2019). These challenges call for stricter regulation, better veterinary practices, and the promotion of alternative health management approaches such as probiotics and vaccines.

Overall, the integrated evidence from the reviewed literature highlights feed production and energy consumption as the dominant environmental hotspots across aquaculture value chains. This comparative assessment provides a robust empirical basis for targeted mitigation strategies, including FCR-optimized feeds, alternative protein sources, renewable energy integration, material substitution, and localized supply chains, which are critical for advancing the environmental sustainability of aquaculture systems (Bibbiani et al., 2018; Newton & Little, 2018; Malcorps et al., 2019; Henriksson et al., 2021).

Analysis of Strengths and Methodological Constraints

Aggregating LCA studies reveals environmental hotspots and methodological trends while identify-

ing critical data gaps (Philis et al., 2019). This facilitates cross-study comparisons and establishes best practices for sustainability; however, challenges regarding data transparency, inconsistent system boundaries, and functional units persist. Reliability is often hindered by methodological flaws and poor reporting standards (Beltran et al., 2018). Consequently, Avadí et al. (2018) advocate for standardized reporting aligned with ISO frameworks, emphasizing the explicit documentation of assumptions and inventory data. Full transparency in data and methods is essential for enhancing the credibility, reproducibility, and policy relevance of aquaculture LCAs. This review identifies key methodological concerns that currently undermine the robustness and utility of such studies within the sector.

Functional Unit (FU) Selection: FU is foundational to defining the purpose and scope of the LCA; however, inappropriate selection can fundamentally distort comparative results and lead to misinformed conclusions (Heijungs, Guinée, Beltrán, Henriksson, & Groen, 2019; Greenfeld, Becker, Bornman, Spatari, & Angel, 2022).

System Boundary Definition: Defining overly narrow boundaries risks excluding critical lifecycle stages, such as upstream transportation or downstream waste disposal, thereby compromising the overall comprehensiveness and accuracy of the environmental profile (Aubin et al., 2018).

Data Quality and Collection: Aquaculture LCAs often depend on outdated or secondary datasets, compromising the reliability of environmental profiles and hindering robust meta-analyses. While surrogate data and pedigree-matrix methods offer temporary workarounds, improving the availability and precision of primary inventory data remains a fundamental industry challenge (Beltran et al., 2018).

Allocation in Multi-functionality: Evaluating multi-output systems requires specific allocation strategies, such as economic, mass-based, or system expansion, which significantly influence outcomes. Opaque or improper allocation choices undermine methodological transparency, potentially resulting in flawed sustainability benchmarks and inaccurate environmental claims (Ghamkhar et al., 2021).

Incomplete Impact Coverage: Many LCAs overlook critical categories such as biodiversity, local ecosys-

tem health, and ecotoxicity. Furthermore, the exclusion of disease control treatments, despite their significant ecological consequences, limits the practical relevance of these sustainability assessments in real-world aquaculture management (Philis et al., 2019; Bohnes et al., 2022; Rector, Filgueira, Bailey, Walker, & Grant, 2023).

Interpretation of Results: LCA interpretations often neglect inherent methodological limitations, potentially leading to biased conclusions (Ruiz-Salmón et al., 2021). Maintaining transparency regarding uncertainties and environmental trade-offs is essential, as prioritizing single indicators can mislead stakeholders and result in unintended ecological shifts.

Static Assumptions and System Dynamics: Conventional LCA frameworks often employ static parameters that disregard the temporal variability inherent in aquaculture, such as seasonal nutrient fluctuations or production efficiencies. Excluding these system dynamics might produce cross-sectional outcomes that lack the predictive power necessary to evaluate long-term sustainability trajectories.

Uncertainty and Sensitivity Analysis: Conducting rigorous sensitivity and uncertainty analyses is critical for validating the robustness of LCA outcomes and evaluating the impact of specific methodological choices. Despite its importance, uncertainty is inherent in the LCA framework, yet remains inadequately addressed in much of the existing literature (Haslawati et al., 2022; Sun et al., 2023). For instance, while Monte Carlo simulations are commonly employed, they are often limited by a lack of covariance data, which can result in significantly inflated error margins (Heijungs et al., 2019). Furthermore, the infrequent application of sensitivity analysis in many studies weakens the overall confidence in their conclusions, highlighting a need for more transparent reporting and standardized modelling approaches.

Refinement of LCI Databases: Refining aquaculture-specific LCI databases, particularly for post-farming stages and developing countries, is essential (Bohnes & Laurent, 2019; Avadí et al., 2020). National inventories and open-access databases can improve standardization, reliability, and reproducibility.

Cross-Cutting Challenges: Several cross-cutting issues exacerbate methodological limitations in

aquaculture LCA. These include inconsistent use of normalization and weighting steps and regional biases. Socio-economic dimensions are rarely addressed, despite their relevance to sustainable aquaculture systems.

Unaddressed area: Some important environmental impacts from aquaculture are at present not quantifiable using the LCA framework, such as the spread of diseases and parasites. These impacts have been attracting widespread public concerns and have influenced the development of farming methods in many countries. The associated consequences could, for example, be accounted for as biotic resource use.

a. Emerging Areas in LCA Research

Recent LCA advancements emphasize high-resolution, multi-dimensional evaluations to capture the intricate environmental footprints of complex systems like aquaculture. Methodological innovations are strengthening analytical precision, supporting robust evidence-based policymaking and strategic planning. Furthermore, the proliferation of open-source platforms, such as OpenLCA and Brightway, is democratizing access and fostering global collaboration (Schindler, Kohlhase, Hottenroth, & Tietze, 2025). These architectures enable real-time modelling and transparent data sharing, which are indispensable for accurate sustainability profiling in resource-intensive sectors.

Circular Economy (CE): CE and LCA share the common goal of promoting sustainable resource use and reducing environmental burdens (Corona, Shen, Reike, Carreón, & Worrell, 2019). CE emphasizes retaining resource value through reuse, recycling, and waste minimization (CPMR & MedWaves, 2022), while LCA provides a quantitative framework to assess environmental impacts across a product's life cycle. Key areas of CE integration into LCA include:

· *Extended System Boundaries:* Incorporating reuse, recycling, and waste valorization into cradle-to-grave assessments (van Stijn, Eberhardt, Jansen, & Meijer, 2021).

· *Resource Efficiency:* Identifying hotspots for remanufacturing, redesign, or material recovery (Regueiro et al., 2022).

· *Circular Business Models:* LCA can evaluate the environmental implications of models such as product-service systems and sharing platforms, helping to validate their circularity claims.

Blockchain Practices and Greening Supply Chains: Blockchain offers significant potential to enhance the transparency and credibility of LCA. Its decentralized, tamper-proof nature supports secure data sharing and real-time environmental tracking, particularly when integrated with IoT and big data analytics (Zhang, Zhong, Farooque, Kang, & Venkatesh, 2020; Lin, Li, Kulkarni, & Zhao, 2021). Blockchain-enabled LCA can improve traceability and accountability in complex supply chains like aquaculture, addressing long-standing challenges such as data inconsistency and opacity (Karaszewski, Modrzyński, Müldür, & Wójcik, 2021).

Integration of Artificial Intelligence (AI) and Machine Learning: AI and machine learning are transforming LCA modelling by enabling predictive analytics, real-time scenario simulations, and hotspot detection. These tools can optimize feed formulations, resource allocation, and system design in aquaculture, enhancing sustainability and economic efficiency (Ibn-Mohammed et al., 2023). As LCA datasets become more complex and large-scale, AI can help automate data processing and scenario planning (Ghoroghi, Rezgui, Petri, & Beach, 2022).

Dynamic (Time-Dependent) LCA: In aquaculture, factors such as seasonal cycles, technological upgrades, and market dynamics can influence environmental performance. Dynamic LCA accounts for temporal variations in emissions, resource use, and system efficiency over time (Su, Ju, Ding, Yuan, & Cui, 2022). Time-dependent modelling enhances forecasting accuracy and supports adaptive decision-making.

Social Life Cycle Assessment (S-LCA): S-LCA expands LCA to include human and community impacts across the product life cycle. This includes labour conditions, health and safety, gender equity, and socio-economic contributions (Hannouf, Padilla-Rivera, Assefa, & Gates, 2024). In aquaculture, S-LCA is particularly relevant for assessing worker welfare, community livelihoods, and social inclusion in coastal areas. Combined with environmental and economic LCA, it forms the Life Cycle Sustainability Assessment (LCSA) framework for holistic evaluation.

Planetary Boundaries (PB) Framework: Integrating LCA with the planetary boundaries framework

facilitates a transition toward absolute sustainability (Wu, Huang, Ridoutt, Yu, & Chen, 2021). Unlike conventional assessments that focus on relative reductions, this approach evaluates whether production impacts remain within Earth's safe operating space, specifically regarding climate stability, land-system change, and biogeochemical flows. For the aquaculture sector, this framework provides a critical benchmark for systemic reforms, ensuring that intensification does not breach fundamental environmental thresholds.

These emerging frontiers are redefining the role of LCA as a dynamic and integrative tool, capable of supporting real-time decision-making and guiding sustainable innovation.

Recommendations for Environmentally Friendly Solutions

Mitigating the environmental impacts of aquaculture necessitates integrating low-impact solutions across the production lifecycle, specifically targeting energy, nutrition, and resource management. Targeted interventions in these domains can significantly curtail resource depletion, carbon emissions,

and ecological degradation. Table 3 outlines sector-specific strategies and innovations designed to enhance environmental performance and align the industry with broader sustainability objectives.

Conclusion

Life Cycle Assessment has proven to be a valuable tool for evaluating the environmental performance of aquaculture production systems and supporting sustainable fisheries and aquaculture development. This review highlights that feed production and energy consumption consistently represent the major environmental hotspots across species and production systems, influencing key impact categories such as global warming potential, eutrophication, and acidification. While intensive systems such as recirculating aquaculture and biofloc technologies offer improved control over water use and nutrient discharge, their overall environmental benefits are strongly dependent on energy efficiency and the source of electricity.

The review also reveals considerable variation in methodological choices among published LCA studies, particularly in functional units, system

Table 3. Sectoral specific strategies and environmental benefits

Sector	Recommended Sustainable Solutions	Environmental Benefits	Key References
Feed	* Insect, microbial, and plant-based proteins * Alternative lipids and meal replacers	* Reduces pressure on wild pelagic stocks * Promotes circularity and lowers feed footprint	Basto-Silva, Guerreiro, Oliva-Teles, and Neto (2019); Wind et al. (2022)
Electricity	* Renewable integration (Solar, Wind, Geothermal) * Smart grids and efficiency audits	* Curbs direct GHG emissions * Enhances energy security and grid resilience	Bibbiani et al. (2018); Bujas et al. (2022)
Production	* Green Chemistry and Eco-design * Lean manufacturing and circular practices	* Minimizes hazardous waste and emissions * Optimizes resource utilization efficiency	Chary, Brigolin, and Callier (2022); Jones et al. (2022)
Water	* RAS / Biofloc technologies * Advanced treatment and recycling systems * Minimizes nutrient and chemical discharge	* Drastically reduces freshwater abstraction	Song et al. (2019); Bergman et al. (2020)
Transport	* Logistics optimization and sustainable packaging * Electric/hybrid fleet adoption	* Lowers fuel usage and transport emissions * Reduces energy demand in the cold chain	Fouda et al. (2022); Gaeta et al. (2022)

boundaries, allocation methods, and impact category selection. Such inconsistencies limit the comparability of results and reduce the practical utility of LCA outcomes for fisheries managers, technology developers, and industry stakeholders. Addressing these methodological challenges is essential to ensure that LCA-based assessments provide reliable guidance for technology selection and system optimization in aquaculture operations.

Future research should prioritize applied assessments using region-specific data, improved characterization of feed ingredients, and the integration of renewable energy solutions to reduce climate impacts. Strengthening the link between LCA findings and operational decision-making will enhance the role of LCA as a practical tool for advancing environmentally responsible aquaculture technologies and supporting sustainable fish production systems. From an industry perspective, the findings suggest that meaningful reductions in environmental impacts can be achieved primarily through improvements in feed formulation, energy efficiency, and the adoption of renewable energy sources, rather than through changes in production technology alone.

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